INBAR Working Paper

National Assessment

Bamboo Resource Assessment in Five Regions of Ghana

Resource Management Support Centre, Forestry Commission of Ghana

2020

About the International Bamboo and Rattan Organisation

The International Bamboo and Rattan Organisation, INBAR, is an intergovernmental organisation dedicated to the promotion of bamboo and rattan for sustainable development. For more information, please visit www.inbar.int.

About this Working Paper

– This work is an INBAR publication produced as part of the Inter-Africa Bamboo Smallholder Farmers Livelihood Development Programme funded by the International Fund for Agriculture Development (IFAD).
– The Resource Management Support Centre (RMSC) is the technical wing of the Forestry Commission (FC) of Ghana. The centre is responsible for the exploration, development, facilitation, institutionalisation, implementation and monitoring of effective and affordable forest management systems in Ghana. The Forestry Commission of Ghana is a partner agency in the implementation of the Inter-Africa Bamboo Smallholder Farmers Livelihood Development Programme.
– Content may be reprinted without charge provided INBAR and the authors are credited.

International Bamboo and Rattan Organisation

P.O. Box 100102-86, Beijing 100102, China Tel: +86 10 64706161; Fax: +86 10 6470 2166
Email: info@inbar.int

Acknowledgements

We would like to express our deepest appreciation to everyone who supported in diverse ways to complete this assignment. Our special gratitude goes to the International Fund for Agricultural Development (IFAD) for funding this assessment, INBAR West Africa Regional Office team especially; Dr. Ernest Nti Acheampong, Michael Kwaku, and Daniel Obloni Kweitsu and the entire INBAR secretariat whose invaluable contribution, suggestions and encouragement facilitated the delivery of the expected outputs of the assignment.

Furthermore, we would like to acknowledge the key role played by the experts in the execution of this assignment: Messrs. Kofi Affum-Baffoe, Mohammed Yakubu, Yaw Atuahene Nyako, Lawrence Akpalu, Samuel Ayesu and the field staff at RMSC whose rich experience and technical insight led to the successful execution of the assignment. Much appreciation also goes to the Manager, Business Planning Emmanuel Adu-Sarpong and his team Isaac Kwabena Osei, Martina Addai, Raphael Agyapong Manu and Abigail Adjei Abalo for providing effective coordination and support.

While acknowledging the cooperation of the Forest Services Division for their willingness to share information and support during the field surveys, we extend our appreciation to our internal reviewers whose kind co-operation and encouragement contributed hugely to the successful completion of this study and final report.

Mr. Alexander Boamah Asare

Director, RMSC

List of Abbreviations

AGB	Above Ground Biomass
AGC	Above Ground Carbon
ANOVA	Analysis of Variance
BA	Basal Area
BGC	Below-Ground Carbon
BI	Bamboo Index
D	Diameter
DBH	Diameter at Breast Height
DSD	Dry Semi Deciduous
ERDAS	Earth Resources Data Analysis System
ESRI	Environmental System Research Institute
ETM	Enhanced Thematic Mapper
FAO	Food and Agriculture Organization
FC	Forestry Commission
FCTC	Forestry Commission Training Centre
FORIG	Forestry Research Institute of Ghana
FPP	Forest Preservation Program
FRM	Forest Range Managers
FSD	Forest Services Division
GHG	Greenhouse Gases
GIS	Geographical Information System
GMA	Ghana Meteorological Agency
GPS	Global Positioning System
GSD	Ghana Survey Department
HFZ	High Forest Zone
ICT	Information and Communication Technology
IFAD	International Fund for Agriculture Development
INBAR	International Bamboo and Rattan Organisation
IPCC	Intergovernmental Panel on Climate Change

IRS	Internal Revenue Service
ITTO	International Tropical Timber Organization
IZ	Inner Zone
LCLU	Land Cover Land Use
ME	Moist Evergreen
ML	Maximum Likelihood
MNSW	Moist Semi Deciduous North West
MODIS	Moderate Resolution Imaging Spectrometer
MS	Multispectral Imagery
NDVI	Normalised Difference Vegetation Index
NIR	Near Infrared
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RMSC	Resource Management Support Centre
SD	Standard Deviation
SDG	Sustainable Development Goals
SI	Stress Index
SM	Southern Marginal
SOC	Soil Organic Carbon
SWIR	Short Wave Infrared
TM	Thematic Map
UN	United Nations
UNIDO	United Nations Industrial Development Organisation
USAID	United State Agency for International Development
UTM	Universal Transverse Mercator
VHR	Very High Resolution
WE	Wet Evergreen

Table of Contents

List of Figures

List of Tables

Executive summary

To maximise the contribution of bamboo to national economies and environmental protection, countries need accurate, up-to-date, spatially explicit data and maps of bamboo resources. The identification of growing areas (extent and distribution) of bamboo resources is critical for proper planning to inform decision-making and policies for sustainable management and use. It is against this background that this study was necessitated. The study conducted a review of existing literature on bamboo resource assessment and obtained field-based measurements of sampled bamboo stands to determine the structural characteristics and ecological variation of bamboo in five (5) regions, namely the Ashanti, Central, Eastern, Western and Western North regions. The Sentinel 2 images were used to develop a bamboo distribution map for the project regions. In all, 456 bamboo stands were located for sampling by aid of snowball sampling techniques. These selected stands were used as training data inputs for image classification. An accuracy of 79.28% was achieved for the classified bamboo species distribution map. A total of 42,889.63 ha were estimated to harbour bamboo stands. Of these, most (10,325.51 ha) were located in the Ashanti region, followed by the Central (9,518.23 ha), Western (9,397.49 ha), Eastern (8,991.80 ha) and Western North regions (4,656.60 ha). Ecologically, there was a higher distribution of bamboo in moist ecozones (mainly moist semi-deciduous and moist evergreen) than in dry ecozones (dry semi-deciduous and savannah).

Bamboo stands exhibited structural variation across ecological zones. The average number of culms per clump was higher in the wet evergreen (WE) eco-zone (97.2 ± 17.5) and lower in the dry semi-deciduous (DSD) eco-zone (57.9 ± 4.8). Also, the mean culm diameter was greatest in stands found within the moist evergreen (ME) eco-zone (7.9 ± 0.1cm) and least in the DSD eco-zone (6.90 ± 0.2cm). The average stem thickness varied between 5.3 ± 0.2 and 15.0 ± 0.5 mm for the moist semi-deciduous north-west (MSDNW) eco-zone and the southern marginal (SM)/WE zones, respectively. Clumps of bamboo in the DSD eco-zone were closer together (8.2 ± 0.2m) than in the MSDNW eco-zone (9.9 ± 0.2m). Additionally, the basal area was highest for bamboo in the ME eco-zone (49.3 ± 3.35 m2ha-^{1}) and lower in the DSD inner zone (IZ) eco-zone (30.86 ± 3.68 m2ha-^{1}). The WE had the highest number of culms per clump (97.2 ± 17.5) while the DSD (IZ) was estimated to have the lowest (57.9 ± 4.8). The stand density was highest in the ME (9982.5 ± 709.6 culms/ha-^{1}) and lowest in the DSD (IZ) (8139.5 ± 905.4 culms/ha-^{1}). Cumulatively, a total of 570,305,736.80 culms were estimated to be present in the study regions,

with the Western and Eastern regions recording the highest and lowest, respectively. Culms in the diameter size class 6.1cm–9cm were widely distributed across the various ecological zones. On the bamboo carbon stock potentials for the five regions, analysis of remote sensing data indicated a total value of 9,589,837.14 tC (35,163,867.31 tCO_2-e), with the Ashanti region having the highest total carbon stock (3,979,277.62 tC (14,590,836.21 tCO_2-e)) and the Eastern region having the lowest (969,097.63 tC (3,553,230.34 tCO_2-e)).

In conclusion, the study has provided information on spatial distribution, structural characteristics and density of bamboo resources, as well as aboveground carbon stock of bamboo for five (5) selected regions in Ghana. It is recommended that the bamboo inventory be replicated to cover the remaining eleven (11) regions in the country, as this will facilitate national planning and sustainable management of bamboo resources.

1. Introduction

Bamboo is one of the best-yielding renewable natural resources in the world, having over 1,500 documented applications (Syeda and Kumar, 2014). In its lifetime, a single bamboo clump/stand can produce culms of 15 kilometres in length (Syeda and Kumar, 2014). Bamboo includes all plants in the *Bambusoideae* subfamily of the grass family *Poaceae*, a single evolutionary radiation of 1,642 species, including 1,521 woody bamboos. They occupy a broad range of environments across the world, largely in tropical to warm temperate ecosystems, with some varieties growing in cold temperate regions (INBAR, 2016). There are two main categories of bamboo: clumping (sympodial) and running or open (monopodial). The clumping type of bamboo spreads slowly at a rate of 1–4 feet (0.5–1 meter) per year and is easy to control. In Ghana, the main category of bamboo is sympodial, and there are seven (7) indigenous species of bamboo, namely: *Oxthenanthera abyssinica, Bambusa vulgaris, Bambusa vulgaris var. vittata, Bambusa perveriabilis, Dendrocalamus strichus* and *Bambusa multiplex* (Forestry Commission, 2020). *Oxthenanthera abyssinica* is mostly found in the northern part of the country, while the other six (6) species are concentrated in the southern sector (Ebanyenle and Oteng-Amoako, 2007). The most prevalent is *Bambusa vulgaris*; among the species, *Bambusa vulgaris* makes up about 90–95% of the bamboo resources in the country (Ebanyenle and Oteng-Amoako, 2007), whereas *Bambusa multiplex* accounts for about 4%. Tekpetey (2011) and Ebanyenle et al. (2005) estimate bamboo forest to cover about 300,000 ha and 400,000 ha of Ghana, respectively, although these estimates were not based on any remotely sensed data and are lacking in accuracy. Also, bamboo in Ghana is often found along streams and other water bodies and is particularly abundant in ME forest areas due to favourable growth conditions for growth. The soil types that dominate in bamboo-endemic regions are forest ochrosols, forest chrosols-oxysols intergrades and forest oxysols. In the forest zone, specifically in the Western region, the soils are mostly lateritic.

On ownership, bamboo is considered a non-timber forest product (NTFP) under the Reserve Settlement Commissioner's Report, and customary user rights are granted to the stools and the respective land-owning communities. Consequently, no specific legal provisions separate the ownership, control and management of NTFPs from the ownership, control and management of the land and timber resources that make up the forest. Though stool lands, as provided for in the Constitution, are owned by the communities and vested in the appropriate stools in trust for and on behalf of them, the Concessions Act, 1962 (Act 124) imposes state trusteeship on stool lands in addition to stool trusteeship for all lands within forest reserves. Therefore, it is the State that has control, as a trustee, of forest reserve lands and the trees/NTFPs occurring thereon, which include bamboo.

However, in off-reserve areas, the actual ownership of naturally occurring trees is not separated from the ownership of land by either the Constitution nor by any of its implementing acts or regulations. Therefore, the ownership of natural trees overlaps with the ownership of the land on which the trees occur. This means that communities are the owners of forest resources on stool lands, and the stools have control over these resources in trust for and on behalf of the communities. According to the Forestry Commission Act, 1999 (Act 571) the Commission has the mandate to regulate the utilization of forest and timber resources in off-reserve areas as opposed to managing, vetting and registering contracts to market timber, setting standards and guidelines and providing for checks and procedures along the timber supply chain in the reserves.

Fourteen (14) other introduced species were imported to Ghana from Hawaii in 2003 by Opportunity Industrialization International Centre (OICI). The Bamboo and Rattan Development Programme (BARADEP) facilitated their distribution to institutions and NGOs to multiply and monitor their growth conditions and adaptability in Ghana.

Bamboo plays an increasing role in ecosystem services, biodiversity conservation and socio-economic development. It has been recognised as an important carbon sink and has potential for mitigating climate change (Song et al., 2011; Dubey et al., 2016; Agarwal and Purwar, 2017). Despite its enormous benefits, the high potential of bamboo for socio-economic development and environmental conservation has still not been fully realised due to limited information on the abundance and distribution of bamboo in Ghana. According to INBAR (2014), bamboo as a versatile plant offers carbon sinks to countries and international climate initiatives that will significantly reduce the negative effects of greenhouse gases on the planet. Bamboo plays a role in all three kinds of carbon sinking: the plant offers charcoal and gas alternatives to fossil fuels, fast-growing and remarkably renewable stands of dense vegetation, and harvested materials with an array of uses that date from the dawn of humanity. Currently, different types of Bamboo are now multiplying and improving in step with the accelerating advance of science. Bamboo has enormous potential to contribute to poverty reduction, youth employment, and environmental protection, as well as to broader UN Sustainable Development Goals (SDG 1, 2, 7, 11, 12, 13 and 15). The Ghana Forest and Wildlife Policy (2012) and Forestry Development Master Plan

(2016–2036) address the promotion and development of bamboo as a substitute for timber, which has become imperative as a result of the dwindling wood resource situation in the timber sector in Ghana. Also, bamboo offers an opportunity to increase income and employment opportunities for the rural poor, with possibilities of annual harvests. It is worth emphasizing that globally, the annual production and consumption of bamboo products is valued at USD 60 billion, and global import and export is valued at USD 2.5 billion (INBAR, 2018).

The conventional method of surveying and estimating the growing bamboo stock is time-consuming and costly. Therefore, an approach utilizing developments in space technology, particularly the repetitive satellite remote sensing across various spatial and temporal scales, offers the most economic means of assessing, planning, managing and monitoring forestry resources, including bamboo (Goswami et al., 2010). This study applied remote sensing (RS), geographic information system (GIS) and field-based measurements to estimate bamboo resources in five (5) domiciled bamboo regions in Ghana. The results have provided baseline data for a decision-making and policy framework in terms of the planning and development of bamboo resources in Ghana. Additionally, the contribution of bamboo to climate change mediation (i.e. as a carbon sink) and the extent and distribution of bamboo resources in the five (5) regions has been determined. This will aid investors in determining where to site bamboo-based industries.

2. Objectives and outcome

2.1 Main objective

To determine the spatial distribution of bamboo and bamboo carbon stocks in the high forest zone (HFZ) of Ghana.

2.2 Specific objectives

i. To determine the spatial distribution of bamboo species in Ghana using GIS and RS techniques;

ii. To establish bamboo structural and ecological characteristics of the study regions; and

iii. To estimate bamboo carbon stock value for the bamboo population in Ghana.

2.3 Scope of task

i. Desk study on existing RS methodologies for bamboo species mapping worldwide.

ii. Identifying and obtaining suitable RS imagery for bamboo forest mapping in Ghana.

iii. Production of bamboo species distribution map in Ghana, specifically in the Western, Western North, Central, Ashanti and Eastern regions.

iv. Conducting field-based measurements using sample plots to capture structural and ecological variables in bamboo species.

2.4 Outputs

The following data/maps have been developed to inform decision-making and the development of policy frameworks for sustainable utilization and development of bamboo resources in Ghana.

a) Bamboo Species Distribution Map for each of the five (5) regions

b) Bamboo Species Distribution Map for twelve (12) political districts

c) Bamboo Carbon Stocks

2.5 Organisation of report

This report provides a concise account of work done for the Bamboo Resource Assessment in five (5) regions of Ghana. The report has been organised in five (5) chapters.

Chapter 1: Provides an introduction and background for the study, discussing bamboo distribution throughout the world, the number of species and bamboo's contribution to global socio-economic development, as well as climate change mediation. The general problem of the study and its scope and purpose are also indicated in the first chapter.

Chapter 2: Includes the objectives, tasks and output of the study.

Chapter 3: Presents the methods and material. It provides details of the satellite imagery obtained for the bamboo forest mapping, image analysis and accuracy assessment of the classified map. It also touches on the approaches adopted in determining culm ages, structural and ecological variations of bamboo, clumps per hectare, culms per clump and culms per hectare. The allometric equation used in determining the carbon values of the bamboo stands has been provided.

Chapter 4: Presents the results and discussion, which focuses on the extent and distribution of bamboo resources. It provides details of the outcome of the inventory concerning culm ages, structural and ecological variations of bamboo, clumps per hectare, culms per clump and culms per hectare. It also touches on the culm and clump densities and the mean culm diameter and height, as well as thickness and carbon values of the bamboo stands.

Chapter 5: Presents the main conclusions in terms of bamboo locations, abundance and carbon stock accumulation. It also summarises recommendations for sustainable development of the resources.

2.6 Limitations to the study

The study was limited to five (5) regions out of sixteen (16) due to limited funds. The small, patchy nature of bamboo makes it difficult to map it with medium-resolution satellite images (which were used for this work). The medium-resolution satellite images have spatial resolution ranging from a few meters to several meters (10 m, 15 m, 22 m, 30 m, among others). These images are mostly used in resource monitoring, since they are open source and free to access. Some of the bamboo stands may not be the size of a pixel, and when that is the case, such bamboo stands are not mapped. The heterogeneous nature of Ghana's landscape also makes it difficult to delineate bamboo from other vegetation types; the heterogeneous nature leads to a lot of mixed pixels, resulting in misclassification. The misclassification results in either overestimation (in the case of dominant vegetation) or underestimation (in the case of sparse vegetation).

3. Methodology

3.1 Description of study area

The study area covers five (5) of the sixteen (16) regions in Ghana, as presented in Figure 1. These regions are the Ashanti, Central, Eastern, Western and Western North regions. Generally, the study area falls within the semi-equatorial climate, which is characterised by high and seasonal bi-modal rainfall. The Ashanti region has forest vegetation in the south and savannah in the northeast, with a mean monthly temperature ranging from 22.80–26.30 22.8 °C. The Central region lies within the dry equatorial and moist semi-equatorial zones, with a mean monthly temperature ranging from 24 °C to 30 °C. It has a coastal savannah vegetation type with grassland and few trees along the coast and semi-deciduous forest in the inland areas. The Eastern region lies within the wet semi-equatorial zone, with temperatures ranging from 26 °C in August to 30 °C in March. The Western region lies in the equatorial climatic zone, with temperatures ranging from 22 °C at nightfall to 34 °C during the day. Finally, the south-western areas are rainforests, and the high tropical forest and semi-deciduous forest occupy the north. The major rainy season is (in general) from March until July, while the minor rainy season starts in September and goes until the end of November. On the temperature, the hottest periods are February and March. The mean annual temperature falls within 22.60 °C–26.70 °C. The minimum and maximum mean annual precipitation range between 1046 mm and 1680 mm (Table 3.1).

