INDO PAC J OCEAN LIFE
Volume 5, Number 2, December 2021
Pages: 61-73

P-ISSN: 2775-1961
E-ISSN: 2775-1953
DOI: 10.13057/oceanlife/o050203

Carbon stock of above ground mangroves in the Lower Volta Area, Ghana

MYERS JOHN HENRY, CHRISTOPHER GORDON, OPOKU PABI♥
Institute for Environment and Sanitation Studies, University of Ghana. Legon, Annie Jiagge Rd, Accra, Ghana. Tel.: +233-302-962-720,
♥email: opabi@staff.ug.edu.gh

Manuscript received: 4 July 2021. Revision accepted: 1 November 2021.

Abstract. *Henry MJ, Gordon C, Pabi O. 2021. Carbon stock of above ground mangroves in the Lower Volta Area, Ghana. Indo Pac J Ocean Life 5: 61-73.* The mangroves and other blue carbon systems are under high pressure because of coastal development and population. The degradation of mangrove continuity leads to the loss of the carbon stocks which is stored in the mangrove ecosystem. This study used GIS-based analysis using allometric equations and Landsat images to estimate the mangrove above-ground carbon stock in the Lower Volta area in Ghana. The classified Landsat images were used to obtain the mangrove area coverage. The ASTER GDEM covering the mangrove was calibrated to obtain the above-biomass, mangrove heights, and above ground carbon stock estimated using a global allometric equation. This study identified the socio-economic factors influencing mangrove exploitation and assessed local residents' willingness to use an alternative energy source, Liquefied Petroleum Gas (LPG). The carbon stock in 2014 for the study area was estimated at 269,379.5 Mg, and the carbon stock was estimated at 50.102 Mg per hectare. The changes in carbon stock on a time series analysis revealed that the study area lost its carbon stock between 1991 and 2014 at 161,428.65 Mg. The results indicated that significant factors influencing mangroves' exploitation were the commercial supply of fuel wood, increased income, and supply of fuel wood for domestic use. The local residents were less likely to use LPG as an alternative due to price and safety considerations and preferred mangroves as an energy source. All major stakeholders were recommended to contribute towards effectively managing and protecting the mangrove resource.

Keywords: Allometric, carbon stock, coastal, Ghana, ecosystem

INTRODUCTION

Mangroves refer to tropical vegetation positioned at the interface between land and sea, found along the coast and estuaries throughout the tropics and subtropical regions that uniquely adapted to thrive in soils with high salinities (Joshi and Ghose 2003). Although mangroves account for 1% of tropical forests, it is the most carbon-rich containing an average of 1,023 Mg carbon per hectare (Spalding et al. 2010; Donato et al. 2011). With the effects of climate change more apparent, significant reductions in greenhouse emissions are urgently needed, aligning with the need to properly manage habitats that act as critical carbon sinks to reduce greenhouse gas (Smith and Gattuso 2009).

The mangroves in Ghana are mainly found along the fringes of lagoons on the western coast, bordering the Volta River's lower reaches and deltaic areas. They are best developed along a stretch on the west coast between Cote d'Ivoire and Cape Three Points (FAO 2005). Mangroves are important because they provide ecosystem services, including protection of coastlines, erosion, and floods; nursery grounds for juvenile fish, crabs, and mollusks; and supporting livelihoods by providing goods such as wood fuel, timber, and non-timber forest products (Alongi 2002). Gordon et al. (2009) estimated the value of mangrove-related harvesting and contribution to marine fisheries is well over $ 6,000,000 annually in Ghana. This estimate excludes others, such as coastline protection and nesting sites for migratory birds.

In Ghana, mangroves are threatened by land-based sources of pollution, hydrological and land use change, and population growth. The mangrove area in this country fell by 24%, from 181 km^2 to 137 km^2, between 1980 and 2006 (Corcoran et al. 2007). The continuous degradation increases the risk of stored carbon accumulation being released into the atmosphere and CO_2 concentration (Kauffman et al. 2014). The mangroves as efficient carbon sinks have been recognized recently and incorporated into climate change mitigation, which focuses on reducing CO_2 and other GHGs by conserving and restoring natural systems. (Nellemann et al. 2009).

Blue carbon refers to the carbon stock stored in oceans and coastal ecosystems, such as; mangroves, seagrass meadows, and tidal salt marshes. It includes the carbon stored within the soil, the living biomass below ground (roots), the living biomass above ground (leaves, branches, stems), and the non-living biomass, e.g., dead wood and leaf litter (Mcleod et al. 2011). The coastal ecosystems store more carbon than terrestrial ecosystems, especially in the soil. The limited carbon storage potential in terrestrial soils is because of the supply of oxygen availability, which allows bacteria to carbon oxidation resulting in its release back into the atmosphere (Schlesinger et al. 2001). The soil is usually saturated with water, keeping oxygen concentrations very low, leading to continual vertical carbon accretion and a high overtime build-up (Chmura et al. 2003). Therefore the soils in coastal ecosystems can store carbon for long periods (centuries to millennia) than those in terrestrial ecosystems (Chambers et al. 2001)

Mangroves have high above-ground and below-ground biomass, productivity, and high carbon sequestration rates despite their small global area (Komiyama et al. 2008; Donato et al. 2011; Mcleod et al. 2011). Approximately 2,000 Mg/ha of carbon is stored in the mangrove ecosystem, one hundredfold more than in high tropical forests. The spatial variations understanding in carbon stocks and forest biomass are important to inform global climate change models and developing policies, planning actions, and programs to mitigate their climate change effects (Nepstad et al. 2011; Grabowski and Chazdon 2012), while mangroves are highly threatened, especially with over a third of the world's mangroves lost through conversion into agriculture and aquaculture (Alongi 2002).

The aims of this study are: (i) To map out the mangrove area within the study area and determine the features of the land cover. (ii) To estimate the carbon stock and the above-ground biomass using allometric equations and determine the changes over the past 25 years. (iii) To assess the perception of change by the local community in the mangrove area. (iv) To assess the willingness to use alternative energy sources such as LPG and identify socio-economic factors that drive mangrove exploitation.

MATERIALS AND METHODS

Study area

The study area comprised sections of the Keta Municipal area and the South Tongu Districts of the Ghana Volta Region, where the highest mangroves in the savannah zone occur (Akpalu 2007). It lies within latitude 5°46 N and 5°57 N and longitude 0°41 E and 0°53 E and covers an area of about 280 km^2. It covered several towns and villages, Sesieme, Anyanui, Hawui, Gamenu, Tunu, and Bomigo (Figure 1).

The vegetation within the study area includes the northern part of tall grasses interspersed with medium-sized trees and the middle with short grasses and some short trees. Mangroves and tall grasses characterize the southern part along the Volta Estuary. These areas experienced a double maximum rainfall pattern, with the major season from March to July and the minor season beginning in September through November. It has rainfall between 800-1,000 mm annually.

Mangrove vegetation continuously stretches at the southwestern end of the municipality, from Anyanui to Bomigo, which formed the basis of the selection of the area.

Data collection

Satellite imagery

Landsat Thematic Mapper (TM) imagery of the study area at a spatial resolution of 30m × 30m was obtained from the Global Land Cover Facility of the United States Geological Survey (http://earthexplorer.usgs.gov/). That was to determine the mangrove area, land cover features, and the above-ground carbon stocks estimation in the mangroves.

Three Landsat TM images, 1991, 2002, and 2014 of the mangroves within the study area were obtained to classify mangroves to determine the areal coverage. The selected data sets shown in Table 1 were cloud-free images acquired between January and March.