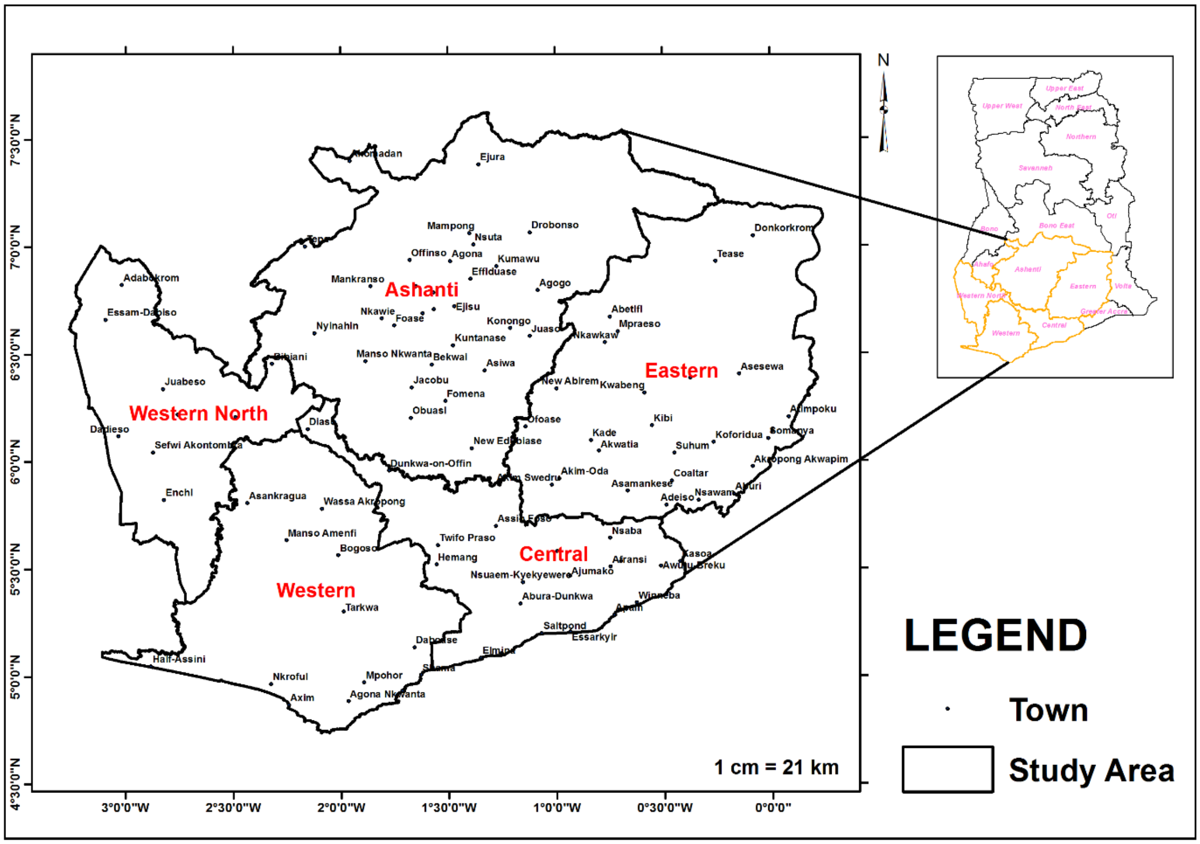


Figure 1. Map of project regions

Table 1. Climatic conditions of the study area

Annual Climatic Averages	Regions			
	Ashanti	Eastern	Western / Western North	Central
Rainfall (mm/yr)	1279–1460	1515–1608	1545–1680	1046–1538
Temperature (ºC)	22.80–26.30	22.60–26.20	25.80–26.40	26.0–26.70
Relative Humidity (%)	85	89	85	89

Source: Köppen and Geiger Climate Data Organisation (2019)

3.2 Bamboo forest mapping

3.2.1 Acquisition of satellite imagery

The study acquired Sentinel 2 images (medium-resolution satellite imagery) for bamboo forest mapping due to the complexity of identifying and differentiating bamboo stands from other vegetation types, such as plantation trees and agricultural crops, in the project landscape. The Sentinel 2 images were downloaded from the Sentinel Scientific Data Hub website (https://scrihub.copernicus.eu/). The Sentinel images, the details of which are presented in Table 2, come in tiles and each tile is identified by a unique name. The images were downloaded as zip files, and WinRAR was used to extract them into their various bands where they were stored for further analysis.

Table 2. Details of the Sentinel 2 images

Satellite	Sensor	Level of Processing	Tile Name	Number of Bands	Date
Sentinel 2	Multispectral Imager (MSI)	L1C	T30NVN	13	19-02-2018
			T30NVM		26-12-2018
			T30NVL		25-04-2018
			T30NWP		02-02-2019
			T30NWN		26-12-2018
			T30NWM		28-12-2018
			T30NWL		28-12-2018
			T30NXP		22-01-2019
			T30NXN		12-01-2018
			T30NXM		28-12-2018
			T30NXL		28-12-2018
			T30NYN		28-12-2018
			T30NYM		02-01-2018
			T30NYL		02-01-2018
			T30NZN		08-12-2018
			T30NZM		04-01-2018

The boundaries of the study sites (i.e. Ashanti, Eastern, Central, Western and Western North regions) were extracted from the administrative regional shapefile obtained from the Ghana Survey Department. The Sentinel images and the community, road and study area shapefiles had the same coordinate system – that is, Universal Transverse Mercator (UTM) Zone 30 North. For this reason, the processes of geo-referencing, geo-coding and transformation were ignored.

3.2.2 Image pre-processing

Operations to prepare data for analysis and compensate for systematic errors are what is termed as image pre-processing. These errors can cause difficulty in comparing more than one image of the same scene taken under different conditions. It is thus important to 'restore' the images to their correct or original condition by removing these effects. The pre-processing operations performed in this work were layer stacking, haze correction and sub-setting.

3.2.3 Layer stacking

Sentinel tiles are made up of bands. Each band is defined by the particular range of wavelength within which it captures radiation to produce an image. The bands for each tile were stacked to generate a composite image using the 'layer stack' tool in ERDAS Imagine version 2018. This operation is necessary to obtain more spectral information from the composite image than can be gained by analysing the individual bands separately. Bands 2 (blue), 3 (green), 4 (red), 5 (vegetation red edge), 6 (vegetation red edge), 7 (vegetation red edge), 8 (near-infrared), 8A (narrow near-infrared), 11 (shortwave infrared) and 12 (shortwave infrared) were stacked. Bands 5, 6, 7, 8A, 11 and 12 were re-sampled from a spatial resolution of 20 meters to 10 meters to combine them with the remaining bands, which have a spatial resolution of 10 meters. After the layer stack operation, the stack images were displayed in different band combinations to determine in which of them the bamboo exhibit consistent reflectance (colour) and shape patterns. These were the true colour band combination (bands 2, 3 and 4), false infrared band combination (bands 3, 4 and 8) and shortwave infrared band combination (bands 11, 8 and 4). The field data were overlaid on these band combinations and labelled. The idea was to associate the bamboo data with a particular colour in the various band combinations.

3.2.4 Haze correction

Haze has an additive effect to the overall image, resulting in higher digital number (DN) values, and as such, it reduces the contrast (Lillesand et al., 2004). Its impact differs per band, highest in the blue range, lowest in the IR range (Lillesand et al., 2004). The 'haze correction' tool in ERDAS Imagine 2018 was used for this operation. This tool identifies the lowest DN value in each band and then subtracts it from the remaining DN values for each band. This operation improves the contrast of the images. The composite images generated from the layer stack operation were used as inputs for this operation. To improve the visualization of the images, an image enhancement technique called histogram equalization was performed. This was done in ERDAS Imagine 2018 using the 'histogram equalise' tool. This operation further enhances the contrast and makes it easy to detect subtle differences among earth surface features identified in the images.

3.2.5 Generating subsets

The interest of this study was to identify and map bamboo within the project regions. Since some of the Sentinel images extended beyond the boundary, there was a need to extract areas that fell within it for further analysis. The 'clip' tool under the data management toolbox in ArcGIS 10 was used to extract areas of the composite images (outputs from the haze correction) that fell within the study area.

3.2.6 Image classification

Image classification is performed to identify and assign real-world thematic classes to the image pixels (Lillesand et al., 2004). The image classification was done in two stages: unsupervised and supervised classification.

Unsupervised classification

In the unsupervised classification method, a computer software categorises the pixels into common land uses using their spectral characteristics without any training data (Lillesand et al., 2004). The iso-data unsupervised classification algorithm in ERDAS Imagine 2018 was used to classify each clipped image (output from the sub-setting operation) into 20–40 classes. The classes were merged based on spectral similarity to form 8–10 classes. The community and road shapefiles were overlaid on the outputs to check the distribution of these classes within the study area and for easy navigation for field data collection. A map was produced from the classified image together with the community and road shapefiles. This was used as a preliminary map for field data collection.

Training data collection

Training data for image classification was collected by two field assessment teams. The teams used a snowball methodology to locate 456 locations of bamboo stands in the five (5) regions. The data collected from the field included the coordinates of the bamboo stands using a global positioning system (GPS) receiver and the land use (bamboo) description of the area. All the data were entered into a field sheet, transferred into a Microsoft Excel Sheet and imported to ArcGIS 10 to create shapefile for the field data. To capture more bamboo locations for validation, an additional 31 bamboo stands were chosen on Google Earth and added to the existing GPS points. In all, 487 bamboo locations were identified, out of which 111 stands were selected for bamboo clump assessment and enumeration across the four regions.

To identify and map other land use/land cover types within the study area, existing field data collected for the development of land use maps for the Forests 2020 Project, Forest Preservation Program (FPP) and REDD+ were included in the training datasets to run the supervised classification. From the field data, the following land use types were identified and grouped as presented in Table 3: close forest, open forest, water, other vegetation, settlement/bare surface and bamboo. This formed the classification scheme for this study.

Table 3. Land use types within the project regions

No.	Land use	Description
1.	Settlement/bare surface	Building, rocky surfaces, cleared, mining site and burnt areas
2.	Bamboo	Areas with bamboo clumps
3.	Other Vegetation	Shrubs, grass, bush, marshy area and cropland
4.	Close Forest	Areas with a trees canopy cover of more than 60%
5.	Open Forest	Areas with trees canopy cover between 15%–59%
6.	Water	River, streams, dams and lake

Source: RMSC-FC, 2020

Supervised classification

In this type of classification, the image analyst 'supervises' the pixel categorization process by specifying to the computer algorithm numerical descriptors of the various land cover types present in a scene (Lillesand et al., 2004). The classification was done in ERDAS Imagine 2018. The polygon tool was used in training the pixels (signatures). This was made easier by the knowledge of the study area gained from the field visit and field data, as well as by images from the Google Earth application.

After displaying the bamboo points on all the tiles and varying the band combination, the points were associated with consistent colour and shape patterns. This was observed in the false infrared band combination and shortwave infrared band combination. In the false infrared band combination, bamboo showed as light red; in the shortwave infrared band combination, it showed as light green to yellowish-green. In both band combinations, bamboo exhibited significant form and outline that distinguished it from the surrounding vegetation. It appeared as a small, mostly linear patch of vegetation. This observation made it possible to train more classes for bamboo in addition to the field data. Another trend was observed from the Google Earth application. The Google Earth application, which is made up of high-resolution satellite images, showed particular characteristics for bamboo. This was derived from the crown-cover style of bamboo, which has a star-like appearance. These observations from the Sentinel 2 and Google Earth images were also used to validate the classified images. The bamboo class was extracted and overlaid on the Sentinel 2 images and Google Earth application and was visually inspected to ensure they coincide with the characteristics that were observed.

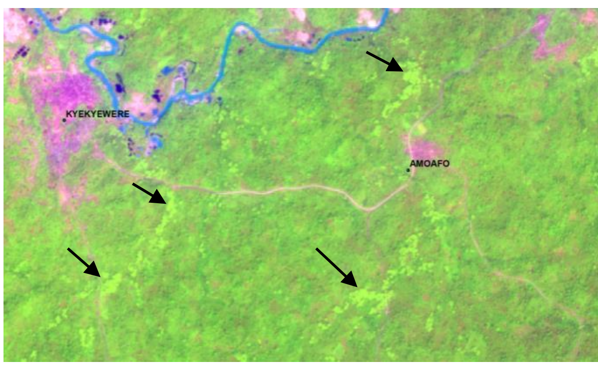


Figure 2. Bamboo on shortwave infrared band combination

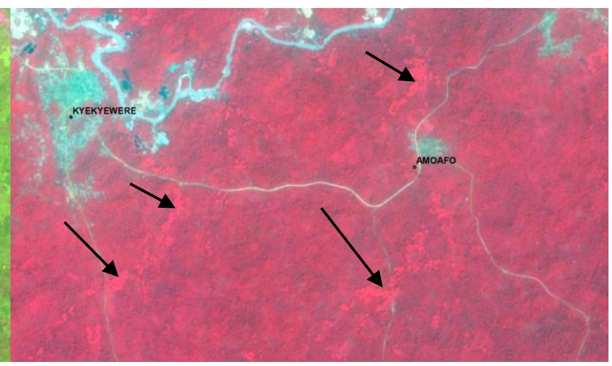


Figure 3. Bamboo on infrared band combination

During the training of pixels, each class (land use) had subclasses. The purpose of the subclasses was to reduce the margin of error. After training the pixels, the maximum likelihood algorithm was used in running the classification. The maximum likelihood (ML) classifier considers not only the cluster centre but also its shape, size and orientation. This is achieved by calculating a statistical distance based on the mean values and covariance matrix of the clusters (Wim H. Bakker et al., 2004).

After the classification, the outputs were displayed in ArcGIS 10. The subclasses were merged using the reclass tool in ArcGIS 10. This operation is called reclassification. The reclassified maps were then filtered to remove the ‘salt-and-pepper appearance’ and enhance the cartographic presentation after image classification. This was done using the ‘majority filter’ tool in ArcGIS 10.

The outputs from the filtering operation became the final land use maps. After filtering, the various tiles were mosaicked. This was done using the mosaic to new raster tool in ArcMap 10.

Accuracy assessment

The field data collected for the bamboo inventory were used to assess the accuracy of the final map. The accuracy assessment was done only for the bamboo areas. The confusion matrix analysis was used. This uses accuracy assessment methods to produce statistical outputs, which can be used to check the quality of the classification results. The matrix further compares class-by-class based on the field data and the classification results.

3.3 Bamboo resource inventory

3.3.1 Sampling design

Adaptive cluster sampling was used as a basis for the sampling strategy because it is considered the most appropriate and efficient method for sampling bamboo and rattan, which are species that tend to occur at fairly low densities and in an aggregated manner (Thompson, 1991). A purposive sampling method through a snowball approach was used to select the bamboo stands based on the extent of bamboo clumps. In the selection of the clumps for assessment, the third and fifth clumps were systematically selected.

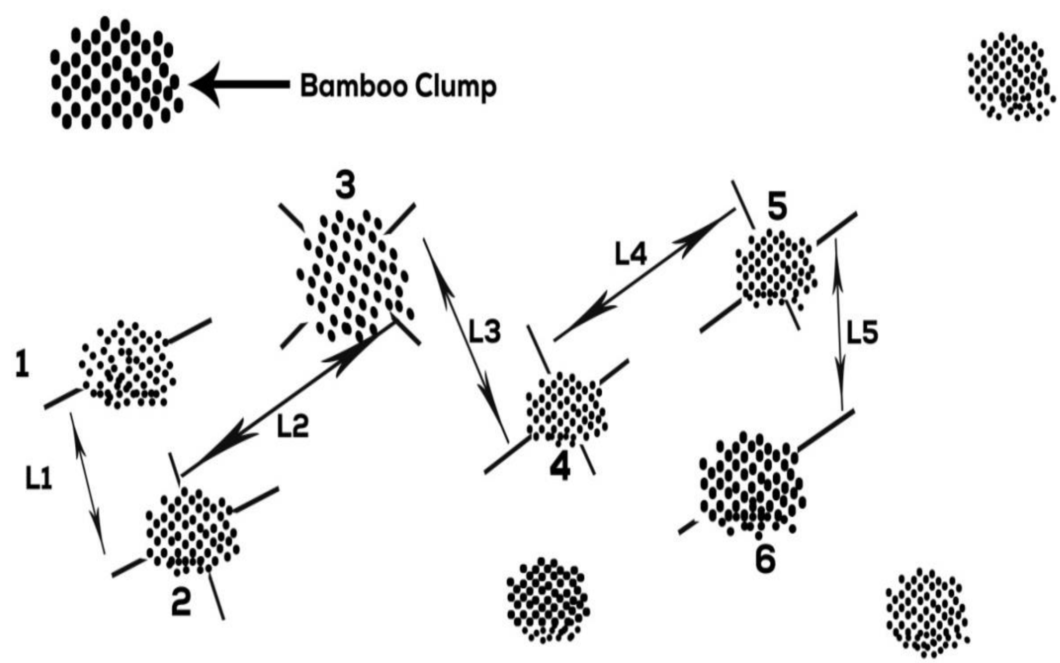


Figure 4. Systematic selection of clumps for measurement

3.3.2 Enumeration of clump bamboo

Within a study plot, seven (7) bamboo stands were assessed and the GPS coordinates recorded. The GPS coordinates of other bamboo stands identified were also recorded but not assessed. Thus, a total of one hundred and twelve (112) bamboo stands were assessed and their coordinates recorded. Two clumps were selected per stand for assessment, and a total of 224 clumps were enumerated. At each site, the area of the bamboo cluster was usually determined by traversing the entire bamboo site with a GPS.

Six (6) bamboo clumps located close to one another were then selected and the distances between them measured and recorded as L1, L2, L3, L4 and L5, as indicated on the field data sheets (Appendix I). Two (2) bamboo clumps (L3 & L5) were then selected among the six clumps at each site and their girths measured and recorded. Within each of the two clumps, two culms for each year group (Year 1, Year 2 and Year 3+) were selected and felled using a handsaw. The diameters, heights and thicknesses of the felled culms were measured for a total of six culms per clump and 12 culms per site. The following parameters were taken for carbon estimation of the bamboo:

- Girth of the bamboo clump
- Distance between the clumps
- Number of culms per age class (1 year, 2 years and 3+ years)
- Height of the culms
- Diameter of the culms
- Thickness of the culms
- Total area of the bamboo site

3.3.3 Tools and equipment

- Diameter tape for diameter measurement
- Veneer calliper for culm thickness
- Linear tape for distance, bamboo girth measurement and height of culm
- Handheld GPS for taking coordinates of bamboo plots and calculating area
- Hand saw for cutting down the bamboo culm for height measurement

3.3.4 Data analysis

Field data were entered in Microsoft Excel and analysed using formulas developed by INBAR in 2019. Mean values were generated from plot-level values per site or ecological zone. Differences in means were tested at 5% probability level using ANOVA. Correlation analyses were carried out to determine the relationship among the structural characteristics of bamboo stands. Results are presented in tables and charts.

Estimating culms for diameter classes, age classes and total culms per hectare

The average of bamboo culms per diameter class (D), age classes (A) and total average bamboo culms per ha was estimated. The formulas used to estimate the number of bamboo culms distributed in D or A class I per ha and total were as follows:

$$N_{iculm} ha^{-1} = \frac{10^4 \times \sum_1^n N_{iculm}}{n \times AP}$$

$$N_{culm} ha^{-1} = \sum N_{iculm} ha^{-1}$$

where $\mathbf{N_{culm}}$ is the number of bamboo culms distributed in D or A class I per ha; $\mathbf{N_{iculm}}$ is the number of bamboo culms distributed in D or A class I in all plots; **n** is the number of sample plots; **AP** is the area of the plot in m^2; and $\mathbf{N_{culm}ha^{-1}}$ is the averaged total bamboo culms per ha. This analysis provides information on bamboo stock, consisting of D and A distributions and total bamboo culms, averaged per ha for each forest stratum.

Estimating clump per hectare measurements with a clump-based sampling

$$N_{clump}\ ha^{-1} = \frac{1}{n}\sum_1^n \frac{10^4}{\left\{\frac{\sum_{i=1}^5 L_i}{5}\right\}^2}$$

where $\mathbf{N_{clump}ha^{-1}}$ is the number of bamboo clump per ha, $\mathbf{L_i}$ is the distances of the six nearest clumps in m (i = 1–5), and **n** is the number of sample plots/points.

Allometric equation

An allometric model developed by Amoah et al. (2020) was used to determine the aboveground biomass of bamboo. The equation was developed with data from Bobiri Forest Reserve located in the MSD ecological zone.

$$Y = 0.367\ x\ DBH^{2.314}$$

where **Y** is aboveground bamboo culm biomass and **DBH** is culm diameter at breast height.

Estimation of bamboo biomass per hectare

Above Ground Biomass (AGB) bamboo ha^{-1} based on the bamboo culm algometric equations and the averaged culm of clump sampling was estimated with the following equation:

$$AGB_{bamboo}ha^{-1} = \frac{1}{m}\sum_{1}^{m}\overline{AGB}_{bamboo} \times N_{culm}ha^{-1}$$

4. Results and discussion

4.1 Results on extent and distribution

Bamboo extent according to land use

Bamboo covers less than 1% of the study regions, as shown in Table 4 and presented in Figure 5, and most of the bamboo identified and mapped were natural stands, with few of them being plantation.

Table 4. Land use of the study regions

Land use	Area (ha)	Percent Cover
Close Forest	960,150.92	12.42
Open Forest	1,416,784.28	18.32
Water body	253,481.53	3.28
Other Vegetation	4,637,021.32	59.97
Settlement/Bare Surface	421,673.55	5.45
Bamboo	42,889.63	0.55
Total	**7,732,001.23**	**100**

Source: RMSC-FC, 2020

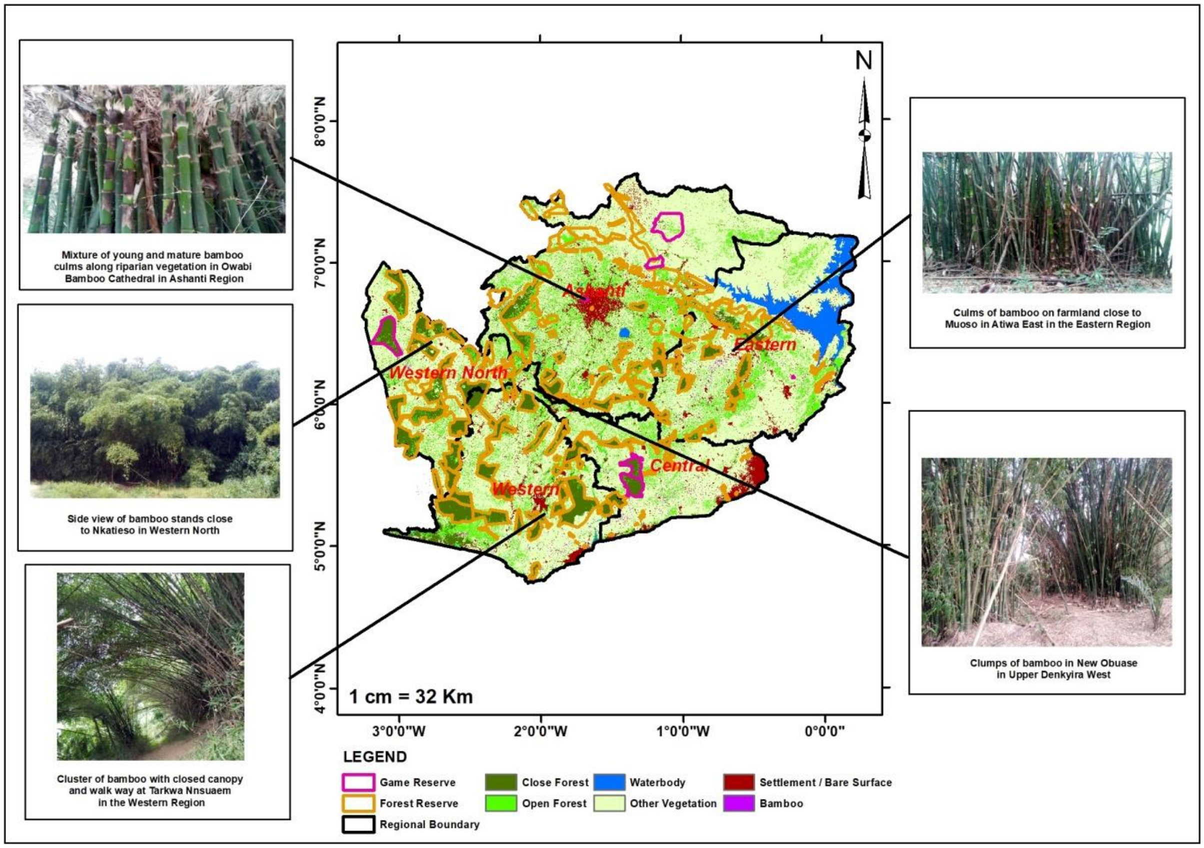


Figure 5. 2019 land use map of the study regions

The natural stands of bamboo occurred in both forest reserves and off-reserve areas, with 94.5% occurring in off-reserve areas. These stands existed in three forms: linear, small patches of vegetation and those mixed with other vegetation types. The linear bamboos were found along rivers and streams, showing as riverine vegetation (Figure 6).

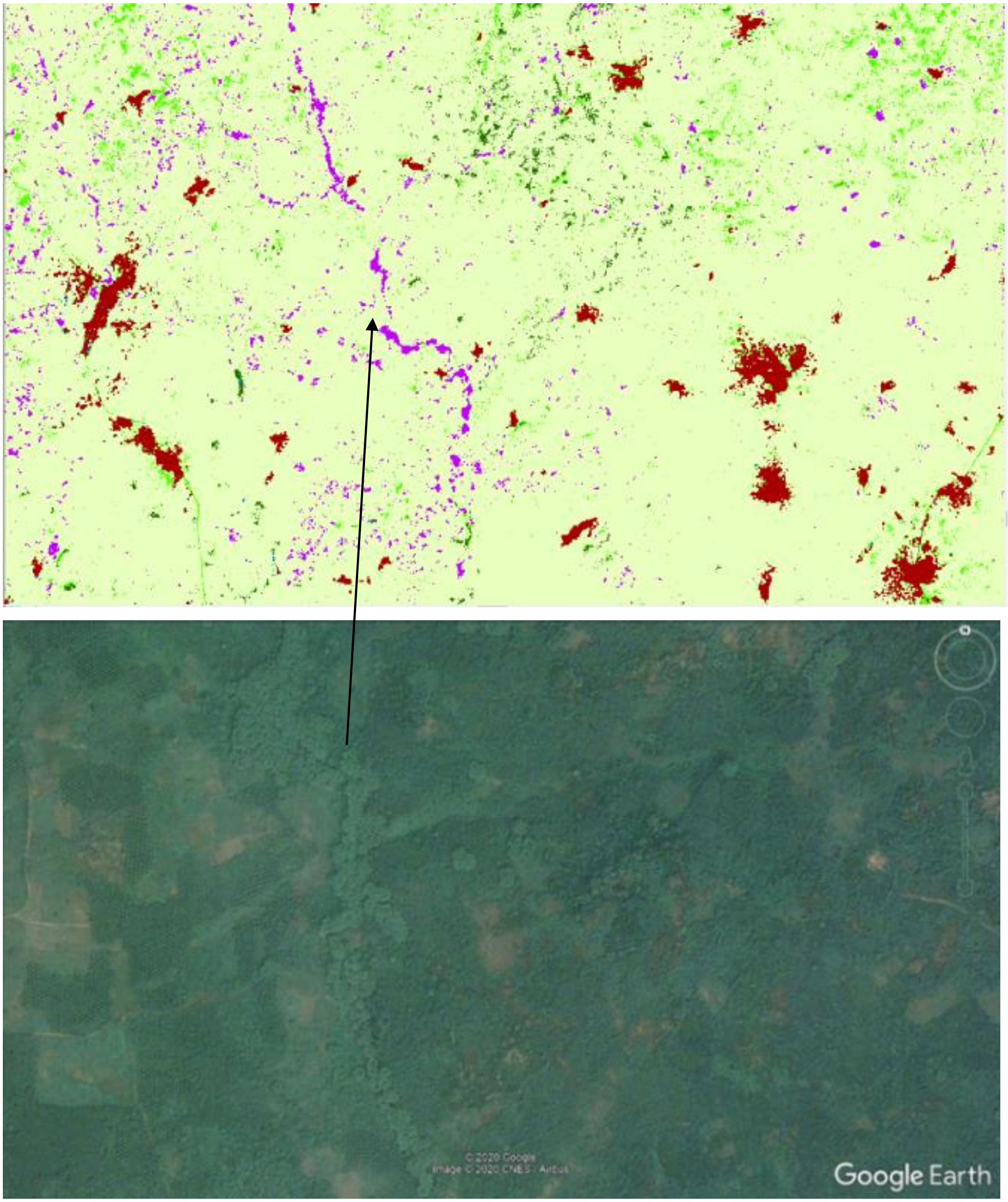


Figure 6. Linear bamboo on LCLU map shown on Google Earth at Pataase in the Central region

The patchy ones were found in waterlogged areas, such as marshes (Figure 7). The last form, isolated bamboo clumps mixed with other vegetation types, such as oil palm, rubber plantation and shrubs, did not show as continuous bamboo stands as found in the first two sets.

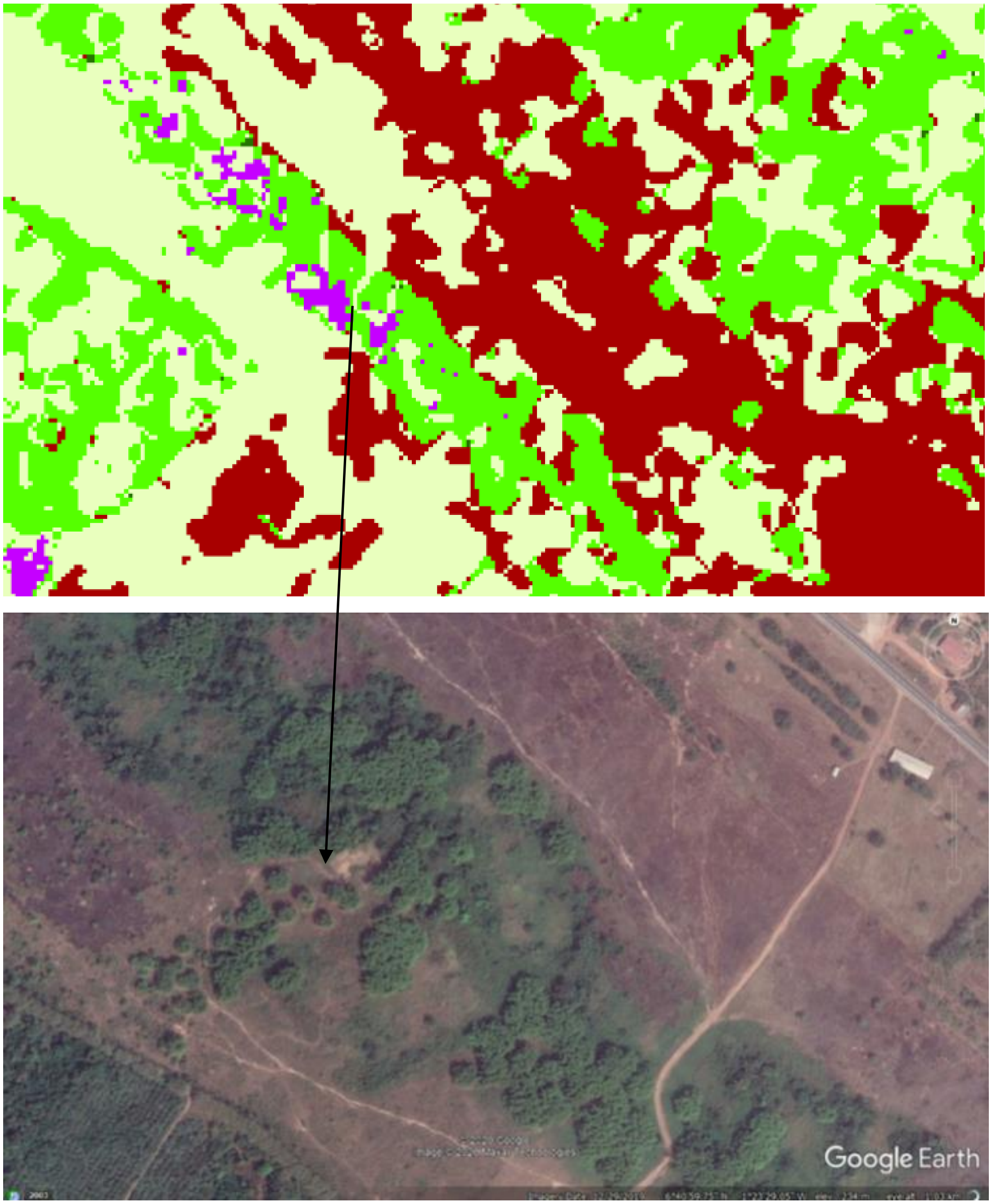


Figure 7. Patch bamboo stand on LCLU map and shown on Google Earth at Boankra in the Ashanti region

The close, dense and continuous canopy structure of the natural bamboo stands made them easily identifiable and mappable compared with the plantation stands. The bamboo plantation stands identified were young with very little or no canopy structure. Because of this, they did not exhibit the bamboo reflectance and structural characteristics that were observed in the Sentinel 2 and Google Earth application images. The reflectance of the bamboo plantation stands was similar to that of other vegetation types, such as grass. This made it difficult to map them using the classification algorithm and the Sentinel 2 images, which rely heavily on the spectral (reflectance) characteristics to distinguish them. To map the plantation stands, ground data were heavily relied upon in addition to information from the Forest District Offices of the Forest Services Division (FSD).

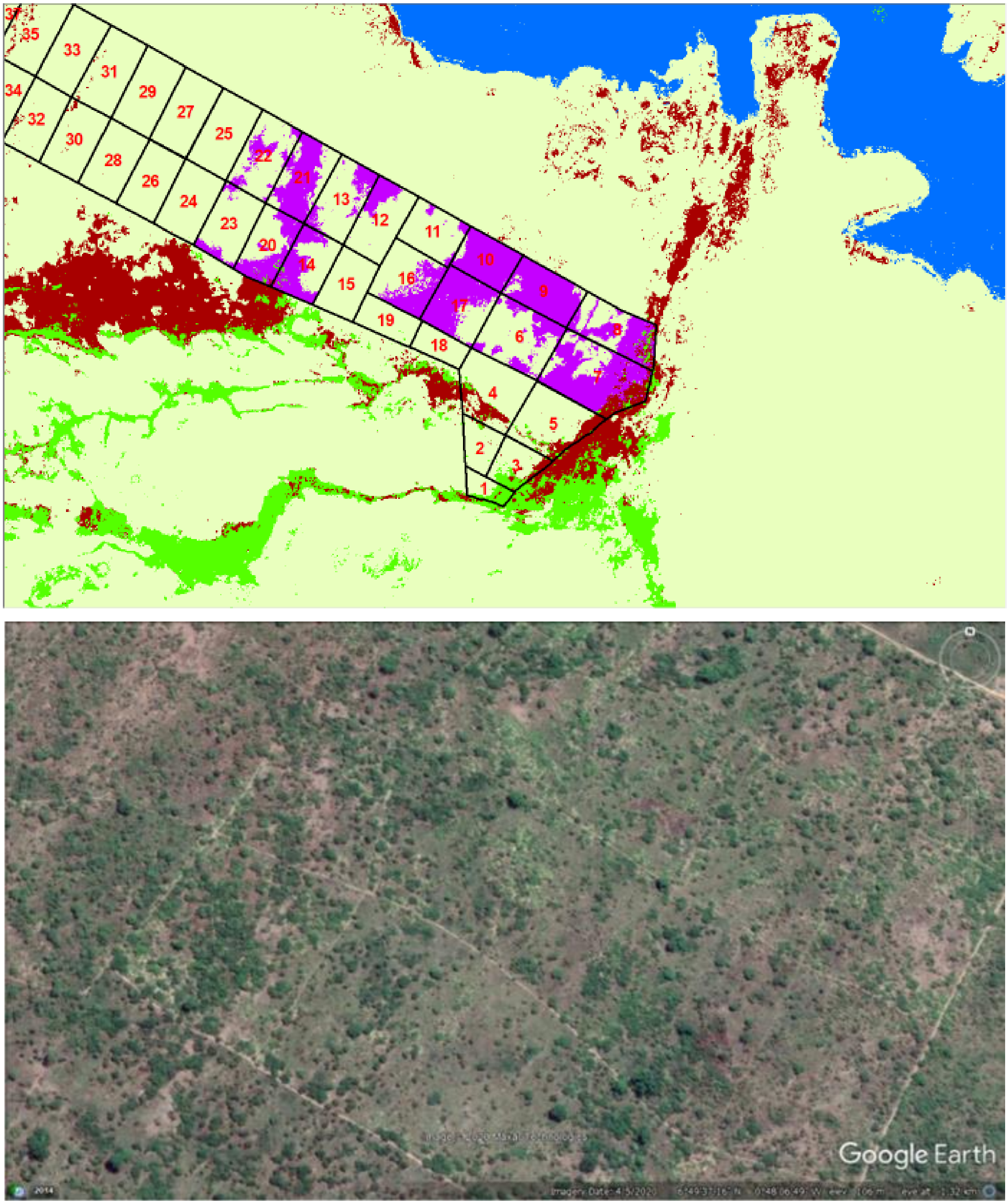


Figure 8. Bamboo plantation in Bandai North Forest Reserve on LCLU map and shown on Google Earth in Juaso in the Ashanti region

Bamboo extent according to eco-zones

The moist semi-deciduous (south-east subtype) (MSDSE) and upland eco-zones recorded the highest (14,802.16 ha) and lowest (206.84 ha) bamboo abundance, respectively, as shown in Table 5. A total of 34,096.88 ha, representing 80% of the total bamboos, were found in the moist ecological zones, with the remaining bamboo found in the dry ecological zones.

Table 5. Bamboo extent according to eco-zones

Eco-zone	Bamboo (ha)
Wet evergreen	3,142.87
Moist semi-deciduous (north-west subtype)	5,463.77
Moist semi-deciduous (south-east subtype)	14,802.16
Dry semi-deciduous (fire zone)	312.36
Dry semi-deciduous (inner zone)	6,148.83
Moist evergreen	10,481.24
Upland	206.84
Southern marginal	1,769.74
Savannah	561.81
Total	**42,889.63**

Source: RMSC-FC, 2020

The MSDSE and ME ecological zones together contributed about 59% of the total bamboo within the study area. This is because the two ecological zones cover a greater portion of the landscape where bamboo is dominant. The MSDSE eco-zone, for instance, covered a greater portion of bamboo-dominant areas in the Ashanti and Eastern regions, while the ME eco-zone covered most of the bamboo dominant areas in the Central, Western and Western North regions. Apart from these two moist ecological zones, the DSD (IZ) eco-zone had more bamboo cover than the remaining moist ecological zones. Most of the bamboo in the DSD (IZ) eco-zone was from the Central region where this ecological zone covers a greater portion of the bamboo dominant areas in the region. It also covered a small portion of the bamboo dominant areas in the Eastern and

Western regions. This contributed to its high bamboo coverage. The savannah within the study area falls within the transitional zone. This zone has characteristics of both the savannah and high forest zone.

Distribution

Tables 6 and 7 present the regional and district distribution of bamboo.