Table 1. Dates of Landsat images acquired

Year	Month	Satellite
1991	March	Landsat 4
2002	January	Landsat 7
2014	March	Landsat 8

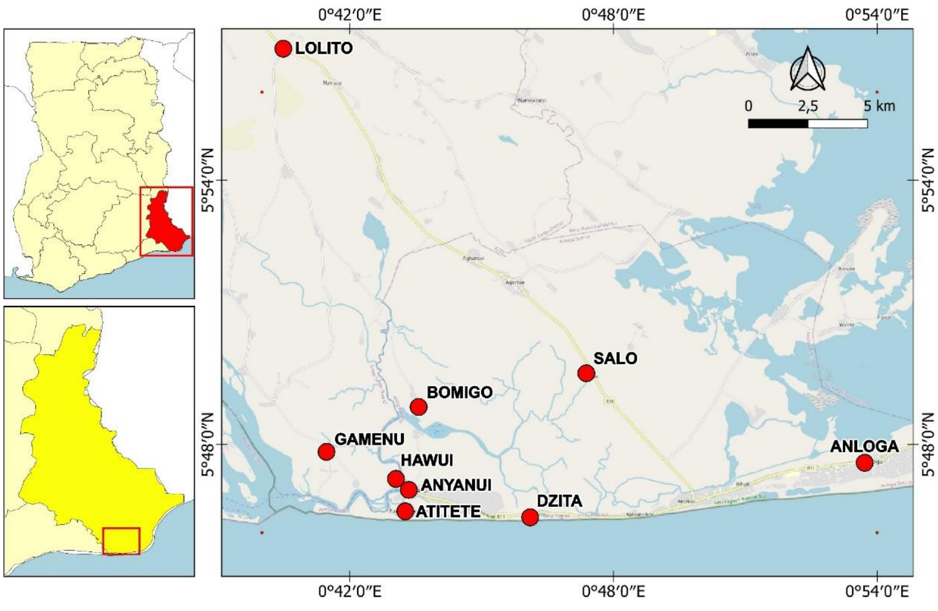


Figure 1. Map of the study area in the Volta Delta, Ghana

The Advanced Space-borne Thermal Emission and Reflectance Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 was obtained from NASA's Land Processes Distributed Active Archive Centre. The ASTER GDEM is the earth's surface map derived from landscape observation on an optical stereo instrument, including its land cover. The data was generated at a sampling space of 30 meters. It was obtained for the mangrove heights estimation based on the assumption that mangroves are located at sea level, and elevation measurements can be calibrated for the canopy height estimation of mangroves (Simard et al. 2006)

Questionnaire administration

Fieldwork was carried out in February 2016 in two villages (Bomigo and Hawui) in the Lower Volta Area. These settlements were selected due to mangroves were harvested extensively in these villages. The study's objectives were to access the perception of the change in mangroves area, assess the willingness to use LPG as an alternative energy source, and identify socio-economic drivers of mangrove exploitation.

The total population of these two communities (Ghana Statistical Service 2012) was about 1,000. However, with an annual growth rate of 2.5 % per annum, the population was projected to be about 1,200 in 2016, and a sample size of 120 was selected.

A total of 120 questionnaires were administered by purposive sampling to residents of the two mangrove harvesting communities. Data gathered from respondents covered the following: (i) Demographics, (ii) Occupation, (iii) Benefits derived from mangroves and how these changes. (iv) Socio-economic factors that drive mangrove exploitation. (iv) Willingness to use Liquefied Petroleum Gas as an alternative energy source

Data analysis

Pre-processing and spatial sub-setting of Landsat images

Three clear, cloud-free Landsat images were selected to classify the study area: March 1991, January 2002, and March 2014. These periods also parallel to Ghana's dry season, making field sampling and ground truthing relatively easier than in the wet season. These study areas are contained within Landsat path 193 and row 56. The Landsat images were subsets using the spatial/spectral tool in ENVI 4.7. The tool obtained a region of interest with a high concentration of mangrove vegetation.

Analysis using ENVI 4.7 and ArcMap 10.1

The methods to analyze data included image classification (supervised and unsupervised), the development of land cover classes, an accuracy assessment (confusion matrix), and change detection analysis.

The loaded bands to obtain the natural/true color of the images were; bands 7, 5, and 3 for Landsat 8 and Landsat 4; bands 3, 2, and 1 for Landsat 7.

Unsupervised classification

An unsupervised classification using Iterative Self-organizing Data Analysis (ISODATA) in ENVI 4.7 was initially conducted in the study area to determine mangroves' coverage. That was to help in the field validation and later supervised classification (Fatoyinbo et al. 2008; Fatoyinbo and Simard 2013). Furthermore, different from the K-mean method, which requires prior knowledge to estimate the number of clusters, the ISODATA could create as many classes as possible based on the data by automatically calculating class means equally distributed in the data space and then using minimum distance techniques could iteratively clustering the remaining pixels. Each iteration process recalculates means and reclassifies pixels concerning new means. Unless a standard deviation or distance threshold is specified, the pixels are then classified to the nearest class. The iteration process continues until the number of pixels in each class changes by less than the maximum number of iterations reached or the selected pixel change threshold (Tou and Gonzalez 1974)

Supervised classification

This classification method was the clusters of pixels in a dataset into classes corresponding to user-defined training areas. The training areas of different Regions of Interest (ROIs) were carefully selected for supervised classification in ENVI 4.7. The assumption used for the Maximum Likelihood supervised classification is that each band's class statistics are normally distributed and determine whether a pixel belongs to a specific class based on the highest probability (maximum likelihood).

ENVI implements maximum likelihood classification for each pixel in the image by calculating the following discriminant functions (Richards 1999)

$$g_i(x) = 1\text{n}\, p(\omega_i) - 1/_2\, 1\text{n}\, |\Sigma_i| - 1/_2 (x - m_i)^T \Sigma_i^{-1} (x - m_i) \quad \text{(Eq. 4)}$$

Where: i = class

x = n-dimensional data (where n is the number of bands)

$p(\omega_i)$ = probability that class ω_i occurs in the image and is assumed the same for all classes

$|\Sigma_i|$ = determinant of the covariance matrix of the data in class ω_i Σ_i^{-1} = its inverse matrix

m_i = mean vector

The identification of mangroves during the classification was aided by data from the World Atlas Earth scan by Spalding et al. (2010) and high-resolution imagery from Google Earth.

The resulting classes were combined into a final classification with four land cover types: (i) Mangroves, (ii) other vegetation, (iii) water, and (iv) bare ground.

Confusion matrix

A confusion matrix, the error matrix, was used to assess the image classification accuracy. It does so by comparing the image classification to the ground truth information. The result of an accuracy assessment provides an overall accuracy of the map based on an average of the accuracies for each class in the map.

$$\text{Overall accuracy} = \frac{\text{Number of pixels correctly classified}}{\text{Total number of pixels}} \quad \text{(Eq.5)}$$

Kappa measures the agreement or accuracy between the classification map and the reference data as indicated by the major diagonals, and the chance agreement indicates the row and column totals (Jensen 2003). The kappa coefficient is given by the formula below:

$$\text{Kappa (k)} = \frac{P_0 - P_e}{1 - P_e} \quad \text{(Eq.6)}$$

Where: P_0: the proportion of correctly classified cases, and P_e: represents the proportion of correctly classified cases expected by chance.

Change detection analysis

After each image belonging to the respective years was classified, a multi-date post-comparison and change detection algorithm was used to determine changes in the land cover in the intervals; 1991-2002 and 2002-2014. The change detection computed class or pixel change, change in the area, and percentage change for all classes

Field measurements

A survey of mangrove sites within the study area was conducted from the 10th to the 13th of February, 2014. This period was within the range of time the study's satellite images were acquired and the dry season, making the mangroves fairly accessible. The preliminary maps of mangrove areas were obtained from initial visits and classifications as bases for the field survey.

A total number of 14 sites were visited during the field survey. In addition, GPS readings of mangrove locations were taken as ground control points across the study area covering towns including Dzita, Atitete, Salo, Anyanui, and Bomigo.