Table 6. Regional distribution of bamboo

Regions	Area (ha)
Ashanti	10,325.51
Central	9,518.23
Eastern	8,991.80
Western	9,397.49
Western North	4,656.60
Total	**42,889.63**

Source: RMSC-FC, 2020

Table 7. Bamboo distribution in forest districts in the study regions

Range (ha)	Forest Districts	Area (ha)	Percentage (%)
> 4000	Tarkwa	4,002.57	9.33
3001 - 4000	Bekwai, Takoradi, Winneba, Cape Coast and Kade	17,607.68	41.05
2001 - 3000	Mankranso, Sefwi Wiawso, Assin Fosu, Oda and Begoro	11,818.92	27.56
1000 - 2000	Nkawie, Juaso, Asankragwa, Enchi and Juabeso	6715.64	15.66
<1000	Mampong, Offinso, New Edubiase, Kumawu, Bibiani and Dunkwa	2,744.82	6.40
Total		**42,889.63**	**100.00**

Source: RMSC-FC, 2020

The results indicate a wider distribution of bamboo in the five regions. Apart from the Western North region, which had the lowest distribution of bamboo, the variation of bamboo distribution among regions was not as severe as among districts. The Ashanti region had the highest percentage of the total area of bamboo coverage at 24.07%, followed by the Central region (22.19%), the Western region (21.91%), and lastly, the Eastern region (20.96%).

Bamboo distribution in the Central and Western regions was concentrated in the southern parts of these regions. In the Central region, bamboo was very dominant in the communities of Jukwa, Jukwa Bremang, Dwabor, Akroful, Ayeldu, Ajumako, Abora Dunkwa, Achiasi and Batanyaa. In the Western region, bamboo distribution was dominant in the Mpataba, Azuleti, Samenye, Nyaaso, Bramiankor, Avrebo, Nkroful, Alabanketa, Mpohor, Tarkwa, Tanda, NyameYawkrom and Enyinamu communities.

In the Eastern and Ashanti regions, the bamboo distribution was skewed towards the MSD (north-west and south-east) ecological zones, which coincide with the high forest zone of Ghana. Very little of the bamboo was found in the dry and savannah ecological zones. In the Eastern region, bamboo dominance was found in the communities of Abomoso, Sankubenase, Tweapease, Akyem Swedru, Akyem Abodom, Akyem Asene, Akyem Manso, Kade, Anyinam, Enyiresi, Abakoase, Dompim and Adwobue. In the Ashanti region, bamboo distribution was dominant in

Boankra, Anweaso, Bekwai, Mfensi, Nobewam, Tokwai-Kokoben, Konongo Domase, Juaso and Banda North Forest Reserve (Plantation).

Bamboo was evenly distributed across the Western North region. However, there were communities where bamboo dominance was very obvious. These communities include Amoyaw, Patakro, Juabeso, Sui (Agya Nkrumah), Sefwi Tanoso and Kwawkrom.

To further consider the distribution of bamboo in the study regions, bamboo maps showing distribution within specific forest districts and its political administrations are attached as Appendices 3–17. Figure 9 shows one such map for the Tarkwa Forest District and Figure 10 shows the bamboo distribution map in ecological zones.

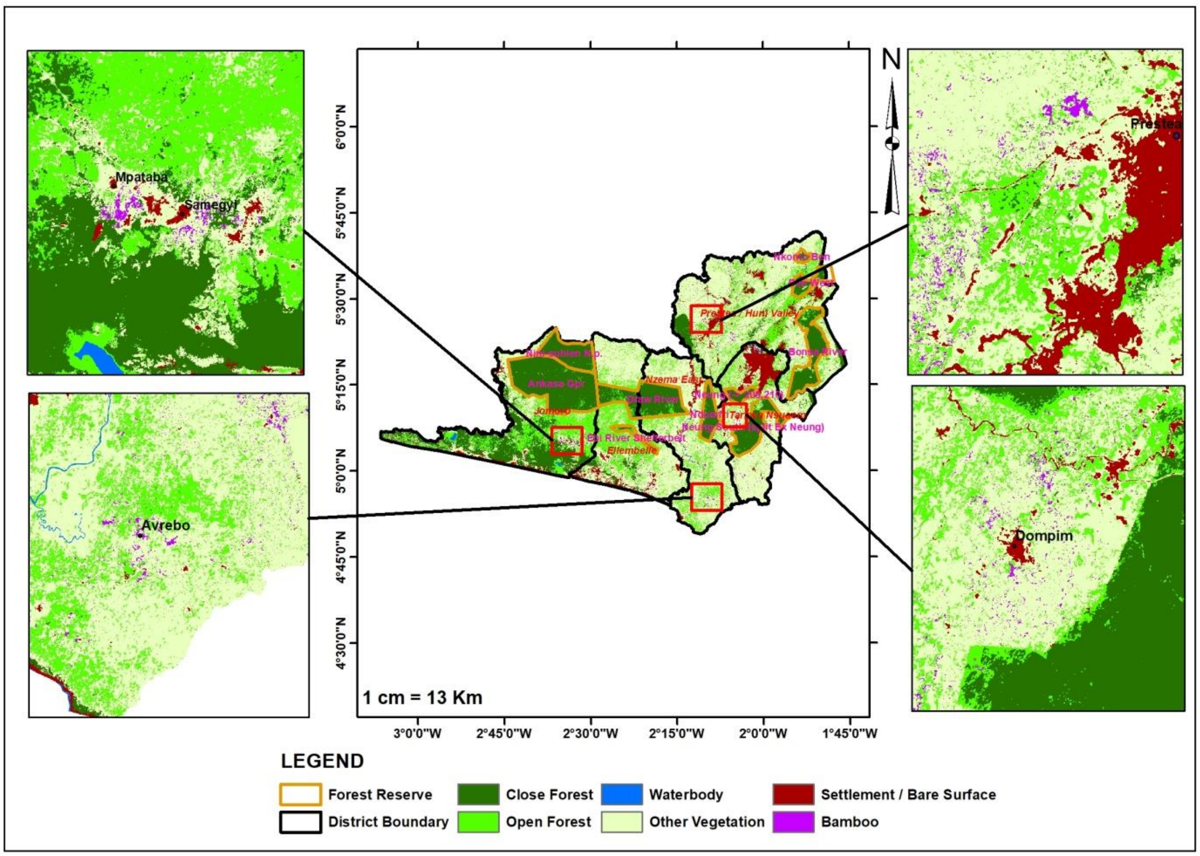


Figure 9. Bamboo distribution map in Tarkwa Forest District

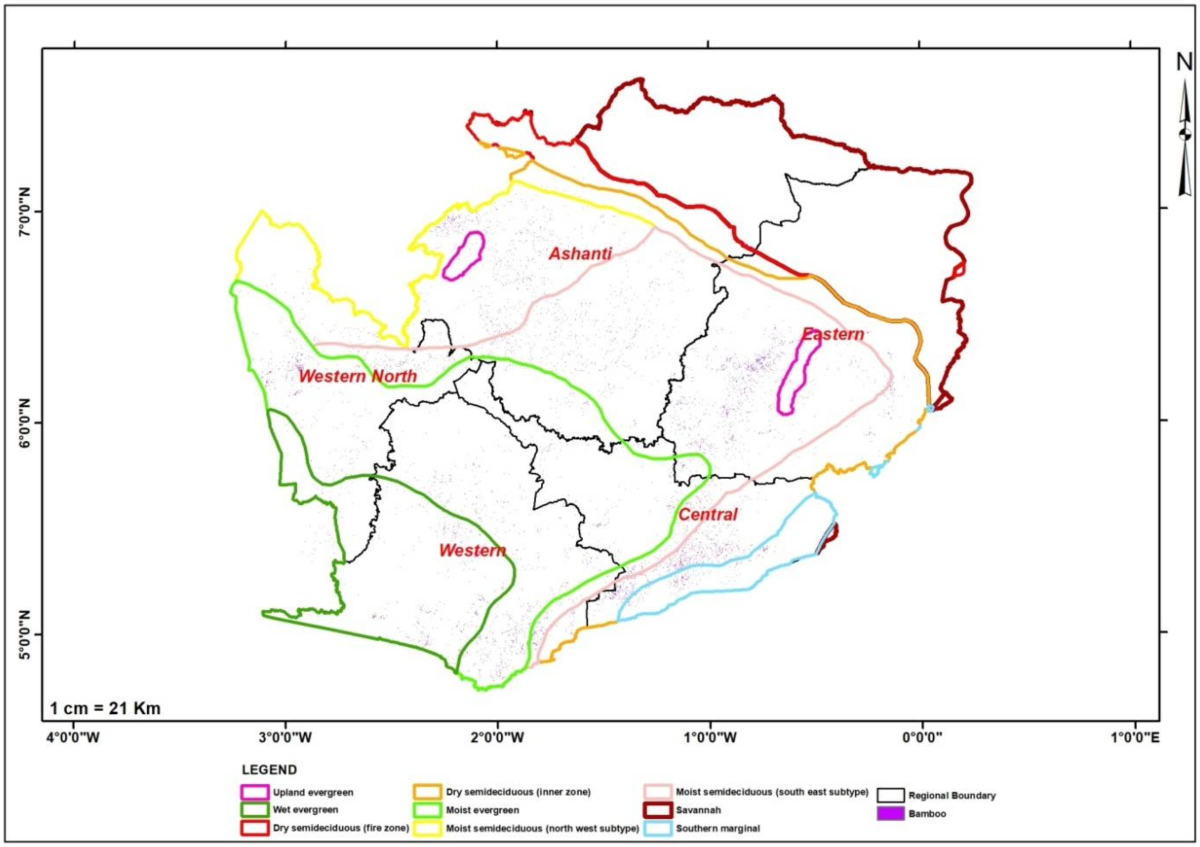


Figure 10. Bamboo distribution map in ecological zones

Distribution within protected areas

The protected areas, which are made up of forest and game reserves and national parks, contribute 2,367.75 ha, representing 5.52% of the total bamboo area. Of this, 2,338.05 ha were found in the forest reserves while 17.78 ha were found in game reserves and national parks. This means that a greater portion of the bamboo is outside the protected areas.

Accuracy assessment

The user accuracy was obtained by dividing the number of correctly classified bamboo pixels by the total number of pixels that were classified (the row total) (88/111), whereas the producer accuracy was derived by dividing the number of correctly classified bamboo pixels by the number of test set pixels used (the column total), (88/88), as shown in Table 8.

Table 8. Accuracy assessment

Class Name	Close Forest	Open Forest	Other Vegetation	Settlement / Bare Surface	Bamboo	Row Total
Bamboo	3	9	8	3	88	111
Column Total	3	9	8	3	88	111

Source: RMSC-FC, 2020

The overall accuracy was 79.28%, with a producer accuracy of 100% and user accuracy of 79.28%. The overall accuracy figure indicates a very good classification output. The producer accuracy indicates that 100% of bamboo stands have been correctly identified and mapped, while the user accuracy indicates that out of the 100% of the bamboo stands mapped, only 79.28% of the bamboo identified are truly bamboo. From the accuracy assessment, most of the confusion was from the open forest and other vegetation. This was caused by the dense, close canopy structure of some of the natural bamboo stands that make them appear as forest. Also, young oil palm and rubber plantation exhibited similar reflectance to that of bamboo, especially in areas where they are mixed. This means that the bamboo areas that were misclassified were mostly from these two classes.

4.2 Discussion on extent and distribution of bamboo

The results of the nature of the bamboo indicate that the majority of the bamboo identified and mapped were natural stands with very little plantation. The natural stands exist in small patches and some appear as riverine vegetation, as indicated in the general observation in the results section. They are unable to grow and dominate areas where they are prevalent. This, coupled with very little effort in bamboo plantation, has contributed to the small amount of bamboo (0.55%) in the landscape. To boost bamboo stands in Ghana, there must be conscious effort through the establishment of bamboo plantation. The greater portion of the bamboo stands (94%) lie outside the protected areas where there is less protection and proper management of this resource. This is because most of these lands are privately owned or managed by stool lands. This makes the resource susceptible to overexploitation leading to further reduction if measures are not put in place to check its exploitation.

The regional distribution of bamboo showed wider and almost even distribution, especially within the Ashanti, Eastern, Central and Western regions. This development indicates that the climatic conditions and soil properties within these regions favour the growth and establishment of bamboo plantation. This also means that the socio-economic and cultural dynamics that may lead to the overexploitation of this resource do not vary much among the five (5) regions.

Relating the distribution of bamboo across the political regions to the ecological zone distribution shows a pattern of a higher abundance of bamboo in moist environments than in dry environments. Bamboo distribution was higher in the moist ecological zones (MSD, WE and ME) than the dry ones (DSD (IZ), SM and savannah). This means that any initiative towards increasing bamboo stands within the regions should be focused on these two ecological zones. This trend was observed in all regions except the Central region, where a greater portion of the bamboo was found in the dry environment. About 70% of the bamboo stands in this region are found in the DSD(IZ), SM and savannah ecological zones.

Bamboo stands in the Central and Western regions show a trend of higher concentration towards the southern parts of these regions. Though a similar trend of bamboo distribution was observed in both regions, the higher concentration of bamboo stands in the DSD, SM and savannah ecological zones in the Central region is because the southern part of the region is made up of these ecological zones. This was not the case in the Western region, where a greater portion of the southern part of the region is made up of the ME and WE ecological zones, with the DSD (IZ) zone forming a smaller portion.

The DSD (IZ) eco-zone, which runs from the Ashanti through to the Eastern, Central and Western regions, showed peculiar bamboo distribution across these regions. This ecological zone seems to favour bamboo growth towards the southern part of the country. Within this ecological zone, there were very few bamboo stands in the Ashanti and Eastern Regions, but a significant amount of the stands were found in the southern parts of the Central and Western regions. This means that geographic location affects bamboo distribution.

4.3 General stand structural characteristics

The prevalent bamboo species identified in the study area is *Bambusa vulgaris*. The overall bamboo stand characteristics are summarised in Table 9. Generally, there was little variability in stand characteristics among the bamboo stands. The overall mean culm diameter was found to be 7.7 ± 0.1 cm dbh, with an average culm height of 17.4 ± 0.2 m. Mean culm thickness (13.2 ± 1.5 mm), the number of culms per hectare (9196.4 ± 383.8) and clumps per hectare (121.2 ± 14.6) varied substantially among the bamboo stands. Stand basal area per hectare (44.5 ± 2.1) also varied among the bamboo stands. The average number of culms per clump was 84.6 ± 2.1.

Table 9. General stand characteristics

Parameter	Estimated mean value (+SE)
Ave. diameter (cm)	7.7 ± 0.1
Ave. height (m)	17.4 ± 0.2
Ave. thickness (mm)	13.2 ± 1.5
Ave. length (m)	9.6 ± 0.2
Ave. clump girth (m)	16.2 ± 0.3
Ave basal area (m^2ha^{-1})	44.5 ± 2.1
Ave. Nculm / clump	84.6 ± 2.1
Ave. Nculm.ha^{-1}	9196.4 ± 383.8
Ave. Nclump.ha^{-1}	121.2 ± 14.6
Ave. AGC	169.56 ± 5.7

SE = Standard Error

Culm ages across ecozones

The number of culms per clump was higher within the WE ecological zone (97.2 culms) relative to the other eco-zones assessed (Table 10). Mature culms per clump (Year 3+) were predominant across all eco-zones, representing over 44% of the total standing culms. Young culms (Year 1) were least represented in the various bamboo stands (27%). Culm stems per hectare followed a similar pattern, with matured stems dominating the stands within the various eco-zones. The young culms develop on the outer zone of the clump and are therefore more vulnerable to anthropogenic disturbances compared to the mature ones located within the inner circle.

Table 10. Number of culms per clump and culms per hectare for age groups across ecological zones

Eco-zone	Age (years)					
	N_{culm}/clump			N_{culm}/ha		
	1	2	3+	1	2	3+
Dry semi-deciduous (inner zone)	17.6	16.7	23.7	2619.1	2415.5	3557.1
Moist evergreen	23.4	25.8	42.5	3127.8	3240.9	4736.8
Moist semi-deciduous (north-west)	22.8	31.0	30.3	2524.9	3408.1	3704.9
Wet evergreen	26.5	20.0	50.7	2776.9	2064.2	4862.8
Overall mean	**22.6**	**27.7**	**34.4**	**2758.6**	**3233.9**	**4091.2**

Structural and ecological variations of bamboo

This section provides information on bamboo stands at the eco-zone, regional and district levels. Bamboo stands exhibited variation in structural characteristics across the various ecological zones examined in this study (Tables 11 and 12). Mean culm diameter, culm height, clump girth and stand basal area varied significantly among eco-zones, while mean culm thickness, culms per hectare, clumps per hectare and clump-clump distance did not show significant variation.

Table 11. Bamboo stand structural characteristics across ecological zones

Parameters	Ecozone					
	DSD (IZ)	ME	MSNW	WE	Overall	P-value
Ave. D (cm)	6.90±0.2	7.9±0.1	7.7±0.1	7.9±0.1	7.7±0.1	0.002
Ave. H (m)	14.76±0.6	17.9±0.4	17.6±0.3	18.4±0.2	17.4±0.2	0.000
Ave. T (mm)	9.2±1.4	11.9±4.2	15.0±0.5	5.8±0.2	13.2±1.5	0.540
Ave. L (m)	8.2±0.2	9.4±0.3	9.9±0.2	9.7±1.1	9.6±0.2	0.065
Ave. Clump Girth (m)	12.14±1.05	15.3±0.6	17.6±0.4	12.25±1.7	16.2±0.3	0.000
Ave BA (m^2ha^{-1})	30.86±3.68	49.3±3.35	43.35±3.12	46.9±6.12	44.5±2.1	0.010
Ave. Nculm/clump	57.9±4.8	91.2±3.6	84.1±2.8	97.2±17.5	84.6±2.1	0.006
Ave. $Nculm.ha^{-1}$	8139.5±905.4	9982.5±709.6	8774.8±519.5	9703.9±8	9196.4±383.8	0.106
Ave. $NClump.ha^{-1}$	147.71±31.6	126.6±30.2	113.1±17.6	127.0±74.4	121.2±14.6	0.350

*****_Moist evergreen (ME), moist semi-deciduous north-west (MSNW), wet evergreen (WE); diameter (D), height (H), thickness (T), clump-clump distance (L), Basal Area (BA_

Table 12. Bamboo stand structural characteristics across study regions and forest districts

Region	District	Estimated area	Ave. D (cm)	Ave. H (m)	Ave. T (mm)	Ave. L (m)	Ave. Clump girth (m)	Ave.BAha^{-1}	Nculm.ha^{-1}	Clumpha^{-1}
ASHANTI	Bekwai	11.92	8.1	18.6	18.0	10.6	20.2	51.71	10109.4	108.9
	Juaso	5.39	8.1	18.4	19.5	9.3	17.6	48.56	9374.6	131.7
	Mankranso	8.09	7.6	16.3	17.7	9.0	15.7	37.24	7872.2	127.9
	New Edubiase	18.88	7.3	16.8	18.4	11.1	18.5	37.65	8754.7	101.2
	Nkawie	6.70	7.5	15.2	15.8	11.2	17.1	32.80	7416.4	113.7
Overall mean			**7.7**	**17.1**	**17.9**	**10.3**	**17.8**	**41.59**	**8705.4**	**116.7**
CENTRAL	Assin Fosu	14.18	7.4	18.6	5.3	9.3	16.8	58.55	13219.1	119.1
	Cape Coast	181.46	7.8	18.0	6.3	9.9	13.7	43.60	9265.8	129.0
	Dunkwa Offin	12.10	7.9	19.9	5.7	9.8	14.3	62.77	12731.6	105.2
Overall mean			**7.7**	**18.9**	**5.8**	**9.7**	**15.0**	**55.23**	**11795.0**	**117.5**
EASTERN	Begoro	14.19	7.8	20.6	19.8	12.1	23.8	25.12	5184.1	77.6
	Kade	12.42	7.2	16.8	18.2	9.0	13.7	34.77	8301.9	153.2
	Oda	6.00	8.1	18.8	19.4	8.9	18.8	50.16	8944.0	135.5
Overall mean			**7.7**	**18.7**	**19.1**	**10.0**	**18.8**	**36.68**	**7476.7**	**122.1**
WESTERN	Asankragua	3.25	7.7	17.3	6.0	9.2	13.7	52.88	10121.8	151.3
	Enchi	1.98	7.0	16.8	6.0	8.9	13.1	54.89	14276.2	152.3
	Sefwi Wiawso	5.43	7.2	15.8	6.2	8.9	15.1	56.59	13926.5	135.6
	Takoradi	14.67	6.8	13.0	6.1	7.0	10.1	50.41	13266.7	270.7
	Tarkwa	34.42	8.9	19.3	5.5	10.1	14.1	48.79	8163.9	104.8
Overall mean			**7.6**	**16.5**	**5.9**	**8.8**	**13.2**	**52.64**	**11898.7**	**161.1**
Total		**351.07**	**7.7**	**17.6**	**13.7**	**9.6**	**16.0**	**46.68**	**10083.7**	**262.6**

**Culm diameter (D), culm height (H), culm thickness (T), clump-clump distance (L), culm basal area (BA)*

Mean culm diameter and height

Mean culm diameter was greatest for stands found within the WE and ME eco-zones (7.9 ± 0.1 cm) and least in the DSD (IZ) eco-zone (6.90 ± 0.2 cm). Mean diameter across the four regions showed little variation, although the Western region recorded the least diameter (7.6 cm). However, mean culm diameter varied considerably among the forest districts, with Tarkwa recording the highest value (8.9 cm) and Takoradi the lowest (6.8 cm). Mean culm height across all eco-zones was 17.4 ± 0.2 m, but there were differences among eco-zones, with values in the DSD (IZ) being significantly lower than in the other eco-zones. The WE recorded the highest mean height of 18.4 ± 0.2m. Culm stems were generally taller in the Central region (18.9 m) and shorter within the Western region (16.5 m). Among the forest districts, stems were tallest in the Begoro district (20.6 m) and shortest within the Takoradi (13 m). Tables 4.8 and 4.9 summarise information on mean diameter and height.

Culm thickness

Culm stem thickness was generally 13.2 ± 1.5 mm across all the eco-zones. Stem thickness showed great variation (5.3 ± 0.2–15.0 ± 0.5 mm) among the eco-zones, with the MSNW recording the highest value and the WE the least mean value. The Central and Western regions exhibited thinner culm stems (5.8–5.9 mm) compared to the Ashanti and Eastern regions (17.9–19.1 mm). Culm thickness was generally highest in the Bekwai district (43.9 mm) and lowest within Assin Fosu (5.3 mm). The aggregated mean value across the eco-zones was 9.6 ± 0.2 m.

Clump-clump distance

Clumps in the bamboo stands were closer together in the DSD (8.2 ± 0.2 m) but dispersed in the MNSW (9.9 ± 0.2 m). Stands in the Western region were characterised by shorter distances (8.8 m) compared to those in the Ashanti region (10.3 m). Bamboo stands in Begoro and Takoradi had the highest (12.1 m) and lowest (7 m) values in the various forest districts, respectively.

Number of culms per clump

The number of culms per clump for each eco-zone, region and district are summarised in Tables 4.6 and 4.7. The aggregated mean culms per clump for all the eco-zones was 84.6 ± 2.1. The WE had the highest number of culms per clump (97.2 ± 17.5) while estimates for the DSD (IZ) were lowest (57.9 ± 4.8). Similarly, the mean culms per clump across the four regions was 84.7. Among the various regions, stands in the Central region tend to have more culms per clump, while stands in the Eastern region have fewer (71.9). Among the districts, Dunkwa Offin recorded the most culms per clump on average (120.1) compared with the other districts. Fewer culms were estimated for the Takoradi district (49.3) vis-a-vis the others.

Culm density and clump density

The stand density was highest in the ME (9982.5 ± 709.6 culmsha^{-1}) and the lowest in the DSD (IZ) (8139.5 ± 905.4 culmsha^{-1}). Culm density was found to be very high in the Western region (11898.7 culmsha^{-1}) and lower in the Eastern region (7476.7 culmsha^{-1}). At the district level, stand density was highest within the Enchi district (14276.2 culmsha^{-1}) and lowest in the Begoro district (5184.1 culmsha^{-1}). Average clump density was greater in the SM (160.2 ± 0.01 clumpsha^{-1}) but lesser in the MSNW (113.1 ± 17.6 clumpsha^{-1}). The aggregated mean clump density was 121.2 ± 14.6 clumpsha^{-1} across all the eco-zones. While clump density was high in the Western region (161.1 clumpsha^{-1}), it was comparably low in the Ashanti region (116.7 clumpsha^{-1}). The mean clump density for all four regions was 131.9 clumps ha^{-1}. Clumps were denser within the Takoradi district (270.7 clumps ha^{-1}) as opposed to the Begoro district, where they occurred in low densities (77.6 clumps ha^{-1}).

Total number of culms

The total number of culms is analysed at the regional level. A total of 432,486,162.03 culms are estimated for the four regions surveyed (Table 13). The Western region recorded the highest number of culms (167,225,400.68). The Eastern region recorded the lowest number of culms (67,228,991.06).

Table 13. Total number of culms per region

Region	Area (ha)	Mean culm/ha	Total
Ashanti	10,325.51	8,705.4	89,887,694.75
Central	9,518.23	11,795.0	112,267,522.85
Eastern	8,991.80	7,476.7	67,228,991.06
Western / Western North	14,054.09	11,898.7	167,225,400.68
Total	**42,889.63**	**10,083.7**	**432,486,162.03**

Source: RMSC-FC, 2020

Diameter class distribution

Generally, bamboo culms within the 0–3 cm diameter class were not recorded during the survey. The bamboo stands were dominated by culms in the 6.1–9 cm diameter class (Figure 11; Table 14). Analysis of the number of culms across the various ecological zones indicated that culms in the diameter size class 6.1–9 cm were widely distributed. Large-diameter-size-class culms (9.1–12 cm were only recorded in the ME and MSDNW eco-zones. Culms in the 3.1–6 cm and 9.1–12 cm diameter classes were not recorded in the SM and WE eco-zones. Age class distribution indicates an abundance of mature culm (Year 3+) compared to less mature ones.

Table 14. Diameter size class distribution of number of culms per hectare by ecological zone

Eco-zone	0–3 cm	3.1–6 cm	6.1–9 cm	9.1–12 cm	Total
Dry semi-deciduous (inner zone)		2059.0	3069.8		5128.8
Moist evergreen		5540.1	3987.6	2624.3	12152.0
Moist semi-deciduous (north-west subtype)		2231.2	3292.5	2995.3	8519.1
Southern marginal			3658.6		3658.6
Wet evergreen			3234.6		3234.6

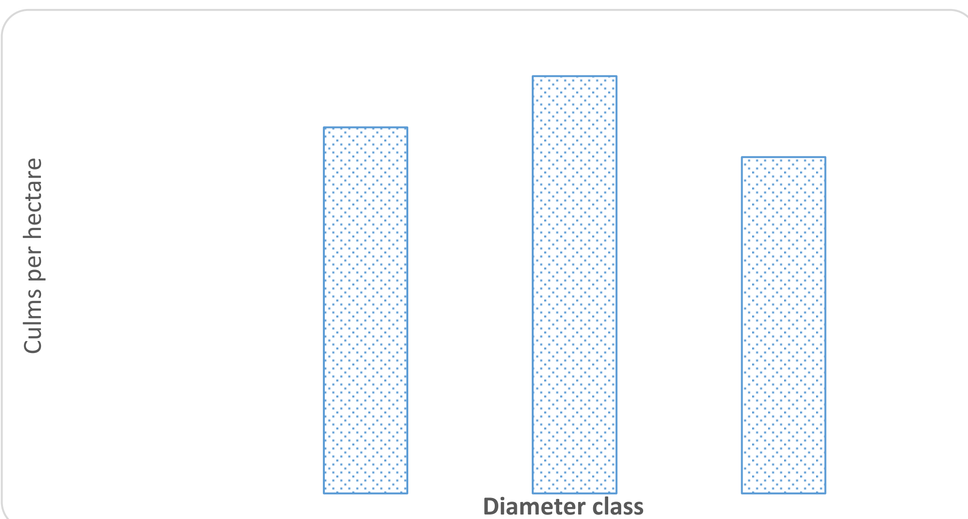


Figure 11. Diameter distribution of culms per hectare

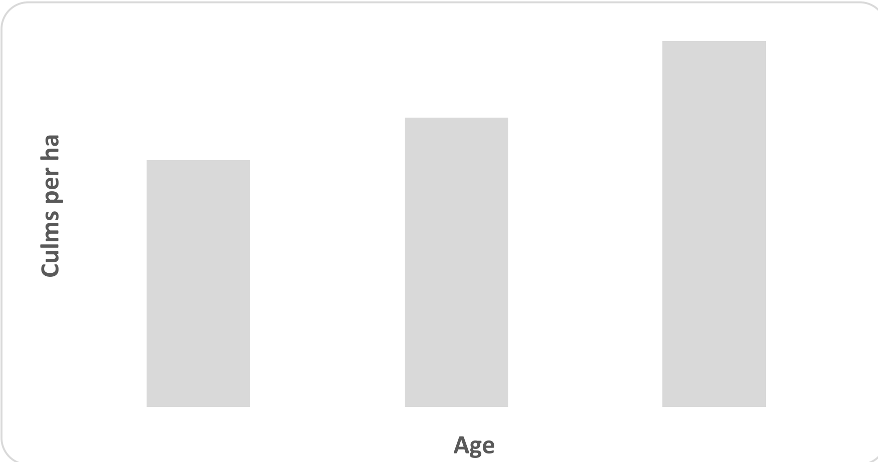


Figure 12. Age class distribution

4.4 Estimation of bamboo biomass and carbon in eco-zones

Biomass and carbon stock estimates were generated using the local allometric equation. A carbon fraction of 0.47 and CO_2 equivalent (carbon × 3.67) was used (IPCC, 2006). The average aboveground carbon stock across all five ecological zones indicated that bamboo biomass and carbon estimates per hectare were highest for bamboo stands in the MSDNW eco-zone (186.07 tha^{-1}). Mean aboveground carbon stock per hectare was least for the WE ecological zone (73.38 tha^{-1}). Carbon storage varied significantly among bamboo stands in the different ecological zones ($F = 3.895$, $df = 3$, $p = 0.010$). A total carbon stock of 214,612.89 tC (787,629.3 tCO_2-e) is estimated for the survey area (Table 10).

4.5 Comparison of bamboo stand characteristics

A negative correlation was found between the number of culms per clump and the level of disturbance of the bamboo stand (Figure 13). A similar observation was also made for clump girth and level of disturbance, but in this case, the relationship was very weak (Figure 14). This indicates that the harvesting and clearing of the bamboo stand for farming affects stand density to some extent. A positive association was found between the number of culms per clump and clump girth. Distance between clumps was negatively correlated with the quantity of carbon storage per hectare. Carbon stock was, however, positively correlated with culm diameter, the number of culms per hectare and basal area estimates per hectare. Given the clump-based method used for the field assessment, it was found that the distance between clumps influenced the estimated carbon storage per hectare. Generally, the bamboo stands' carbon stock is strongly related to culm density.

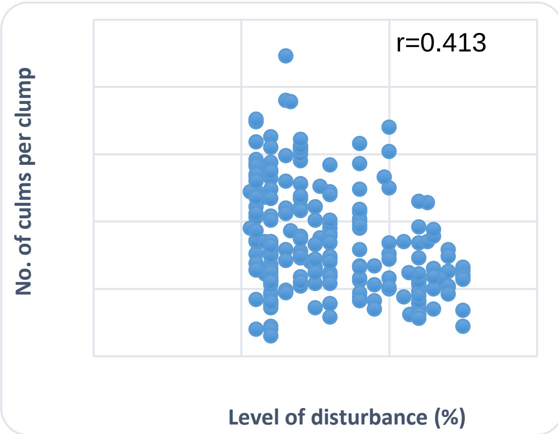


Figure 14. Correlation analysis of the level of disturbance and number of culms per clump

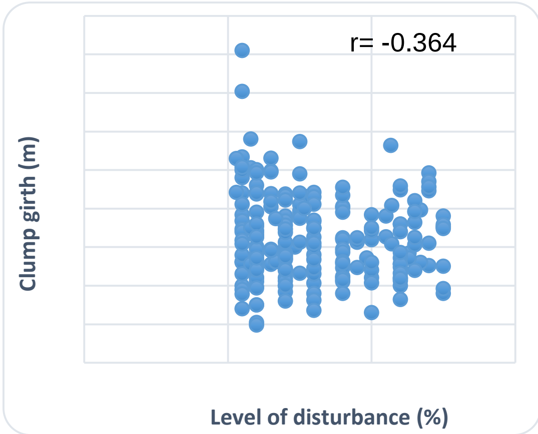


Figure 13. Correlation analysis of the level of disturbance and clump girth

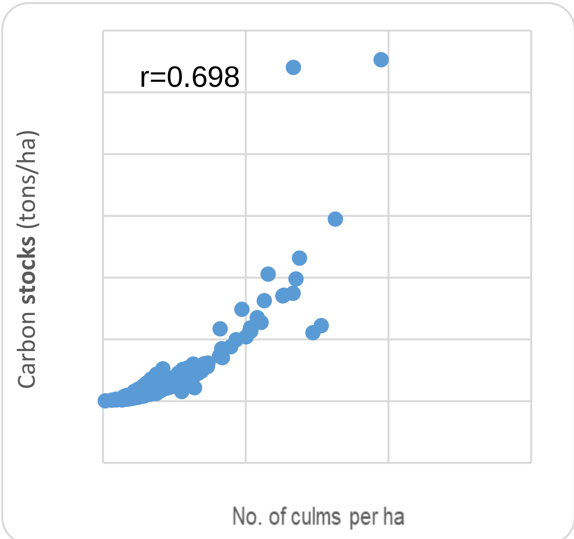


Figure 15. Figure relationship between number of culms per hectare

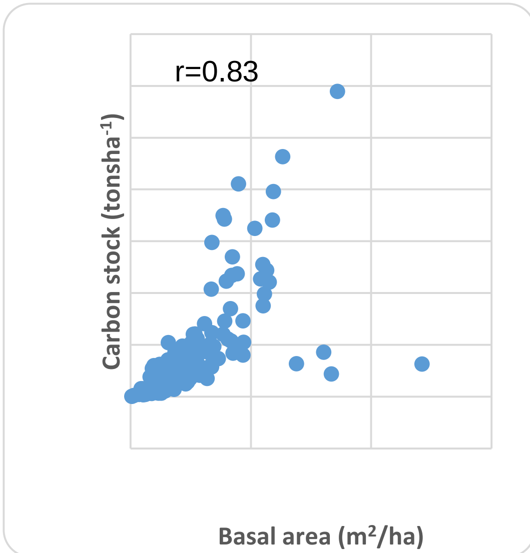


Figure 16. Figure association between basal area (m^2/ha) and carbon stocks (tons/ha)

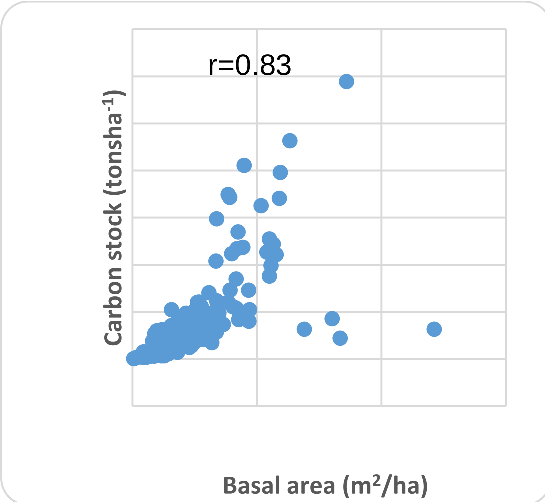


Figure 18. Association between m²/ha and carbon stocks

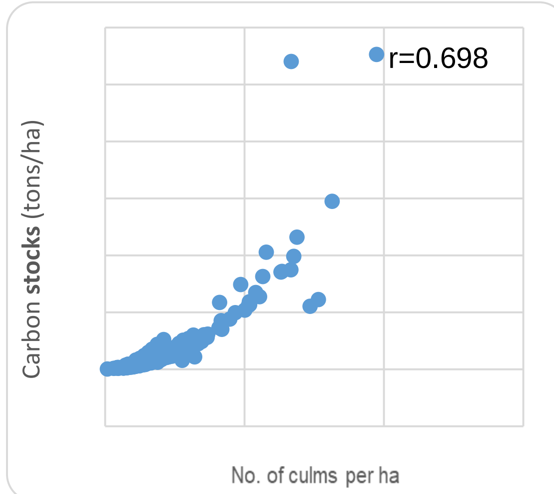


Figure 17. Relationship between number of basal area culms per hectare and carbon (tons/ha)

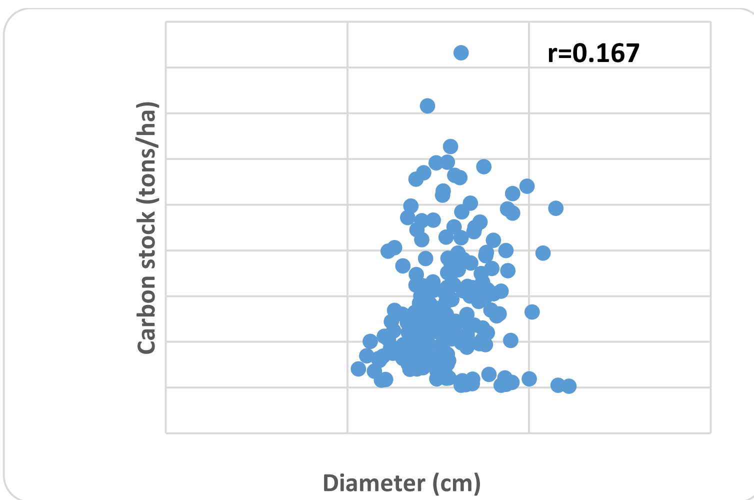


Figure 19. Relationship between culm diameter and carbon stock

4.6 Discussion on bamboos stand density and structure

Bamboo stands occur at varying densities and exhibit structural characteristics that show differences across the various ecological zones and regions analysed. The mean culm density of 8139.5 ± 905.4 culmsha^{-1}–9982.5 ± 709.6 culmsha^{-1} estimated in this study is higher than those reported for *B. vulgaris, O. abyssinica* and *B. vulgaris var. vittata* of 7171 culmsha^{-1}, 6267 culmsha^{-1} and 3325 culmsha^{-1}, respectively, in another study conducted in Bobiri Forest Reserve, located in Ghana (Amoah et al., 2020). Another study conducted in Ghana also showed a lower mean value of 4287 ± 2014 SD culmsha^{-1} in the Mpohor Wassa East district (FoRIG, 2010). Other studies elsewhere found a much lower culm density of 2933.33 culmsha^{-1} for *B. vulgaris* in Bangladesh (Sohel et al., 2015b). A higher value of 12650 culmsha-^{1} was estimated for *Yushania alpina* bamboo stands in Kenya (Muchiri and Muga, 2013).