At five mangrove sites, a total of 20 sample plots of 0.01 ha (10m × 10m) were assessed. Parameters included GPS readings, species, mangrove heights, and the number of trees within a sample plot. The mangrove height was determined by measuring the distance from the tree and the elevation angle using a range finder and a clinometer, respectively. The tree height was computed using obtained tree distance and angle of elevation. The above-ground mangrove biomass was estimated by the tree height measurements

Estimating the above-ground biomass of mangroves

In this study, the land cover map masked all the areas, not within the mangrove area on the GDEM. That included areas above 15 m because the tallest tree recorded from field measurements was 12 m, similar to the tallest mangrove tree observed by Ntyam (2014) at Songhor, also located in the coastal savanna zone. Therefore, an assumption of a maximum tree height of 15 m was established

The ASTER GDEM was calibrated using equation (1) from Simard et al. (2006). The assumption to the equation was applied based on low tree diversity and similar structural and zonation patterns observed globally in mangrove ecosystems (Chapman 1944, 1970; Smith 1992). In addition, this study assumed that mangroves grow at sea level, so topography was not taken into account because the ASTER GDEM has a positive bias to land cover features such as mixed forests and woody wetlands (Meyer and ASTER-GDEM-Validation-Team 2011). However, the elevation measured by GDEM correlates with canopy height and, therefore, could be calibrated to estimate the canopy height of mangroves (Simard et al. 2006).

$$H = -2.19 \times 1.12\ H_{GDEM} \quad \text{(Eq. 7)}$$

The above-ground biomass was estimated using a global allometric equation (7) developed by Saenger and Snedaker (1993a,b) which was used by Fatoyinbo et al. (2008) and Fatoyinbo and Simard (2013) in estimating the biomass of mangroves in Mozambique and Africa, respectively.

$$B_H = 10.8 \times H + 35 \text{ RMSE } 43.8 \quad \text{(Eq. 8)}$$

Where
B_H: above-ground biomass
H: mangrove canopy height
RMSE: root mean square error

The carbon stock was then computed from the above-ground biomass using the conversion factor of 0.5 (Tang et al. 2014), as shown below.

$$C = 0.5 \times ABG \quad \text{(Eq. 8)}$$

Where: C is the carbon stock, and ABG is the above-ground biomass)

Socio-economic factors that drive mangrove exploitation and the willingness to use LPG as an alternative energy source

A multiple regression analysis to determine whether the identified socio-economic factors significantly influenced the decision to exploit mangroves was conducted using the equation below.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + e \quad \text{(Eq.9)}$$

Where Y: a decision to exploit mangroves
β_0: constant of regression
$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$: respective regression co-efficient
X_1, X_2, X_3, X_4, X_5: respective independent variables (factors that influence mangrove exploitation)
e: error of the regression

A logistic regression using the odds ratio was used to determine the willingness of the local people to use LPG as an alternative energy source using the equation below.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + e \quad \text{(Eq. 10)}$$

Where Y: willingness to use LPG as an alternative energy source
$\beta_1, \beta_2, \beta_3$: respective regression coefficient
X_1, X_2, X_3: respective independent variables of price, safety, and preference
e: error of the regression

Limitations of study

The accessibility to mangrove areas due to the lack of roads necessitating movement by boat in some instances was the major challenge during field sampling. Field plots were therefore established along the road from Salo down to Anyanui. In this study, the sizes of plots were significantly smaller than the spatial resolution of satellite images; therefore assumed that the natural height variability of the mangroves area was not fully represented and could not be used to calibrate the ASTER DEM (Simard et al. 2008)

RESULTS AND DISCUSSION

Land-use/cover features

This study identified four land cover features in the Lower Volta area: Mangroves (*Rhizophora* sp. and *Avicennia* sp.), Water, Other Vegetation, and Bare Ground. Table 2 shows the description of each land cover feature.

The proportion and distribution of land cover features by area and percentages are shown for the years 1991, 2002, and 2014 in Tables 3, 4, and 5 and Figure 2. However, there was a continuous decline in mangrove areas from 1991-2014, while bare ground and other vegetation areas increased. There was also a significant decrease in the area covered by water between 1991-2002.

1991 land cover accuracy assessment

An accuracy assessment was conducted with ground reference points and randomly generated points to produce an overall accuracy of 85.43% with a kappa coefficient of 0.787.

Distribution of land cover features (1991)

The total subset representing the Lower Volta covered about 280 km^2. Out of this total, approximately 34.22% was classified as mangroves representing an area of 95.954 km^2. Other land cover types classified included water, mainly the Volta Lake, which covered 11.87%, representing 33.283 km^2, bare ground, including some settlement areas, and 38.51% representing 107.966km^2, and other vegetation types covered 15.40% representing 43.185 km^2, which is summarised in Table 3.

2002 land cover accuracy assessment

An accuracy assessment was conducted with ground reference points and randomly generated points to produce an overall accuracy of 90.09% with a kappa coefficient of 0.864.

Distribution of land cover features (2002)

Of the total area covered by the study area, approximately 35% were classified as mangroves, accounting for 87.700 km^2. Water which was mainly contributed by the Volta lake, contributed 8.50%, representing 21.190 km^2. The bare ground class, including some settlement areas, covered 44.91% of the study area, representing 112.502 km^2. The other vegetation covered 23.51% representing 58.863 km^2 (Table 4).

Land cover accuracy assessment (2014)

An accuracy assessment was conducted with ground reference points and randomly generated points to produce an overall accuracy of 85.18% with a kappa coefficient of 0.7957.

Distribution summary of land cover features (2014)

Out of the total classified area, approximately 22.73% was classified as mangroves representing an area of 63.729 km^2. Water covered 8.41% of the area representing 23.580 km^2, bare ground, which included some settlement areas, covered 43.49%, representing 121.943 km^2, and other vegetation types covered 25.37%, representing 71.143 km^2 (Table 5).

Table 2. Land-use/cover features

Land cover feature	Description
Mangrove	All mangrove tree species, mainly Rhizophora sp and *Avicennia sp*
Water	Natural water sources, including rivers and lakes (Volta lake)
Bare Ground	Bare land areas and other areas with patches of grass
Other Vegetation	All other vegetation types apart from mangroves

Table 3. Distribution summary of land cover features (1991)

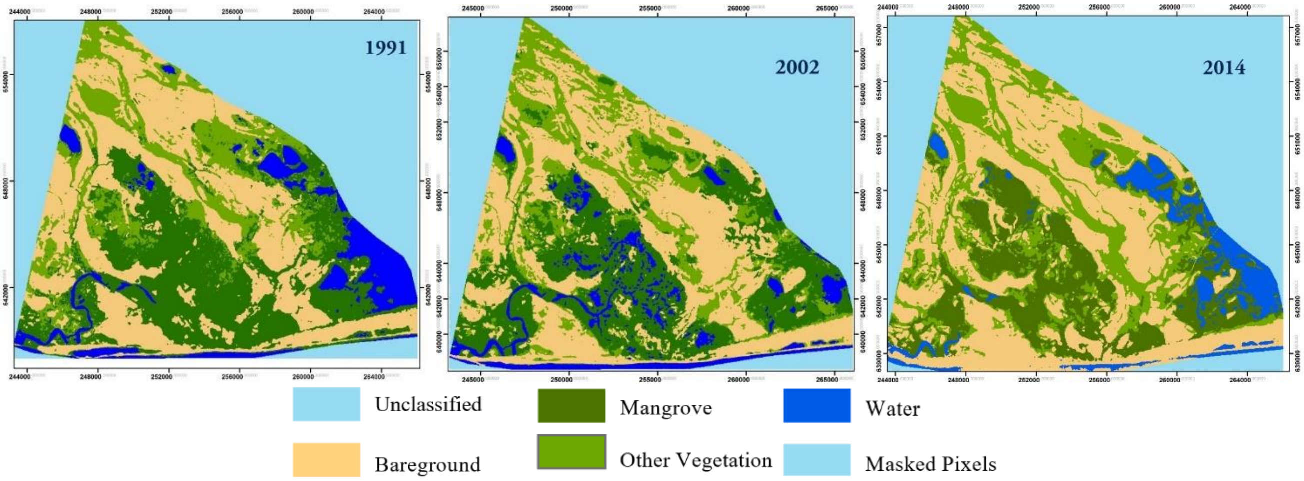
Land cover feature	Points	Percentages	Area/km^2
Mangrove	106,616	34.22%	95.954
Water	36,981	11.87%	33.282
Bare Ground	119,962	38.51%	107.965
Other Vegetation	47,983	15.40%	43.184

Table 4. Distribution summary of land cover features (2002)

Land cover feature	Points	Percentages	Area/km^2
Mangrove	97,445	35.00%	87.700
Water	23, 655	8.50%	21.289
Bare ground	125,002	44.91%	112.501
Other Vegetation	56, 404	23.51%	58.863

Table 5. Distribution summary of land cover features (2014)

Land cover feature	Points	Percentages	Area/km^2
Mangrove	70,810	22.73%	63.729
Water	26,200	8.41%	23.580
Bare Ground	135,492	43.49%	121.942
Other Vegetation	79,048	25.37%	71.143



A B C

Figure 2. Map of land cover features. A. March 1991, B. January 2002, C. March 2014

Patterns of changes in land cover features from 1991 to 2002

The mangrove area in 2002 was reduced by about 8.6% compared with the area covered in 1991. The area covered by water showed a similar pattern of change, decreasing by about 36.0% compared with the area covered in 1991. Within this same period, there was an increase in the area covered by other vegetation and bare ground. The other vegetation area increased by about 36.3%, and the bare ground area cover increased by about 4.2%. The changing pattern over the 10 years showed the conversion of approximately 40% of the mangrove area into other classes; bare ground, water, and other vegetation accounting for about 14%, 7%, and 18%, respectively. The changes in area coverage of each land cover feature from 1991-2002 are shown in Tables 6 and 7.