Most of these studies focus on specific sites and therefore do not account for the large variation that exists among stands as one transitions from the local to the regional level. Other studies also suggest that stand density is influenced by culm diameter, species and silvicultural practice differences among countries (Yen, 2015; Liu et al., 2016). Evidence from other studies suggests that the harvesting of bamboo stands, especially mature culms, is necessary for an increase in shoot production (Singnar et al., 2017; Inoue et al., 2018). Other studies have also reported that harvesting mature culms could promote the production of young culms (Muchiri and Muga, 2013; Wang and Chen, 2015). Most bamboo stands in Ghana are not managed, and the effect of not cutting mature culms or managing stands has resulted in a lack of vigorous shoot-sprouting. Several studies have emphasised that to maintain the vigour of bamboo forests, one fifth of older culms from the entire stand should be removed through annual selective cutting to improve sprouting (Wang and Chen, 2015; Yen, 2016). The INBAR technical manual for sustainable management of clumping bamboo forest indicates that an equal number of bamboo poles/culms of different age classes can be retained for optimal growth, as the number of bamboo poles harvested and shoot recruited for growth into a bamboo culm could be balanced. The composition of the Current Year 1 (0–1 years), Year 2 (1–2 years) and Year 3 (2–3 years) shoots can be maintained in a proportion of 1:1:1 (Durai and Long, 2020).

Commercial exploitation of bamboo is very restricted and not approved on a national scale. Harvesting is mostly done on a subsistence level, and bamboo is mainly used as scaffolding poles during construction. Therefore, a substantial portion of bamboo stands remain unmanaged. Though harvesting and clearing of bamboo stands reduces clump and culm density, the high densities of culms recorded in this study suggest that the impact of disturbance on bamboo stands in the four regions surveyed remains minimal.

4.7 Carbon storage potential of bamboo stands

The mean aboveground carbon (AGC) stock of 22.81 ± 3.58–34.44 ± 3 $tCha^{-1}$ for bamboo stands found in the different ecological zones for this study was comparable with estimates reported by a similar study in Ghana of 50.76 t ha^{-1}, 1.98 $tCha^{-1}$ and 33.87 $tCha^{-1}$ for *B. vulgaris, O. abbyssinica* and *B. vulgaris var. vittata*, respectively (Amoah et al., 2020). However, it is also lower than that reported by other studies conducted in various countries: 50.44 $tCha^{-1}$ for *B. vulgaris* produced in a degraded tropical forest in Bangladesh (Sohel et al., 2015b); 61.3 $tCha^{-1}$ for moso bamboo in an intensively managed forest (Mishra et al., 2014); 40.45 Mg ha^{-1} for *Phyllostachys pubescens* Mazel ex Houx in the forests of China (Zhang et al., 2014); 78.6 $tCha^{-1}$ for *Phyllostachys pubescens* from Japan (Isagi et al.,1997 in Sohel et al., 2015b); 121 $tCha^{-1}$ for *Bambusa bambus* in India (Kumar et al., 2005); and 100 $tCha^{-1}$estimated for *Guadua angustifolia* from tropical forests in Bolivia (Quiroga et al., 2013). The AGC of bamboo stands was found in this study to be strongly correlated with culm density, and therefore, the variation in carbon stock among the various sites could be due to differences in culm density. Also, variation in methodologies and allometric models used in different studies could influence carbon estimation. While most of the studies reported in the literature used standard plot sizes, the clump-based method used in this study uses varying plot sizes due to the variation in distance between bamboo clumps among stands. The varying plot sizes associated with the clump-based method could exert an exponential effect on the carbon stock per unit area measurements.

Several studies have shown that the carbon sequestration potential of bamboo forests compares favourably with other forest ecosystems (Mishra et al., 2014; Amoah et al., 2020). Other studies also found that bamboo can accumulate high biomass during the growth period and has a high potential for sequestering large quantities of carbon as compared with many wood species per unit area (Majundar et al., 2016; Yen, 2016). A study conducted in an upland evergreen forest (Tano Offin Forest Reserve and Atewa Range Forest Reserve) and a WE forest (Cape Three Points Forest Reserve) in Ghana showed that the mean AGCs were 117.8 $tCha^{-1}$, 136.079 $tCha^{-1}$ and 211.2 $tCha^{-1}$, respectively (Schep et al., 2016; Ayesu, 2018). A similar study by Asante and Jengre (2012) reported a mean AGC in peat swamp forest areas in Ghana of 114.29 $tCha^{-1}$. This suggests that bamboo stands have comparable carbon storage potential per unit area to woody tropical forest. Considering the short growth cycle of bamboo culms, the bamboo forest may be superior to tropical tree forests concerning carbon sequestration potential, as tropical trees typically take several years to reach maturity. Moreover, the possibilities of annual harvesting and conversion into durable products coupled with the annual growth of new shoots/culms adds to the carbon stock.

4.8 Implication for REDD+ implementation and poverty reduction in Ghana

In the last decades, tropical forests, which account for about 42% of global forestlands, have suffered massive deforestation and forest degradation (Gorte and Sheikh, 2010). The current level of forest loss in tropical regions and the large areas of degraded lands now underscore the urgent need for interventions to restore biodiversity, ecological function and the provision of ecosystem services. Traditional timber plantations have supplied some goods but have made only minor contributions to fulfilling most of these other objectives. New approaches for reforestation are now emerging, with potential for both overcoming forest degradation and addressing rural poverty.

There is increasing interest in the cultivation of bamboo as a way of restoring degraded forest lands for biomass production and carbon sequestration due to its fast growth (Darabant et al., 2014; Krishna et al., 2015; Forestry Commission, 2016) and its ability to adapt to low-quality and degraded lands (FAO and INBAR, 2018; Mishra et al., 2014). Bamboo is recognised as a potential carbon sink (Lobovikov et al, 2009; Nath et al., 2015) in view of its fast growth and short rotation cycle. Bamboo forests have been reported to have a higher carbon density per hectare than woody plant forests (Mishra et al., 2014; Krishna et al., 2015; Yang et al., 2015). Due to its fast growth and high regeneration rate after harvesting, bamboo forests can potentially sequester a substantial amount of carbon (Mishra et al., 2014; Van der Lugt et al, 2018). The rapid growth rate of bamboo coupled with the annual carbon sequestration of the bamboo forest is very high – up to 25 $tCha^{-1}$/year (Yen et al., 2017) – and its harvesting cycle of 1–3 years (compared to 10–50 years for most timber species) adds to the advantage of bamboo (Singnar et al., 2017; Mishra et al., 2014). Bamboo is also known to provide several ecosystem and environmental services, including environmental amelioration, biodiversity preservation, soil conservation, water filtration/purification, carbon sequestration (Krishna et al., 2015; Van der Lugt et al., 2018) and rehabilitation of degraded lands (Mishra et al., 2014; INBAR, 2018a, 2018b). The use of bamboo in ecological restoration and plantation establishment programmes, especially on marginal lands, watersheds, riverbanks and degraded areas, could immensely contribute to achieving Ghana's emission reduction targets and provide jobs for forest-dependent communities. The need to use bamboo in forest restoration programmes is echoed in Ghana's Forest Plantation Strategy: 2016–2014 (Forestry Commission, 2016).

5. Conclusion

The current study represents a major joint INBAR/Ghana Forestry Commission initiative to assess the status of bamboo resources in Ghana. It is a first attempt at generating a systematic report on the best available information on bamboo resources at a national level. The study has provided information on spatial distribution, structural characteristics, density bamboo resources and aboveground carbon stock.

In terms of the bamboo forest mapping, Sentinel satellite imagery was classified to depict bamboo stands in the five (5) regions of Ghana. The image could identify bamboo areas in Ghana with 79.28% accuracy when using remote sensing techniques. The under-listed summarises the findings:

Spatial distribution and extent

a. The Ashanti and Western regions had the highest bamboo distribution, while the Central and Eastern regions had a comparatively lower distribution.

b. Bamboo is more abundant in moist ecological zones (MSD and ME) than in dry ones (DSD and savannah)

c. There are estimated to be **42,889.63** ha of bamboo within the five regions based on the accuracy assessment of 79.28%.

Structural characteristics

a. The average culm diameter and height were relatively higher for bamboo stands found in the ME and WE forest types.

b. On average, culm thickness was highest for those culms found in the MSD forest type and lowest for stands in the WE forest.

c. The bamboo clumps in the WE eco-zone were widely dispersed compared to those in the other eco-zones. Clumps in the DSD eco-zone were closer to each other.

d. Clump girth was greater for stands in the MSD forest type and lower for those in the DSD eco-zone. Mean basal area estimates were highest for stands in the ME zone and lowest in the case of the DSD zone.

e. The number of culms per clump was found to be greater in the WE zone and lesser in the DSD zone. Also, mean culms per hectare were highest for stands in the ME zone and lowest in the DSD zone.

f. A total of **570,305,736.80** culms were estimated for the four regions surveyed. The Western region recorded the highest number (**241,152,856.69**) while the Eastern region recorded the lowest (**47,712,710.58**).

Aboveground carbon stock

a. Mean aboveground carbon stock estimates per hectare were highest for bamboo stands found in the MSDNW eco-zone and lower for those in the WE zone.

b. There were significant differences in carbon storage among bamboo stands found in the various ecological zones.

c. Total carbon for the four regions is estimated at 9,589,837.14 tC (35,163,867.31 tCO2-e). Among the four regions, the Ashanti region had the highest total carbon stock of 3,979,277.62 tC (14,590,836.21 tCO2-e) while the lowest value was recorded for bamboo stands in the Eastern region (969,097.63 tC (3,553,230.34 tCO2-e)).

d. Bamboo stands' carbon stock is strongly related to culm density.

5.1 Recommendations

1. There should be an upscaling of bamboo inventory to cover other areas not captured in this study, especially other ecological zones and administrative regions in the country. The current study covered only four regions that are not representative of the bamboo resources in Ghana. For national planning and sustainable management of bamboo resources, there is a need to extend the information gathering to the unassessed regions, especially the transition and savannah zones.

2. Allometric equation-based representative data from the various ecological zones should be developed for the different species of bamboo found in Ghana to improve the precision of biomass estimation.

3. Given that bamboo stands are presently not formally managed, especially off-reserve resources, there is a need to put in place systems and strategies for the sustainable utilization of bamboo resources in Ghana.
4. In the context of REDD+ implementation in Ghana, restoration of degraded areas, especially off-reserve (riparian vegetation, bamboo agroforestry and other marginal lands), using bamboo could contribute to climate change mitigation through carbon sequestration. The established bamboo forest could be leveraged for carbon trading.
5. Given the short rotation cycle of bamboo species, the development of bamboo plantation should be integrated into the national forest development to facilitate the provision of raw material and job creation, especially for forest-fringe communities.
6. The establishment of permanent sample plots to monitor growth and generation of the site-specific index for various species and ecological zones could be useful for planning and sustainable management of bamboo resources in Ghana.
7. A bamboo-specific site index will need to be developed to improve upon the prediction of bamboo areas in Ghana when using remote sensing.
8. There is a need for further research into kinds of images that can spectrally characterise signatures for different leaf structures in the region.

6. References

Abbiw, D.K. (1990) Useful plants of Ghana. West Africa use of Wild and cultivated plants. Intermediate Technology Publications Ltd UK and Royal Botanic Gardens Kew UK. Reprint, 1995

Amoah, M., Assan, F.&Dadzie, P. K. (2020) Aboveground biomass, carbon storage and fuel values of *Bambusa vulgaris*, *Oxynanteria abyssinica* and *Bambusa vulgaris var. vitata* plantations in the Bobiri Forest Reserve of Ghana, Journal of Sustainable Forestry, 39:2, 113-136,

Araujoa, L. S., Sparoveka, G., dos Santosb, J. R., & Rodriguesa, R. R. (2008). High-resolution image to map bamboo-dominated gaps in the Atlantic Rain Forest, Brazil. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *37*(B4), 1287-1292.

Armstrong, W.P. (2008) Bamboo: Remarkable Giant Grasses (grass family: Poaceae) (http//waynesworld.palomar.edu/ecoph39).

Asante, W., & Jengre, N. (2012). Carbon stocks and soil nutrient dynamics in the peat swamp forests of the Amanzule Wetlands and Ankobra River Basin. USAID Integrated Coastal and Fisheries Governance Program for the Western Region of Ghana. Accra: Nature Conservation and Research Centre. 45 pp.

Ayesu, 2018 Assessment of Global Climate Regulation in Tano Offin Forest Reserve and Cape Three Points Forest Reserve. Consultancy report for Ghana Wildlife Society, Ghana.

Bamboo and Rattan Development Program Ghana, Bamboo Resources, 2017.

Bamboo in Kenya. Journal of Natural Science Research, 3(10), 77–84.

Bo Lin. (2018) The Preliminary Exploration and Analysis of Bamboo Industry in the Macro and Micro Environment of Ghana. BARADEP supported the study

Bystriakova, N., Kapos, V. and Lysenko, I. (2004) Bamboo Diversity –Africa, Madagascar and the Americas. UNEPWCMC/INBAR, http;/www.unepwcmc.org/resources/publication. A Banson production, UK 88pp

Darabant, A., Haruthaithanasan, M., Atkla, W., Phudphong, T., Thanavat, E., & Haruthaithanasan, K. (2014). Bamboo biomass yield and feedstock characteristics of energy plantations in Thailand. EnergyProcedia, 59,134–141.

De Carvalho, A. L., Nelson, B. W., Bianchini, M. C., Plagnol, D., Kuplich, T. M., & Daly, D. C. (2013). Bamboo-dominated forests of the southwest Amazon: detection, spatial extent, life cycle length and flowering waves. *PloS one*, *8*(1), e54852

Ebanyenle, E. and Oteng-Amoako, A.A. (2007) Site differences in morphological and physical properties of Bambusa vulgaris grown in Ghana. Discovery and Innovation, volume 19 (Afornet Special Edition No.3) ISSN 1015- 0798 pp. 222-22

Estes, L. D., Reillo, P. R., Mwangi, A. G., Okin, G. S., &Shugart, H. H. (2010). Remote sensing of structural complexity indices for habitat and species distribution modeling. *Remote Sensing of Environment*, *114*(4), 792-804. [CrossRef] [Google Scholar]

Fan, J., Li, J., Xia, R., Hu, L., Wu, X., & Li, G. (2014) Assessing the impact of climate change on the habitat distribution of the giant panda in the Qinling Mountains of China. *Ecological Modelling*, *274*, 12-20.

FAO (1997) Provisional outlook for global forest products consumption, production and trade. Forestry Department, Policy and Planning Division, FAO, Rome

Farrelly, D. 1984: Sierra club books, San Francisco, California. pp. 340.

Forestry Commission, (2016). Ghana's Forest Plantation Strategy: 2016-2040.

FORIG (2010) In Bamboo Resources and Charcoal Production and use in some Selected Communities in The Mpohor Wassa East District

Ghosh, A., & Joshi, P. K. (2014). A comparison of selected classification algorithms for mapping bamboo patches in lower Gangetic plains using very high resolution WorldView 2 imagery. International Journal of Applied Earth Observation and Geoinformation, *26*, 298-311.

Gorte, R. W., & Sheikh, P. A. (2010). Deforestation and climate change. Congressional Research Service. 7-5700.

Hu, Q., Wu, W., Xia, T., Yu, Q., Yang, P., Li, Z., & Song, Q. (2013). Exploring the use of Google Earth imagery and object-based methods in land use/cover mapping. *Remote Sensing*, *5*(11), 6026-6042.

INBAR (2006) Bamboo for the environment, development and trade. International Bamboo Workshop, Wuyinshan, Fujian Province, China.

INBAR NEWS. (2018b). Achieving SDG 7: The potential of bamboo charcoal. INBAR news of February 10th 2018. Retrieved April 5th, 2019, fromhttps://inba.int/achieving-sdg-7-the-potential-of-bamboo-charcoal.

Inoue, A., Sato, M., & Shima, H. (2018). Maximum size-density relationship in bamboo forests: Case study of Phyllostachys pubscens forests in Japan. Forest Ecology and Management, 425,138–144.

IPCC (2003) *Good practice guidance for land use change and forestry*. Hayama, Japan: IPCC National Greenhouse Gas Inventories Programme, p590.

IPCC (2006) Chapter 4: Forest Landin *IPCC guidelines for national greenhouse gas inventories.* Japan: the National Greenhouse Gas Inventories Programme, p83.

Joshi, P. K., Roy, P. S., Singh, S., Agrawal, S., & Yadav, D. (2006). Vegetation cover mapping in India using multi-temporal IRS Wide Field Sensor (WiFS) data. *Remote Sensing of Environment*, *103*(2), 190-202. [CrossRef] [Google Scholar]

Kaushal, R., Kumar, A., Jayaraman, D., Mandal, D., Rao, I.V.R., Dogra, P., Alam, N.M., Gupta, A., Tomar, J.M.S., Singh, D.V., Mehta, H. and Mishra, P.K. (2018) ‘Research methodologies for field monitoring, analysis and evaluation of resource conservation aspects of bamboos’, International Bamboo and Rattan Organisation (INBAR), 9(4), p124.

Kigomo, B.N. (1988) Distribution, cultivation and research Status of Bamboo in East Africa. KEFRI, Ecol.ser Monograph

Krishna, G., Mishra, G., Kumar, R., & Pandey, S. (2015). Role of Bamboo forests in carbon

Kumar and Chandnashekar. (2014). Fuel properties and combustion characteristics of some promising bamboo species in India. Journal of Forestry Research, 25(2), 471–476.

Linderman M., Liu J., Qi J., An L., Ouyang Z., Yang J., Tan Y. Using artificial neural networks to map the spatial distribution of understory bamboo from remote sensing data. Int. J. Remote Sens. 2004;25: 1685–1700. doi: 10.1080/0143116031000159897l. [CrossRef] [Google Scholar

Lillesand, T., Kiefer, R.W. and Chipman, J. (2004) Remote Sensing and Image Interpretation. John Wiley & Sons, Hoboken.

Liu, Z., Mi, B., Jiang, Z., Fei, B., Cai, Z., & Lu, X. (2016). Improved bulk density of bamboo pellets as biomass for energy production. Renewable Energy, 86, 1–7.

Lobovikov, M., Lou, Y., Schoene, D., & Widenoja, R. (2009). The poor man's carbon sink: Bamboo in climate change and poverty alleviation. Non-Wood Forest Products Working Document Number, 8(FAO), 72pp.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H. and Wu. J. (2007) *World bamboo resources: a thematic study prepared in the framework of the global forest resources assessment 2005*. Rome: FAO, INBAR, p80.

Majundar, K., Choudhary, B. K., & Datta, B. K. (2016). Aboveground woody biomass, carbon stockspotential in selected tropical forest patches of Tripura, Northeast India. Open Journal of Ecology,6, 598–612.

Mertens, B., Hua, L., Belcher, B., Ruiz-Pérez, M., Maoyi, F., & Xiaosheng, Y. (2008). Spatial patterns and processes of bamboo expansion in Southern China. *Applied Geography*, *28*(1), 16-31. [Google Scholar

Mishra, G., Giri, K., Panday, S., Kumar, R., & Bisht, N. S. (2014). Bamboo: Potential resource for eco-restoration of degraded lands. Journal of Biology and Earth Sciences, 4(2), B130–B136.

Muchiri, M. N., &Muga, M. O. (2013). A preliminary yield model for natural Yushania alpina

Nath, A. J., Lal, R., & Das, O. K. (2015). Managing woody bamboos for carbon farming and carbon trading. Blob Ecology and Conservation, 3, 654–663.

Ohrnberger, D. 1999. The Bamboos of the World. Elsevier, Amsterdam

Ouma, Y. O., &Tateishi, R. (2006). Optimization of Second-Order Grey-Level Texture in High-Resolution Imagery for Statistical Estimation of Above-Ground Biomass. *Journal of Environmental Informatics*, *8*(2).