Table 6. Changes in area cover of land cover features (1991-2002)

Land cover feature	Area (1991) (km^2)	Area (2002) (km^2)	Change (km^2)
Mangrove	95.95	87.70	-8.25
Water	33.28	21.29	-11.99
Other Vegetation	43.18	58.86	+15.68
Bare ground	107.97	112.5	+4.54

Table 7. Changes in land cover features (1991-2002)

Land cover features (Initial 1991, Final 2002)	Bare ground	Mangrove	Water	Other vegetation	Row total	Class total
Percentages						
Mangroves	2.288	60.999	48.073	24.748	99.988	100
Water	1.134	7.368	38.222	0.634	99.996	100
Bare ground	84.095	13.996	3.38	16.525	99.985	100
Other vegetation	12.461	17.63	10.262	58.039	99.977	100
Masked pixels	0.022	0.008	0.062	0.054	0.042	100
Class total	100	100	100	100	0	0
Class changes	15.905	39.001	61.778	41.961	0	0
Image difference	4.201	-8.602	-36.035	36.307	0	0
Area (km^2)						
Mangroves	2.47	58.53	16	10.69	87.69	87.7
Water	1.22	7.07	12.72	0.27	21.29	21.29
Bare ground	90.79	13.43	1.13	7.14	112.48	112.5
Other vegetation	13.45	16.92	3.42	25.06	58.85	58.86
Masked pixels	0.02	0.01	0.02	0.02	0.07	177.24
Class total	107.97	95.95	33.28	43.18	0	0
Class changes	17.17	37.42	20.56	18.12	0	0
Image difference	4.54	-8.25	-11.99	15.68	0	0

Patterns of changes in land cover features from 2002 to 2014

Tables 8 and 9 show the changes in land cover features from 2002-2014 in percentages and area. There was a 27% decline in the mangrove area in 2014 compared with the area in 2002. Conversely, in the previous period between 1991 and 2002, the area covered by water increased by about 11% in 2014. The area covered by bare ground and other vegetation showed a similar increasing pattern. The area covered by other vegetation showed the greatest increase of 20.1%, and the bare ground area increased by about 8.4%.

There were also some significant changes between classes. For example, another vegetation area has about 41% of its area being converted into other classes, including bare ground and mangroves, accounting for 24% and 11%, respectively. The mangrove area also had about 47% of its area converted into other vegetation and water; these accounted for 26% and 12%, respectively. The area covered by water had the highest area (58%) converted into other classes. About 40% was converted to mangroves and 15% into bare ground.

Patterns of changes in land cover features from 1991-2014

Figure 3 shows the changes in terms of area coverage of the land cover features over 23 years. The mangrove area reduced from 95.95 km^2 in 1991 to 87.7 km^2 in 2002. That represented a decline of 8.6%. The mangrove area continued to decline from 87.7 km^2 to 63.73 km^2 representing a 27.3% reduction. A comparison of the mangrove area from 1991 to 2014 showed a significant decline of 33.6%. There was a significant reduction in the area covered by water from 33.28 km^2 in 1991 to 21.29 km^2 in 2002. In contrast, there was a small increase of 2.29 km^2 in the area covered by water from 2002 to 2014. The area coverage of the bare ground and other vegetation increased steadily from 1991 to 2014. The bare ground increased from 107.97 km^2 to 112.5 km^2 in the 1991-2002 period and then from 112.5 km^2 to 121.94 km^{2}in the 2002-2014 period, representing an overall increase of 13.8%. The other vegetation area cover increased from 43.18 km^2 to 58.86 km^2 in 1991-2002 and then from 58.86 km2 to 71.14 km3 in 2002-2014.

Mangrove height and biomass estimation

Figure 4 represents the mangrove height ranging from 1.19 m to 14.61, averaging 6.9 m. Again, height values are represented on a grey scale, with low values graduating from dark regions to high values in lighter regions.

The above-ground biomass of mangroves represented in Figure 5 ranged from 46.9 Mg to 192.788 Mg, with an average of 109.8 Mg. The total above-ground biomass and carbon are shown below in Table 10. Again, height values are represented on a grey scale, with low values graduating from dark regions to high values in lighter regions.

Table 8. Changes in area cover of land cover features (2002-2014)

Land cover feature	Area (2002) (km^2)	Area (2014) (km^2)	Change (km^2)
Mangrove	87.70	63.73	-23.97
Water	21.29	23.58	+ 2.29
Other vegetation	58.86	71.14	+12.28
Bare ground	112.5	121.94	+9.44

Table 9. Changes in land cover features (2002-2014)

Land cover features (Initial 2002, Final 2014)	Bare ground	Mangrove	Water	Other vegetation	Row total	Class total
Percentages						
Mangroves	1.592	53.238	40.279	11.334	99.999	100
Water	0.485	12.233	41.907	5.721	99.927	100
Bare ground	86.062	8.740	15.642	23.937	99.970	100
Other vegetation	11.853	25.772	2.16	58.986	99.966	100
Masked pixels	0.008	0.016	0.013	0.021	0.022	100
Class total	100	100	100	100	0	0
Class changes	13.938	46.762	58.093	41.014	0	0
Image difference	8.392	-27.333	10.759	20.861	0	0
Area (km^2)						
Mangroves	1.79	46.69	8.58	6.67	63.73	63.73
Water	0.55	10.73	8.92	3.37	23.56	23.58
Bare ground	96.82	7.67	3.33	14.09	121.91	121.94
Other vegetation	13.34	22.6	0.46	34.72	71.12	71.14
Masked pixels	0.01	0.01	0	0.01	0.04	177.2
Class total	112.5	87.7	21.29	58.86	0	0
Class changes	15.68	41.01	12.37	24.14	0	0
Image difference	9.44	-23.97	2.29	12.28	0	0

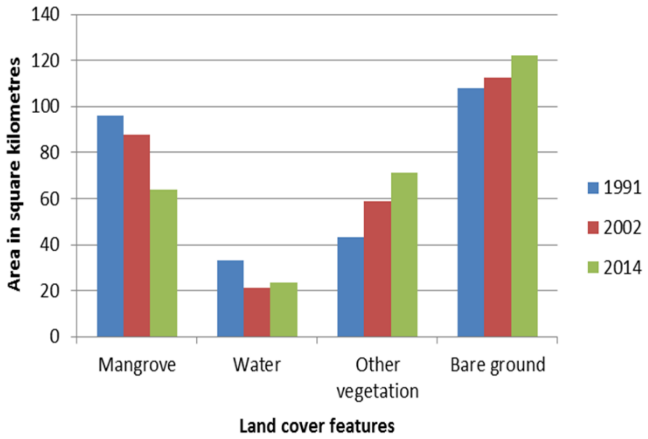


Figure 3. Changes in land cover features from 1991-2014

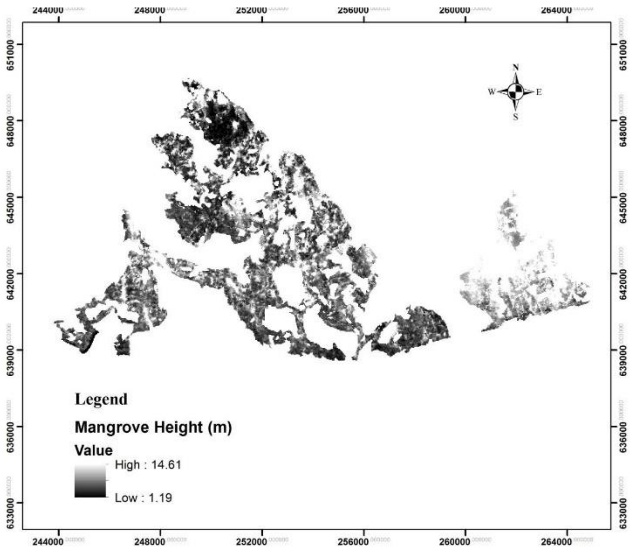


Figure 4. Map of mangrove heights

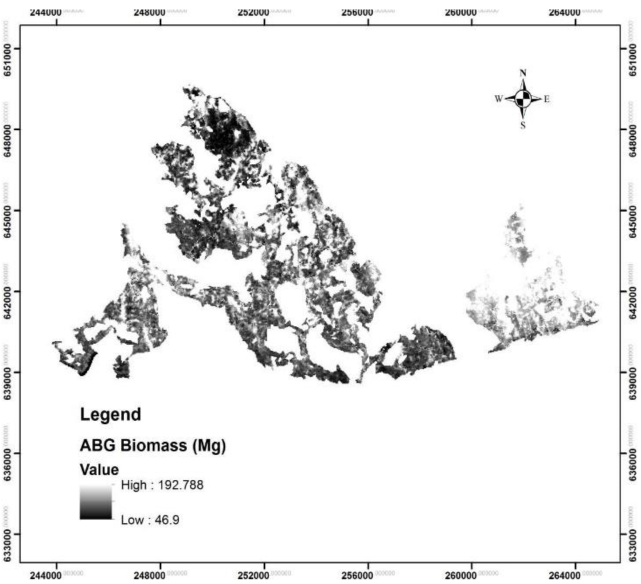


Figure 5. Map showing the above-ground biomass of mangroves (2014)

Table 10. Above-ground biomass and carbon stock of mangroves (2014)

Area (km^2)	Total biomass (mg)	Biomass per hectare (mg/ha)
53.766	538,759.00	100.204
Area (km^2)	Carbon (mg)	Carbon per hectare (mg/ha)
53.766	269,379.50	50.102

Table 11. Changes in Above-ground biomass and carbon from 1991-2014

Year	1991	2002	2014	Change (1991-2014)
Mangrove				
Area (km^2)	95.95	87.70	63.73	-32.22
Biomass (mg)	961,457.38	878,789.08	638,600.09	-322,857.29
Carbon (mg)	480,728.69	439,394.54	319,300.05	-161,428.65

Table 12. Potentially lost CO_2 from 1991-2014

Carbon stock lost (mg)	Potentially lost CO_2 (mg)
161,428.65	602,352.15

Table 13. Average changes in carbon stocks and average rate of change

Period	Change in carbon (mg)	Rate of change per year (mg/yr)
1991-2002	- 413,34.15	- 3,757.65
2002-2014	-120,094.49	- 10,007.87
Average	-807,14.32	-6,882.76

Perception of change

There was a consensus on the general decline of mangroves in the Lower Volta area. However, opinions were divided regarding the mangrove area in the two communities. In Bomigo, about 77% of respondents reported that the mangrove area in their community had increased. Of these respondents, 44% were male, and 56% were female. Regarding occupation, about 5% of those who observed an increase in mangrove coverage were mangrove harvesters, fishermen, and people who engaged in both fishing and mangrove harvesting, accounting for 65% and 30%, respectively. Excessive mangrove planting attibuted about 77% of those who reported an increase in mangrove area coverage. The remaining had no idea the cause of the increase in mangroves, attributed to 23%. On the other hand, about 17% of respondents in Bomingo reported a decrease in the mangrove area. Of this, 60% were male, and 40% were female. Regarding occupation, 40% were mangrove harvesters, and 60% engaged in mangrove harvesting and fishing (Figure 6).

In Hawui, about 79% of respondents reported a reduction in mangrove coverage. Of these, about 67% were male, and 33% were female. Regarding occupation, 67% were in mangrove harvesting, and 33% were fishing. About 93% of respondents who observed a reduction in mangrove areas attributed them to harvesting mangrove resources. The remaining 7% attributed the reduction in mangroves to changes in the Volta River hydrology. Of the 21% of respondents who reported an increase in the mangrove area, about 64% were male, and about 36% were female. Regarding occupation, about 45% were mangrove harvesters, 27% were engaged in fishing, and 28% were fishing and mangrove harvesting (Figure 7).

Social survey results

Socio-economic factors that drive mangrove exploitation

The major factors in the study area that influenced the respondent's decision to exploit mangrove resources were identified as: (ii) Increased income, (ii) wood for construction, (iii) Medicinal purpose, (iv) commercial supply of wood fuel, (v) Supply of wood fuel for domestic use.

A multiple regression analysis was conducted to establish whether these factors influenced the decision to exploit mangroves. The results showed that these factors significantly influence the decision to exploit mangroves at a 95% confidence interval ($p = 0.035$).

An individual significance test was conducted using a t-test statistic to determine the significance of each factor influencing the decision to exploit mangroves. The results revealed that the following factors were significant; commercial supply of fuel wood, increased income, and wood fuel for domestic use, as shown in Table 14 below with a $p < 0.05$. On the other hand, the decision to exploit mangroves did not significantly influence by medicinal purposes and the lack of alternative energy sources.

The R^2 obtained from the regression output was 0.65. That means about 65% of the total variation with benefits derived from mangrove harvesting is attributed to the identified factors shown in Table 14, which indicates that about 35% of the variation is not identified.

In magnitude, increased income has the highest outcome with a coefficient of 0.838. That was followed by the commercial supply of wood fuel with a coefficient of 0.525, supply of wood for domestic use with 0.430, wood for construction with 0.240, lack of alternative energy source with 0.197, and medicinal purpose with 0.142, respectively.

The respondents' demographic characteristics were also analyzed to determine whether they influenced the decision to exploit the mangrove resource. The analysis showed that the demographic characteristics, i.e., marital status, number of children, sex, age, and education level, did not significantly influence the decision to exploit the mangrove resource ($p > 0.05$), as shown in Table 15.

The willingness to use LPG as an alternative was conducted to test energy sources with a binary logistic regression. The results showed that respondents are about 0.445 times less likely to use LPG due to the product's price. It also showed that the local people are 1.497 times more likely to use mangroves due to preference than LPG. Finally, due to safety, it was also shown that people were about 0.743 times less likely to use LPG as alternative energy. These results are shown below in Table 16.

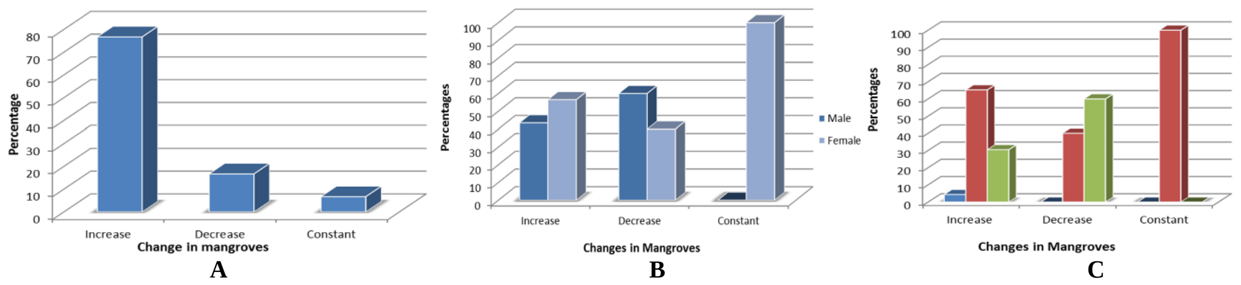


Figure 6. Perception of change in mangroves of Bomingo. A. All, B. Gender base of increase, C. occupation base.