Pouteau, R., Meyer, J. Y., Taputuarai, R., & Stoll, B. (2012). Support vector machines to map rare and endangered native plants in Pacific islands forests. *Ecological Informatics*, *9*, 37-46.

Quiroga, R. A. R., Li, T., Lora, G., & Anderson, L. E. (2013). A measurement of the carbon sequestration potential of Guadua Angustifolia in the Carrasco National Park, Bolivia. Development Research working Paper Series, April, 2013. Institute for Advanced Development Studies, Bolivia.

Ricardo, A., Li, T., Lora, G. and Andersen, L.E. (2013) A measurement of the carbon sequestration potential of *Guadua angustifolia* in the Carrasco National Park, Bolivia, Development Research Working Paper Series, No. 04/2013.La Paz: Institute for Advanced Development Studies, p17.

Sasaki, T., Imanishi, J., Ioki, K., Morimoto, Y., &Kitada, K. (2012). Object-based classification of land cover and tree species by integrating airborne LiDAR and high spatial resolution imagery data. *Landscape and Ecological Engineering*, *8*(2), 157-171.

Schep S., Guzmán, A., van Beukering, P., de Moel, H., Eiselin, M., Ayesu, S., Birikorang, G. & Ansah, K. B. (2016). The Economics of the Atewa Forest Range, Ghana. Living water from the mountain Protecting Atewa water resources project report.

Sesnie, S. E., Gessler, P. E., Finegan, B., &Thessler, S. (2008). Integrating Landsat TM and SRTM-DEM derived variables with decision trees for habitat classification and change detection in complex neotropical environments. *Remote Sensing of Environment*, *112*(5), 2145-2159. [CrossRef] [Google Scholar]

Singnar, P., Das, M. C., Sileshi, G. W., Brahma, B., Nath, A. J., & Das, A. K. (2017). Allometric scaling, biomass accumulation and carbon stocks in different aged stands of thin-waled bamboos Schizosta chyumdullooa, Pseudostachyum polymorphum and Melocanna baccifera. Forest Ecology and Management, 395, 81–91.

Sohel, M. S. I., Alamgir, M., Akhter, S., & Rahman, M. (2015b). Carbon storage in a bamboo (Bambusa vulgaris) plantation in the degraded tropical forests: Implications for policy development. Land Use Policy, 49, 142–151.

Sohel, M.S.I., Alamgir, M., Akhter, S. and Rahman, M. (2015) Carbon storage in a bamboo (*Bambusa vulgaris*) plantation in the degraded tropical forests: implications for policy development',*Land Use Policy*, 49(2015),p142-151.

Source: Adams, C. (n.d.). Bamboo Architecture and Construction with Oscar Hidalgo (http://www.networkearth.org/naturalbuilding/bamboo.html). 16 October 2003.

Tang, Y., Jing, L., Li, H., Liu, Q., Yan, Q., & Li, X. (2016). Bamboo classification using worldview-2 imagery of giant panda habitat in a large shaded area in Wolong, Sichuan province, China. *Sensors*, *16*(11), 1957. [Google Scholar]

Tekpetey S. L. (2011). Bamboo Resources in Ghana: Diversity, Properties, Products and Opportunities.

United Nations Industrial Development Organization (2001) The European Flooring Market and Prospects for Bamboo Industrial Product from Ghana

Van der Lugt, P., ThangLong, T., & King, C. (2018). Carbon sequestration and carbon emissions reduction though bamboo forests and products. INBAR Working Paper. INBAR: Beijing, China.

Vyas, D., Krishnayya, N. S. R., Manjunath, K. R., Ray, S. S., & Panigrahy, S. (2011). Evaluation of classifiers for processing Hyperion (EO-1) data of tropical vegetation. *International Journal* of Applied Earth Observation and Geoinformation, 13(2), 228-235.

Wang, D. F., & Chen, T.-H. (2015). Bamboo resources and carbon storage in Taiwan. Ecology and Environmental Concerns, 10th World Bamboo Congress, Korea.

Wang, T., Skidmore, A. K., Toxopeus, A. G., & Liu, X. (2009). Understory bamboo discrimination using a winter image. *Photogrammetric Engineering & Remote Sensing*, *75*(1), 37-47.[CrossRef] [Google Scholar]

Xu, M., Ji, H., & Zhuang, S. (2018). Carbon stock of Moso bamboo (Phyllostachys pubescens) forests along a latitude gradient in the subtropical region of China. PloS one, 13(2).

Xu, X., Du, H., Zhou, G., Ge, H., Shi, Y., Zhou, Y., ...& Fan, W. (2011). Estimation of aboveground carbon stock of Moso bamboo (Phyllostachys heterocycla var. pubescens) forest with a Landsat Thematic Mapper image. International journal of remote sensing, 32(5), 1431-1448. [Google Scholar]

Yang, J., Wu, J., Jiang, P., Xu, Q., Zhao, P., & He, S. (2015). A study of Phytolith-occluded carbon stock in Monopodial Bamboo in China. Scientific Reports 5:13292,

Yen, T. M. (2015). Comparing aboveground structure and aboveground carbon storage of an age series of Moso bamboo forests subjected to different management strategies. Journal of Forest Research, 20, 1–8.

Yen, T. M. (2016). Culm height development, biomass accumulation and carbon and carbon storage in an initial growth stage for a fast-growing Moso bamboo (*Phllostachys pubescens*). Botanical Studies, 57, 10.

Yiping, L., Yanxia, L., Buckingham, K., Henley, G. and Guomo, Z. (2010) 'Bamboo and climate change',*Technical Report No. 32*. International Bamboo and Rattan Organisation (INBAR), p47.

Yuen, J.Q., Fung, T. and Ziegler, A.D. (2017) 'Carbon stocks in bamboo ecosystem worldwide: estimates and uncertainties',*Forest Ecology and Management*, 393,p113-138.

Zhang, H., Zhuang, S., Sun, B. O., Ji, H., Li, C., & Zhou, S. (2014). Estimation of biomass and carbon storage of Moso bamboo (Phyllostachys pubescens Mazel ex Houz.) in Southern China using a diameter-age bivariate distribution model. Forestry, 87, 674–682.

7. Appendices

Appendix 1: Bamboo Stock Assessment - Data Collection Sheet

A. Bamboo Stand Information

<table>
<tr><td>Region:</td><td>District:</td><td>Nearby Community:</td><td>Coordinate: Long: Lat:</td></tr>
<tr><td colspan="3" rowspan="2">Site / Stand ID:</td><td>Species of bamboo:</td></tr>
<tr><td>Altitude (m):</td></tr>
<tr><td colspan="3">Estimated area (Ha):</td><td>Average bamboo culm height (m):</td></tr>
<tr><td colspan="3" rowspan="3">Distances between clumps (m):
L1:
L2:
L3:
L4:
L5:</td><td>Recorded by:</td></tr>
<tr><td>Date:</td></tr>
<tr><td>Level of Disturbance(%):</td></tr>
</table>

B. Clump Measurement

Bamboo clump sample ID	A (year)	N_{culm}	Culm 1			Culm 2			Culm 3	Clump Girth (m)	Remarks
			D(cm)	H(m)	T(mm)	D(cm)	H(m)	T(mm)	D(cm)		
Clump Sample ID	1										
	2										
	3+										
Clump Sample ID	1										
	2										
	3+										

NB: D = Diameter, H = Height, T = Thickness, N = Number and A = Age

Appendix 2: Validation Data

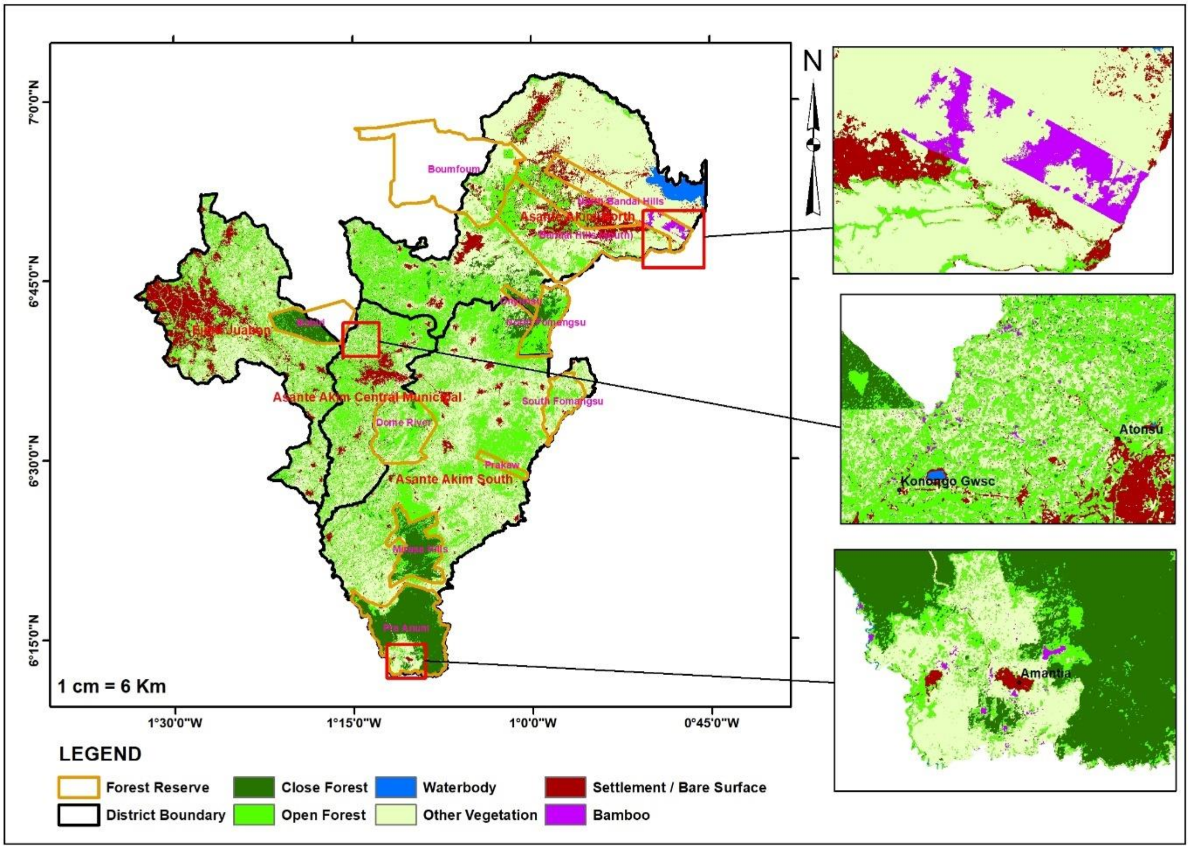
POINT ID	LONG	LAT	VALIDATION STATUS	
1	-1.98971	6.61885	Correctly Classified	
2	-2.20801	6.51146	Correctly Classified	
3	-2.18494	6.50894	Correctly Classified	
4	-2.14192	6.50736	Correctly Classified	
5	-1.95442	6.61550	Correctly Classified	
6	-2.03014	6.57181	Correctly Classified	
7	-1.84257	6.63361	Correctly Classified	
8	-1.88497	6.90072	Correctly Classified	
9	-1.92947	6.97803	Correctly Classified	
10	-1.89494	6.83063	Correctly Classified	
11	-1.89543	6.82974	Correctly Classified	
12	-1.84850	6.88096	Correctly Classified	
13	-2.00010	7.01332	Correctly Classified	
14	-1.71956	7.04849	Correctly Classified	
15	-1.76230	6.12067		Wrongly Classified
16	-1.83201	6.08793	Correctly Classified	
17	-1.86401	6.08988	Correctly Classified	
18	-1.86400	6.08950	Correctly Classified	
19	-1.57689	6.19500		Wrongly Classified
20	-1.50828	6.27658	Correctly Classified	
21	-1.54725	6.33406	Correctly Classified	
22	-1.48088	6.21841	Correctly Classified	
23	-1.24669	5.99250	Correctly Classified	
24	-1.44333	5.93445		Wrongly Classified
25	-1.28173	6.09767	Correctly Classified	
26	-1.24979	6.07240	Correctly Classified	
27	-1.21366	6.06628	Correctly Classified	

28	-1.37477	5.98045	Correctly Classified	
29	-1.08164	6.47189	Correctly Classified	
30	-1.06728	6.45631		Wrongly Classified
31	-1.03805	6.84383		Wrongly Classified
32	-1.14045	6.71511	Correctly Classified	
33	-1.04472	6.84383		Wrongly Classified
34	-1.14805	6.71354	Correctly Classified	
35	-1.12109	6.68624	Correctly Classified	
36	-1.06728	6.45631		Wrongly Classified
37	-1.05036	5.90682	Correctly Classified	
38	-1.09517	5.88094	Correctly Classified	
39	-1.09956	5.85894	Correctly Classified	
40	-1.08259	5.85917	Correctly Classified	
41	-1.08486	5.85608	Correctly Classified	
42	-1.04338	5.76611	Correctly Classified	
43	-0.46028	6.28531		Wrongly Classified
44	-0.47417	6.31272		Wrongly Classified
45	-0.45105	6.36886		Wrongly Classified
46	-0.44775	6.36253		Wrongly Classified
47	-0.45017	6.35684		Wrongly Classified
48	-0.44823	6.34219	Correctly Classified	
49	-0.59429	6.14123	Correctly Classified	
50	-1.12311	6.68900		Wrongly Classified
51	-0.99855	6.38056		Wrongly Classified
52	-0.99855	6.38056		Wrongly Classified
53	-1.00998	6.30518	Correctly Classified	
54	-0.90951	6.22255	Correctly Classified	
55	-0.87014	6.17539	Correctly Classified	
56	-0.84386	6.09353	Correctly Classified	
57	-2.49051	6.21645	Correctly Classified	

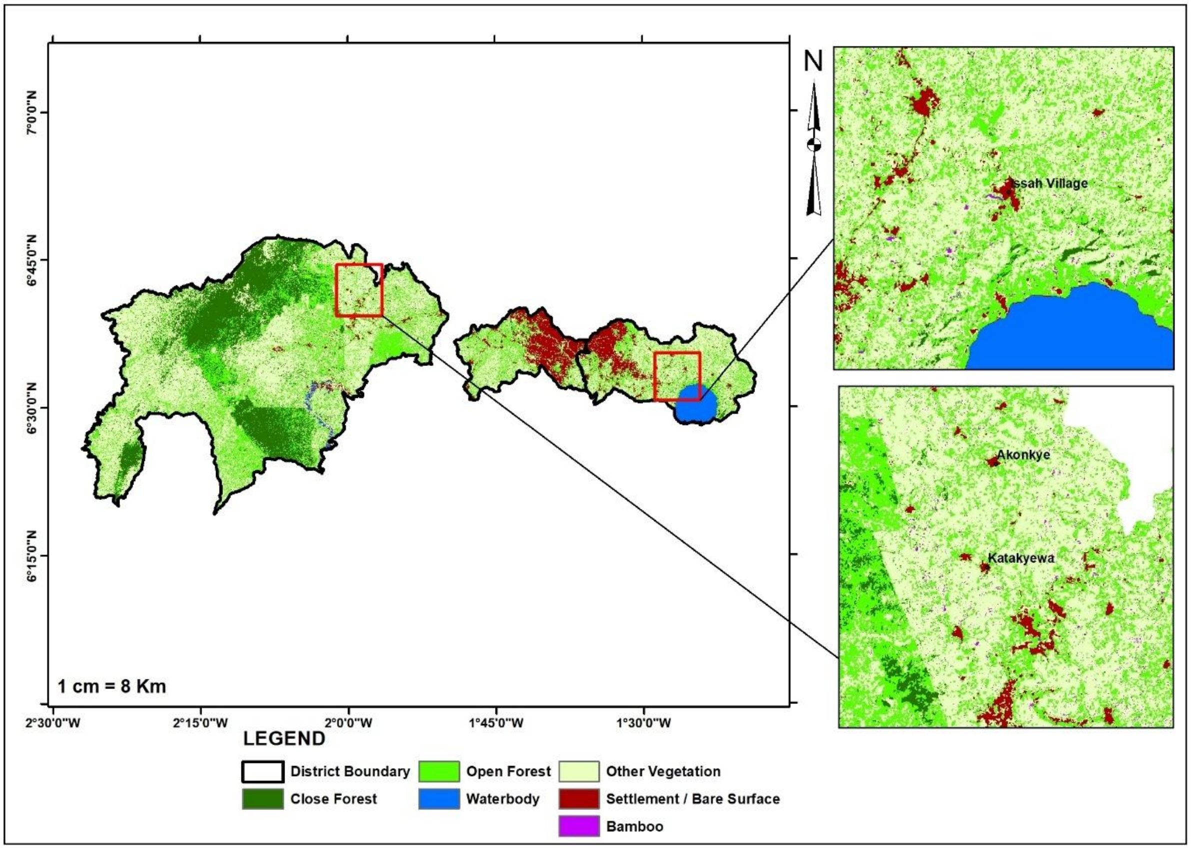
58	-2.53124	6.29525	Correctly Classified	
59	-2.56608	6.40998	Correctly Classified	
60	-2.63510	6.39113	Correctly Classified	
61	-2.63510	6.39113	Correctly Classified	
62	-2.47832	6.21846		Wrongly Classified
63	-2.47733	6.24597	Correctly Classified	
64	-2.49763	6.28001	Correctly Classified	
65	-2.84322	5.82254	Correctly Classified	
66	-2.84234	5.83090	Correctly Classified	
67	-2.79400	5.84794	Correctly Classified	
68	-2.79425	5.85108	Correctly Classified	
69	-2.80611	5.84912	Correctly Classified	
70	-2.89693	5.80185	Correctly Classified	
71	-2.77592	5.77468	Correctly Classified	
72	-1.91364	4.91044	Correctly Classified	
73	-1.70051	4.99168		Wrongly Classified
74	-1.92684	4.88651	Correctly Classified	
75	-1.70219	4.99058		Wrongly Classified
76	-1.64862	5.10489	Correctly Classified	
77	-1.86451	4.89430		Wrongly Classified
78	-1.33927	5.26215	Correctly Classified	
79	-1.34949	5.27663	Correctly Classified	
80	-1.49777	5.28743	Correctly Classified	
81	-1.51662	5.30661	Correctly Classified	
82	-1.38240	5.34580	Correctly Classified	
83	-1.11897	5.26761	Correctly Classified	
84	-1.16220	5.34597	Correctly Classified	
85	-1.11248	5.63094	Correctly Classified	
86	-1.11794	5.63736	Correctly Classified	
87	-1.62147	5.18994	Correctly Classified	

88	-1.43237	5.38652	Correctly Classified	
89	-1.25513	5.64412	Correctly Classified	
90	-1.25419	5.65856	Correctly Classified	
91	-1.34361	5.89759	Correctly Classified	
92	-1.33805	5.89911	Correctly Classified	
93	-1.83461	5.89267	Correctly Classified	
94	-1.83143	5.82888		Wrongly Classified
95	-1.81308	5.86358	Correctly Classified	
96	-1.75427	5.81903	Correctly Classified	
97	-1.69967	5.73793	Correctly Classified	
98	-1.86083	4.89312	Correctly Classified	
99	-1.85192	5.90987	Correctly Classified	
100	-1.83491	5.87689		Wrongly Classified
101	-1.83491	5.87689		Wrongly Classified
102	-2.50178	5.76336	Correctly Classified	
103	-2.47637	5.72502	Correctly Classified	
104	-2.48630	5.80831	Correctly Classified	
105	-2.40421	5.83438	Correctly Classified	
106	-2.40223	5.80858	Correctly Classified	
107	-2.39040	5.74376	Correctly Classified	
108	-2.38731	5.74342	Correctly Classified	
109	-1.85869	5.33183	Correctly Classified	
110	-1.74923	5.22032	Correctly Classified	
111	-1.78136	5.22375		Wrongly Classified