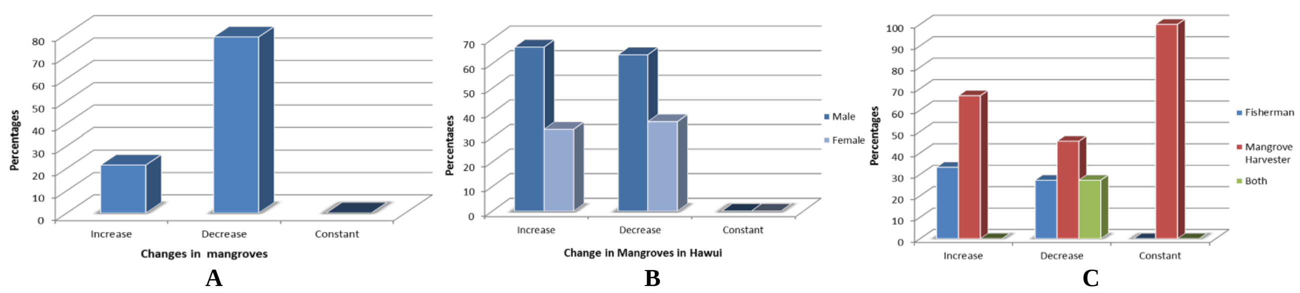


Figure 7. Perception of change in mangroves of Hawui. A. All, B. Gender base of increase, C. occupation base

Table 14. Significance of socio-economic factors in influencing mangrove exploitation

Variable	Co-efficient	Standard error	p-value	Confidence interval
Increased income	0.838	0.304	0.001*	0.425-0.920
Commercial supply of fuel wood	0.525	0.341	0.002*	0.16-1.213
Supply of wood fuel (domestic)	0.430	0.242	0.023*	0.059-0.524
Wood for construction	0.240	0.330	0.125	0.150-0.320
Medicinal purpose	0.142	0.208	0.063	0.105-0.221
Lack of alternative energy sources	0.197	0.202	0.03*	0.212-0.605

Note: *significant at $P \leq 0.05$

Table 15. Significance of demographic characteristics in influencing mangrove exploitation

Variable	Co-efficient	Standard error	p-value	Confidence interval
Age	-0.800	0.158	0.616	-0.067-4.703
Marital Status	0.255	0.255	0.323	-0.804-0.123
Sex	-0.340	0.229	0.146	-0.400-0.240
Educational level	-0.074	0.131	0.575	-0.339-0.191
Number of children	0.060	0.082	0.466	-0.105-0.226

Table 16. Willingness to use LPG as an alternative energy source

Variable	Co-efficient	Standard error	Odds ratio	p-value	Confidence interval
Price	-0.809	0.907	0.445	0.030*	0.75-2.633
Preference	0.404	0.980	1.497	0.001*	0.219-10.221
Safety	0.298	0.966	0.743	0.758	0.112-4.932

Note: *significant at $p \leq 0.05$

Discussion

Image classification accuracy

The image classification's lowest overall accuracy was 85.18% in 2014, and the highest was 90.09% for the 2002 classification. The highest kappa coefficient was 0.864 for the 2002 and 0.796 for the 2014 classifications. According to Rahman et al. (2004), kappa values greater than 80% represent a strong agreement between the classification map and ground reference points. Therefore, the classification map generated from this study strongly agrees with the ground information.

Change detection

The decrease in mangrove vegetation between 1991 and 2002 could be attributed to the exploitation of the mangroves by the local people. Tsikata et al. (1997) reported that the damming of the Volta River at Akosombo and Kpong resulted in the decline of economic opportunities such as marine and inland fishing. Furthermore, the dam's construction resulted in changes in the hydrology and salinity of the water. In addition to declined soil fertility, climatic conditions changes, and population pressure rendered the exploitation of the mangrove resource a major economic activity.

The conversion of 18% and 14% of mangroves to other vegetation and bare ground may reflect the intensity of mangrove exploitation. A degraded mangrove area may be classified as other vegetation or bare ground, depending on the degree of exploitation. The loss of mangrove area is consistent with the increase in area covered by other vegetation (16%) and bare ground (5%). The results also showed a significant decrease in the water amount between 1991 and 2002. This change could be attributed to the differences in the dates of acquisition of Landsat images. The 1991 Landsat image was acquired in March, which marks the beginning of the rainy season, while the 2002 Landsat image was acquired in January, a dry month throughout the country (Ghana Meteorological Agency 2016).

Between 2002 and 2014, the mangrove vegetation area fell by 27%, which could be attributed to an increase in the intensity of mangrove exploitation. While using mangroves as fuel wood has been a traditional practice for the local people (Aheto et al. 2016), following the increased population with an associated increase in demand for both domestic use (Ghana Statistical Service 2008) and commercial markets (Arthurton et al. 2006) may contribute to such significant decrease in mangrove area. The mangrove area loss is consistent with the observed conversion of the mangrove vegetation into other classes of about 47%, mainly other vegetation, which accounted for 26%. Although there was a general increase in the area covered by water which could be attributed to rainfall starting in March, about 58% of the previous cover had been converted into other classes. Furthermore, a significant portion of the area covered by water is shown to have been converted into mangroves by (40%), which could be a classification error due to the inability to discriminate between mangroves and mudflats that occur within the mangroves. The mudflats may occur due to the drying up of the water body.

Figure 7 provides a snapshot of changes between 1991 and 2014. According to Arthurton et al. (2006), Ghana Statistical Service (2008), and Aheto et al. (2016), the observable 33% decline in mangrove areas between 1991 and 2014 could be attributed to the progressive increase in mangrove exploitation. The decline in the mangrove area was consistent with the increase in the area covered by bare ground and other vegetation. The increase of other vegetation in the area could be attributed to the inclusion of degraded mangrove areas as part of the other vegetation class. The increased human settlements due to the increased human population and increase in the bare ground could be attributed to mangrove areas that have been totally degraded.

Estimating mangrove height, biomass, and carbon stock

The ASTER DEM was calibrated with equation (7) derived by (Simard et al. 2006). Calibrated ASTER DEM height estimates were compared with field estimates; this showed a positive correlation with a standard error of 2.3 m was close to the ASTER DEM error reported for flat areas by Tachikawa et al. (2011). The ASTER DEM was therefore considered well calibrated.

The above-ground biomass for 2014 was estimated by applying equation (3) developed by Saenger and Snedaker (1993a,b). This equation was used by Fatoyinbo et al. (2008) and Tang et al. (2014) to estimate mangroves' above-ground biomass, which applies to mangrove forest trees with heights up to 40 m. The mangrove area was reduced from 63.73 km^2 to 53.77 km^2 due to the masking of heights above 15 m. As a result, the total above-ground biomass for the mangrove area was estimated to be 5.38759×10^5 Mg. The above-ground mangrove biomass was 100.204 Mg/ha, similar to the mean above-ground living biomass of 94.49 ± 78 Mg/ha reported by Aheto et al. (2011). That result is also consistent with the mean above-ground biomass estimated by Fatoyinbo and Simard (2013) of 97 Mg/ha. These findings, according to Aheto et al. (2011), are indicative of low structural development of mangroves compared with other areas like French Guiana, where Komiyama et al. (2008) estimated the above-ground biomass to be 169.1 Mg/ha for *Avicennia* sp., and 315.5 Mg/ha for *Rhizophora* sp. trees respectively.

The stand biomass estimation indicates the allocation of carbon in plant tissues which is important for sequestration or carbon accounting (Kairo et al. 2008). The total above-ground carbon stock estimated for the study area was 2.693795×10^5 Mg. The carbon stock was found to be 50.102 Mg/ha, which was within the range of values reported by Adame et al. (2013), Tang et al. (2014), and Rahman et al. (2015). The estimated carbon stock recorded, 50.10 Mg/ha, is within the range of 1.5-88 Mg/ha reported by Adame et al. (2013) and 45.24 -152.57 Mg/ha reported by Rahman et al. (2015). The carbon stock per hectare estimated from this study is similar to the mean above-ground carbon of Ghana's mangrove (56.57 Mg/ha) reported by Tang et al. (2014). Higher values of above-ground carbon (75.4-206 Mg/ha) were reported by Stringer et al. (2015). These differences in the above-ground carbon stocks estimation could be attributed to including downed debris, leaf litter, and standing dead.

An examination of mangrove carbon stock changes revealed that the study area had lost about 161,428.65 Mg of its carbon stock because of the loss of mangroves between 1991 and 2014. Pendleton et al. (2012) expressed carbon stock in terms of potential CO_2 emissions by multiplying carbon stock by a factor of 3.67 (molecular weight ratio of CO_2 to C), which gives a value of 602,352.15 Mg of CO_2 that may have been lost. However, this figure is conservative, as many studies have shown that most ecosystem carbon is stored within the sediment. An analysis of the changes in carbon stock revealed an average rate of 6,882.76 Mg of carbon is being lost yearly (Tables 11, 12, and 13).

Perception of change

The general consensus of a decline in mangroves in the Lower Volta agrees with the loss of mangroves in Ghana reported in the literature (Spalding et al. 2010; Mensah, J. 2013; Aheto et al. 2016). The commercial harvesting of mangroves as a livelihood alternative could be attributed to this mangrove loss. In addition, the livelihoods related to fishing and farming were lost due to a reduction in riverine flow into the Keta lagoon caused by the damming of the Volta River, resorted respondents to an alternative livelihood.

Most of the respondents (77%) in Bomigo reported an increase in the mangrove, attributed to excessive planting, which was reported that mangroves were formerly planted to meet its demand as wood fuel for smoking fish. However, there had been a fall in demand for mangroves for wood fuel because of a progressive reduction in fish catch in Bomigo to be smoked. The extensive growth of mangroves also worsened fishing canoes from accessing fishing areas. In addition, the abundance of mangroves in the area has attracted residents from neighboring villages, such as Hawui and Tunu, who engage in mangrove harvesting.

In Hawui, about 79% of the respondents reported a reduction in the mangrove area, which was attributed to the intensive harvesting of mangroves. The current economic hardships and sole dependence on mangroves for domestic energy make the mangrove resource an integral component of the local economy, and mangrove harvesting is an alternative livelihood option. That has led to a total depletion of the mangrove resource in Hawui, resulting in residents moving to Bomigo to harvest mangroves.

Socio-economic factors that drive mangrove exploitation

Several factors significantly influenced the decision to exploit mangroves: increased income and commercial supply of fuelwood and wood fuel for domestic use. That follows Tsikata et al. 1997; Aheto et al. 2016 reported an attributed to the fact that the mangrove resource is viewed as an economic resource. Each of these factors has direct economic benefits. The sole dependence on fuel wood for cooking energy and the mangrove market's existence at Anyanui contribute to the significance of these factors. The 'medicinal purposes' was not a significant factor influencing the decision to exploit mangroves due to the availability of modern healthcare facilities. Further analysis also revealed that the respondents' demographic characteristics did not influence the decision to exploit mangroves. That could be attributed to the limited economic opportunities making mangrove exploitation the accessible means to sustain their livelihood.

Willingness to use LPG as an alternative energy source

Respondents were less likely to use LPG due to price and the additional cost of LPG being more expensive due to buying a cylinder safety considerations (Bukari 2012); it could also expose users to severe burns and injuries in case of gas accidents. The results also indicated that the respondents were more likely to use mangroves as fuel wood over LPG due to preference, which follows Tsikata et al. (1997), who attributed mangroves as fuel wood to their high caloric value and the attractive gold color they impart onto fish when used in fish smoking.

REFERENCES

Adame MF, Kauffman JB. Medina I. Gamboa JN, Torres O, Caamal JP, Reza M, Herrera-Silveira JA. 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PLoS ONE 8 (2): e56569. DOI: 10.1371/journal.pone.0056569.

Aheto DW, Aduomih OAA, Obodai EA. 2011. Structural parameters and above-ground biomass of mangrove tree species around the Kakum river estuary of Ghana. Ann Biol Res 2 (3): 504-514.

Aheto DW, Kankam S, Okyere I, Mensah E, Osman A, Jonah FE, Mensah JC. 2016. Community-based mangrove forest management: Implications for local livelihoods and coastal resource conservation along the Volta estuary catchment area of Ghana. Ocean Coast Manag 127: 43- 54. DOI: 10.1016/j.ocecoaman.2016.04.006.

Ajonina G. 2011. Rapid assessment of mangrove status to assess potential for payment for ecosystem services in Amanzule in the Western Region of Ghana. USAID, US.

Akpalu DA. 2007. Adoption of children and the contribution of the Osu Children's Home in Ghana. Childr Youth Serv Rev 29 (8): 1070-1084. DOI: 10.1016/j.childyouth.2007.02.004.

Alongi DM. 2002. Present state and future of the world's mangrove forests. Environ Conserv 29 (03): 331-349. DOI: 10.1017/S0376892902000231.

Arthurton R, Korateng K, Forbes T, Snoussi M, Kitheka J, Robinson J, Shah N, Taljaard S, Monteiro P. 2006. Coastal and marine environments. In Africa Environment Outlook 2, Our Environment Our Wealth. United Nations Environment Programme, Nairobi, Kenya.

Bukari D. 2012. Energy Access for the Poor in Ghana: Where lays the answer? CEPLMP Annual Review – CAR 16 (2013).

Chambers JQ, Higuchi N, Tribuzy ES, Trumbore SE. 2001. Carbon sink for a century. Nature 410 (6827): 429. DOI: 10.1038/35068624.

Chapman VJ. 1944. Cambridge Univ. Expedition to Jamaica, A study of the botanical processes involved in the development of the Jamaican shoreline. J Linn Soc Bot (52): 407-553.

Chapman VJ. 1970. Mangrove phytosociology. Trop Ecol 11: 1-19.

Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC. 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochem Cycles 17 (4): 12. DOI: 10.1029/2002gb001917.

Cohen JE. 1997. Estimates of coastal populations. Science 278 (5341): 1209-1213. DOI: 10.1126/science.278.5341.1209c.

Cohen R, Kaino J, Okello JA, Bosire JO, Kairo JG, Huxham M, Mencuccini M. 2013. Propagating uncertainty to estimates of above-ground biomass for Kenyan mangroves: A scaling procedure from tree to landscape level. For Ecol Manag 310: 968-982. DOI: 10.1016/j.foreco.2013.09.047.

Coleman TL, Manu A, Twumasi Y. 2007. Application of landsat data to the study of mangrove ecologies along the Coast of Ghana. Plant Soil 2000: 3-6.

Corcoran E, Ravilious C, Skuja M. 2007. Mangroves of Western and Central Africa. Retrieved from http://www.crc.uri.edu/download/GH2009D002__122713.pdf\nhttp://books.google.com/books?hl=en&lr=&id=xdrMCcDQaaoC&oi=fnd&pg=PA3&dq=Mangro ves+of+Western+and+Central+Africa&ots=2PbPbcYvWl&sig=Uu4QiZuDQaph Zqx-OfSZ8erl0IM

Dankwa HR, Gordon C. 2002. The fish and fisheries of the Lower Volta mangrove Swamps in Ghana. Afr J Sci Technol 3 (1): 8. DOI: 10.4314/ajst.v3i1.15284.

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M. 2011. Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4 (4): 1-5. DOI: 10.1038/ngeo1123.

Duarte CM, Middelburg JJ, Caraco N. 2005. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2: 1-8. DOI: 10.5194/bgd-1-659-2004.

FAO. 2005. Global forest resources assessment 2005: Thematic study on mangroves. FAO, Rome.

Fatoyinbo TE, Simard M, Washington-Allen R, Shugart HH. 2008. Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove, forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data. J Geophys Res Biogeosci 113: 1-13. DOI: 10.1029/2007JG000551.

Fatoyinbo TE, Simard M. 2013. Height and biomass of mangroves in Africa from ICESat/GLAS and SRTM. Intl J Remote Sens 34: 668-681. DOI: 10.1080/01431161.2012.712224.

Ghana Meteorological Agency. 2016. Seasonal Forecast 2016 Ghana. https://www.meteo.gov.gh/gmet/download/seasonal-forecast-2016-ghana/

Ghana Statistical Service. 2008. Ghana living standards survey report of the fifth round (Glss 5). Exp Parasitol 113 (Glss 5): 1-146. DOI: 10.1016/j.exppara.2005.11.016.

Ghana Statistical Service. 2012. 2010 Population and housing census: Final results.

Giri C, Zhu Z, Tieszen LL, Singh, Gillette S, Kelmelis JA. 2008. Mangrove forest distributions and dynamics (19752005) of the tsunami-affected region of Asia. J Biogeogr 35 (3): 519-528. DOI: 10.1111/j.1365-2699.2007.01806.x.

Gordon C, Tweneboah E, Mensah A, Ayivor J. 2009. The application of the ecosystem approach to mangrove management: Lessons for Ghana. Nat Faune 24: 30-41.

Grabowski ZJ, Chazdon RL. 2012. Beyond carbon: Redefining forests and people in the global ecosystem services market. SAPIENS 5.1: 2012.

Howard J, Hoyt S, Isensee K, Telszewski M, Pidgeon. 2014. Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Cifor, Bogor..

IPCC. 2007. IPCC Fourth Assessment Report (AR4). IPCC 1: 976. Retrieved from http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm\nhttp://www.ipc c.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf

Jensen JR. 2003. Introductory Digital Image Processing, a Remote Sensing Perspective. Upper Saddle River, Prentice Hall, NJ.

Joshi H, Ghose M. 2003. Forest structure and species distribution along soil salinity and pH gradient in mangrove swamps of the Sundarbans. Trop Ecol 44 (2): 195-204.

Kairo JG, Lang'at JKS, Dahdouh-Guebas F, Bosire J, Karachi M. 2008. Structural development and productivity of replanted mangrove plantations in Kenya. For Ecol Manag 255 (7): 2670-2677. DOI: 10.1016/j.foreco.2008.01.031.

Kauffman JB, Heider C, Norfolk J, Payton F. 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol Appl 24 (3): 518-527. DOI: 10.1890/13-0640.1.

Komiyama A, Ong JE, Poungparn S. 2008. Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot 89 (2): 128-137. DOI: 10.1016/j.aquabot.2007.12.006.

Mcleod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR. 2011. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 9 (10): 552-560. DOI: 10.1890/110004.

Mensah J. 2013. Remote Sensing Application for Mangrove Mapping in the Ellembelle District in Ghana. USAID Integrated Coastal and Fisheries Governance Program for the Western Region of Ghana. Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island.

Meyer D, ASTER-GDEM-Validation-Team. 2011. ASTER Global Digital

Nellemann C, Corcoran E, Duarte CM, Valdés L, De Young C, Fonseca L, Grimsditch G. 2009. Blue carbon: A Rapid Response Assessment. Environment. Retrieved from http://www.grida.no/files/publications/blue-carbon/BlueCarbon_screen.pdf

Nepstad DC, Mcgrath DG, Soares-Filho B. 2011. Systemic conservation, REDD, and the future of the Amazon Basin. Conserv Biol 25 (6): 1113-1116. DOI: 10.1111/j.1523-1739.2011.01784.x.

Ntyam CSO. 2014. Comparative Study of the Mangrove Ecosystems of Douala-Edea Reserve (Cameroon) and Songor Ramsar Site (Ghana) Using Parameters of Ecological Value. [Doctoral Dissertation]. University of Ghana, Ghana.

Pendleton L, Donato DC, Murray BC, Crooks S, Jenkins WA, Megonigal, Pidgeon E, Herr D, Gordon D, Baldera A. 2012. Estimating global "'Blue Carbon'" emissions from conversion and degradation of vegetated. Coast Ecosyst 7 (9): e43542. DOI: 10.1371/journal.pone.0043542.

Rahman MM, Csaplovics E, Koch B, Kohl M. 2004. Interpretation of Tropical Vegetation Using Landsat Etm + imagery. XXth ISPRS Congress: Geo- Imagery Bridging Continents. Youth Forum.

Rahman MM, Khan MNI, Hoque AKF, Ahmed I. 2015. Carbon stock in the Sundarbans mangrove forest: Spatial variations in vegetation types and salinity zones. Wetlands Ecol Manag 23 (2): 269–283. http://doi.org/10.1007/s11273-014-9379-x

RAMSAR-MAVA-UNEP. 2012. Integrated Critical Mangroves Conservation and Sustainable Use Program Framework Document.

REDD U. 2011. UN-REDD Programme strategy 2011-2015. Retrieved 10 February, 2016, from http://www.un-redd.org/aboutredd

Richards JA. 1999. Remote Sensing Digital Image Analysis. Springer-Verlag, Berlin.

Saenger P, Snedaker SC. 1993a. International Association for Ecology Pantropical Trends in Mangrove Above-Ground Biomass and Annual Litterfall. International Association for Ecology Stable 96 (3): 293-299.

Saenger P, Snedaker SC. 1993b. Pantropical trends in mangrove above-ground biomass and annual litterfall. Oecologia 96 (3): 293-299. DOI: 10.1007/BF00317496.

Schlesinger WH, Lichter J. 2001. Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411 (6836): 466-469. DOI: 10.1038/35078060.

Simard M, Rivera-Monroy VH, Mancera-Pineda JE, Castañeda-Moya E, Twilley RR. 2008. A systematic method for 3D mapping of mangrove forests based on Shuttle Radar Topography Mission elevation data, ICEsat/GLAS waveforms and field data: Application to Ciénaga Grande de Santa Marta, Colombia. Remote Sens Environ 112 (5): 2131-2144. DOI: 10.1016/j.rse.2007.10.012.

Simard M, Zhang K, Rivera-monroy VH, Ross MS, Ruiz PL, Castañeda-Moya E, Twilley RR, Rodriguez E. 2006. Mapping Height and Biomass of Mangrove Forests in Everglades National Park with SRTM Elevation Data. Photogramm Eng Remote Sens 72 (3): 299-311. DOI: 10.14358/PERS.72.3.299.

Smith SV, Gattuso JP. 2009. The Management of Natural Coastal Carbon Sinks. IUCN, Gland, Switzerland.

Smith-III TJ. 1992. Forest Structure. In: Robertson AI, Alongi DM (Eds). Tropical Mangrove Ecosystems, American Geophysical Union, Washington DC.

Soares MLG, Schaeffer-Novelli Y. 2005. Above-ground biomass of mangrove species. I. Analysis of models. Estuar Coast Shelf Sci 65 (1-2): 1-18. DOI: 10.1016/j.ecss.2005.05.001.

Spalding M, Kainuma M, Collins L. 2010. World Atlas of Mangroves. Earthscan, London, Washington DC.

Stringer CE, Trettin CC, Zarnoch SJ, Tang W. 2015. Carbon stocks of mangroves within the Zambezi River Delta, Mozambique. For Ecol Manag 354: 139-148. DOI: 10.1016/j.foreco.2015.06.027.

Tachikawa T, Kaku M, Iwasaki A. 2011. ASTER GDEM Version 2 Validation Report. International Geoscience and Remote Sensing Symposium (IGARSS) 1-24.

Tang W, Feng W, Meijuan JI, Zuo H. 2014. Assessment Of Biomass And Carbon Of Mangroves In West Africa Final Report

Tol RSJ. 2009. The economic effects of climate change. J Econ Perspect 23 (2): 29-51. DOI: 10.1257/jep.23.2.29.

Tou JT, Gonzalez RC. 1974. Pattern Recognition Principles. Addison-Wesley Publishing Company, Reading, Masschusetts.

Trumper K, Bertzky M, Dickson B, van Der Heijden G, Jenkins M, Manning P. 2009. The Natural Fix? The role of ecosystems in climate mitigation. A UNEP Rapid Response Assessment. Director. DOI: 978-82- 7701-057-1.

Tsikata IE, Senah K, Awumbila M. 1997. Mangrove Resource Utilization and Community-Based Management in the Lower Volta: A Socio-Anthropological Study. Lower Volta Mangrove Project Technical Report No.4. 83p Series. In: Gordon C (Eds). DFID/Ghana Wildlife Department/ Ghana Environmental Protection Agency, USAID Integrated Coastal and Fisheries Governance Program for the Western Region of Ghana. Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island.

UNEP. 2014. The importance of mangroves to people: A call to action. In: van Bochove J, Sullivan E, Nakamura T. (Eds). United Nations Environment Programme World Conservation Monitoring Centre, Cambridge.

Von Vordzogbe V, Kufogbe SK, Dave M. 2015. Woodlot agroforestry in the Lower Volta Basin, Ghana: Contribution of tree species admixture to above-ground carbon. West Afr J Appl Ecol 23 (1): 49-62.

Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL, Hughes A, Kendrick GA, Kenworthy W, Short FT, Williams SL. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci USA 106 (30): 12377-12381. DOI: 10.1073/pnas.0905620106.

Yee SM. 2010. Capstone Advisory Committee Final Capstone Project Signature Form REDD and BLUE Carbon: Carbon Payments for Mangrove Conservation. Marine Biodiversity and Conservation Capstone Project. Scripps Institution of Oceanography, UC San Diego, USA.