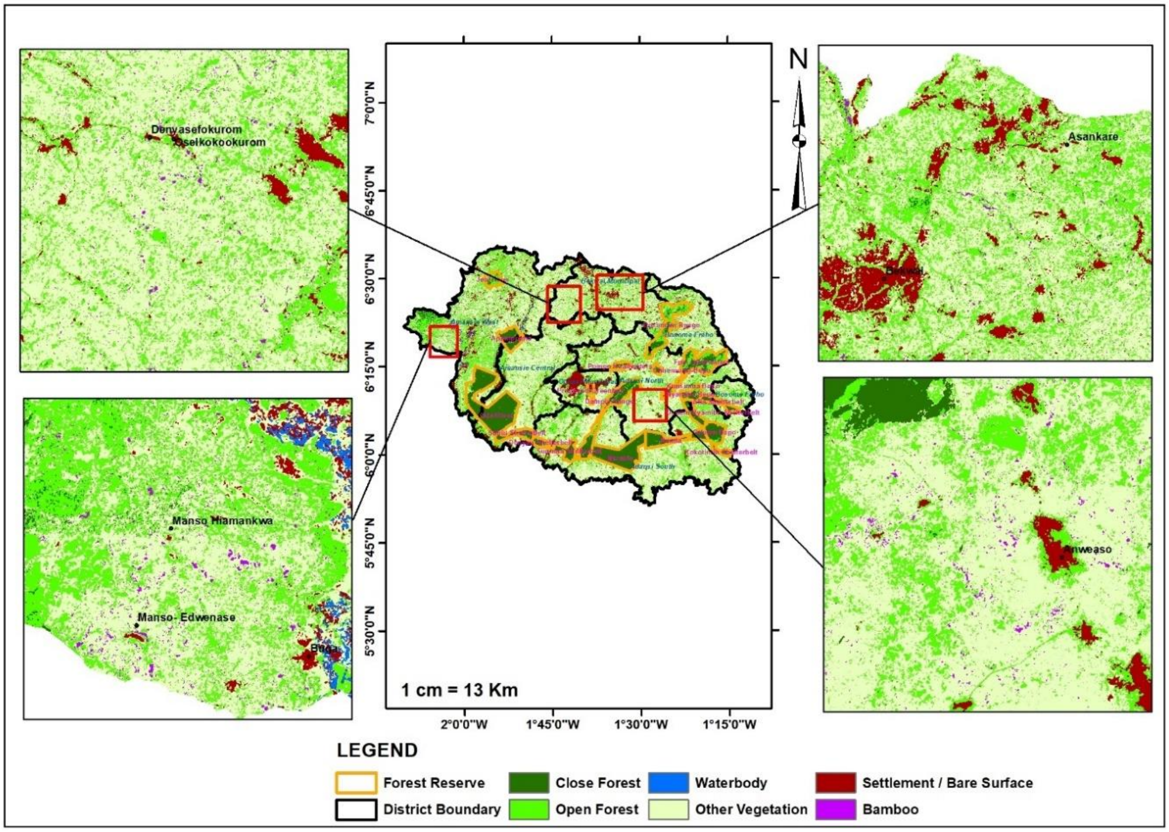
Appendix 3: Bamboo distribution Map in Juaso Forest District



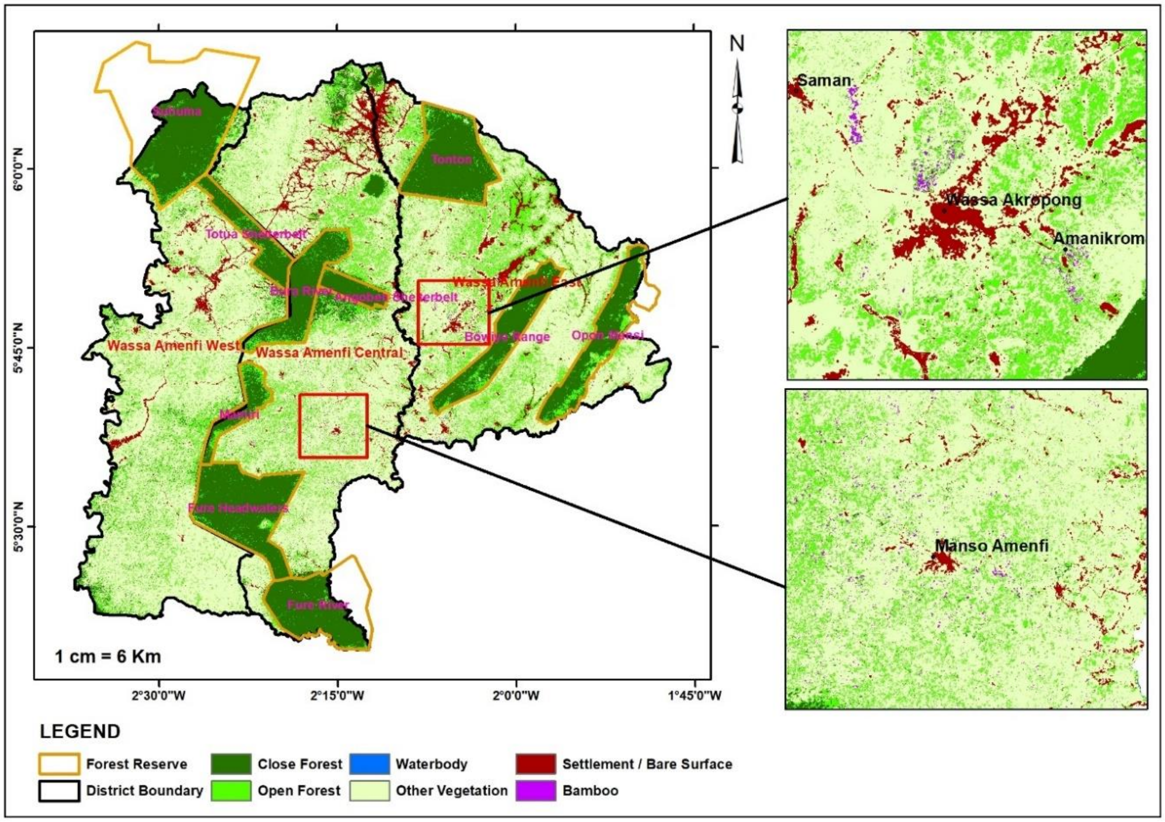
Appendix 4: Bamboo Distribution Map in Nkawie Forest District



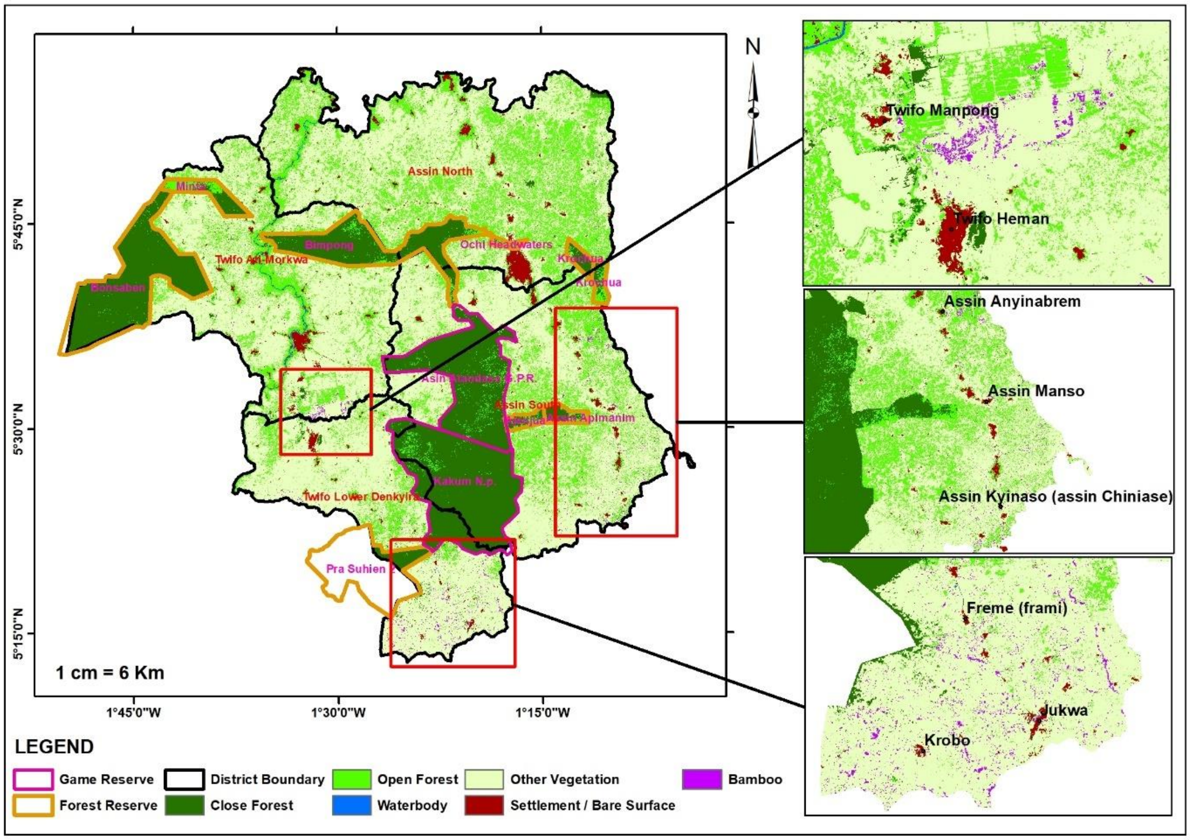
Appendix 5: Bamboo Distribution Map in Bekwai Forest District



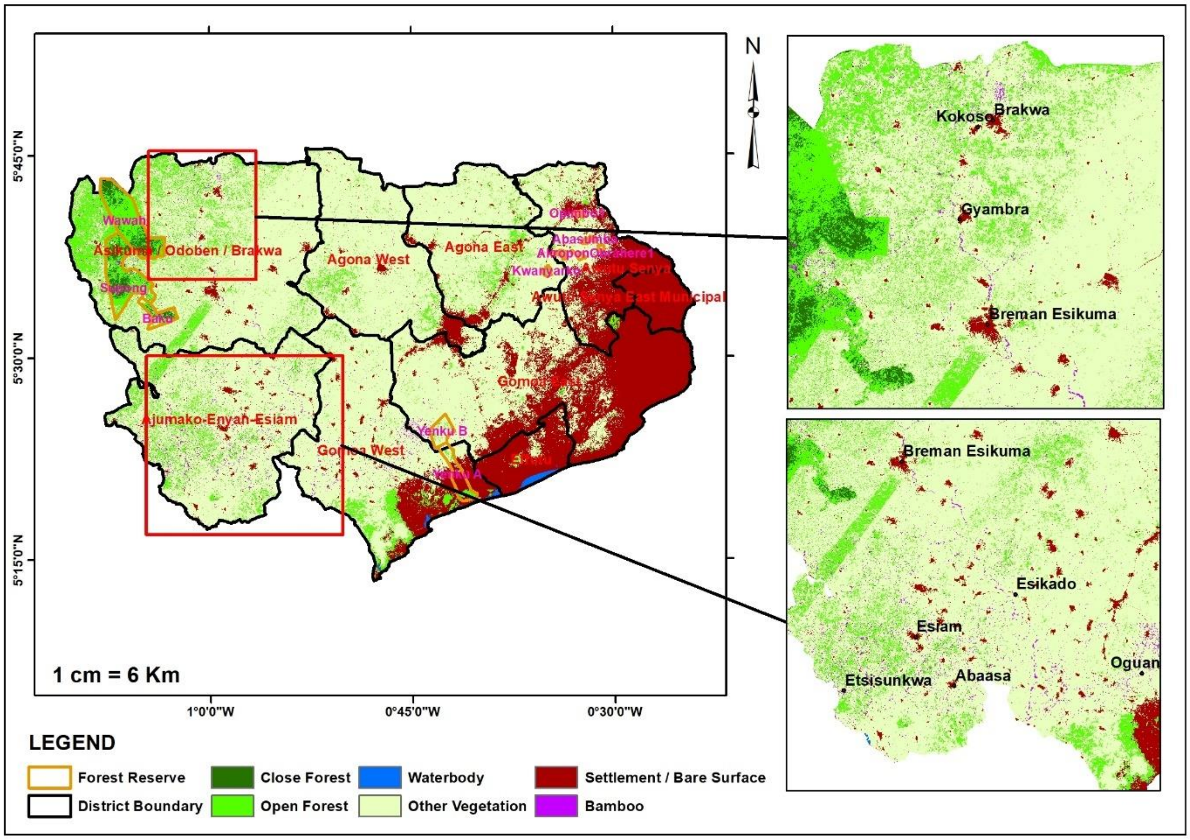
Appendix 6: Bamboo distribution map in Asangrakwa Forest District



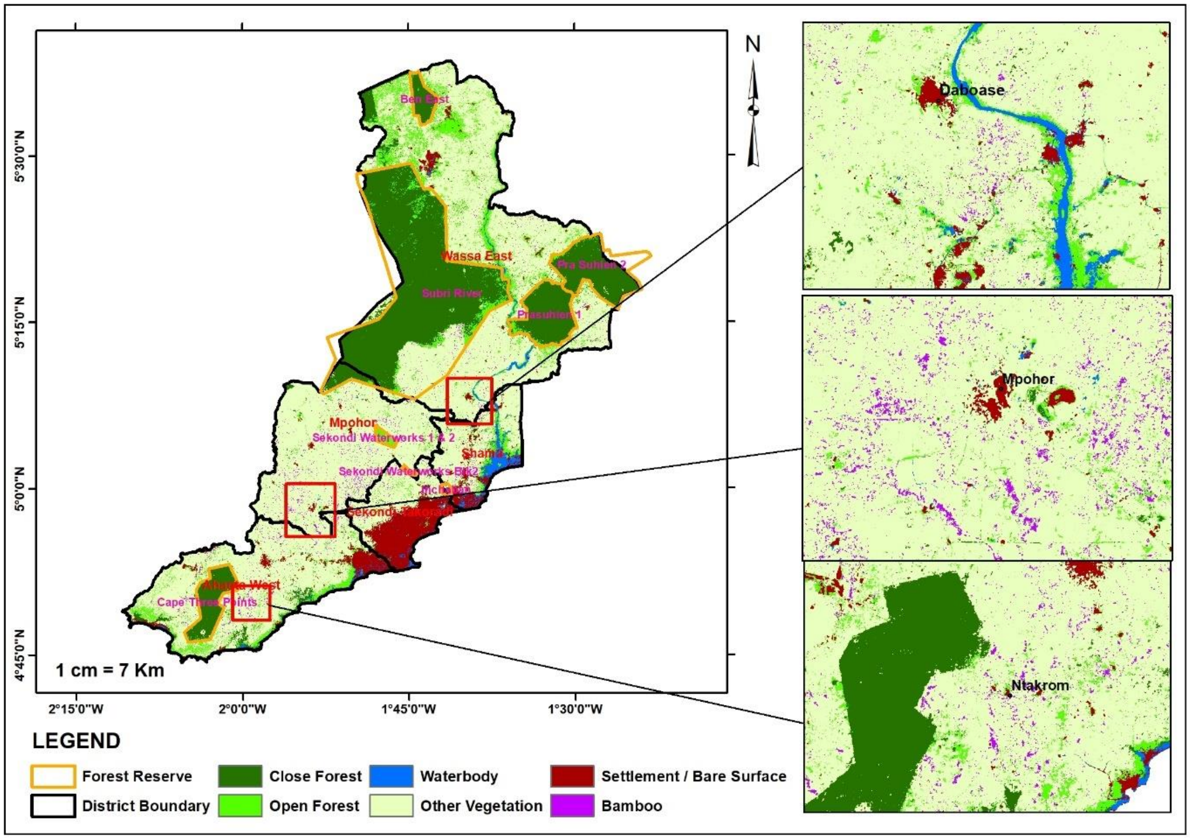
Appendix 7: Bamboo distribution map in Assin Fosu Forest District



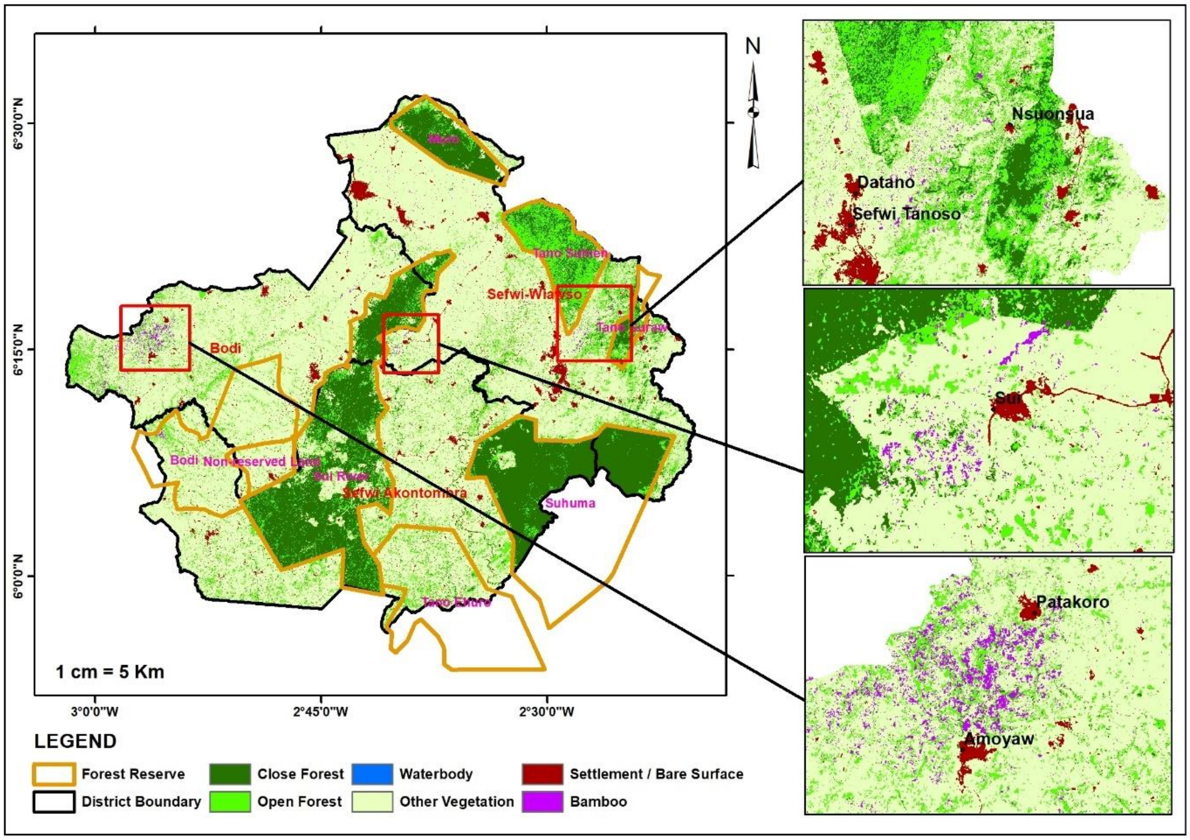
Appendix 8: Bamboo Distribution Map in Winneba Forest District



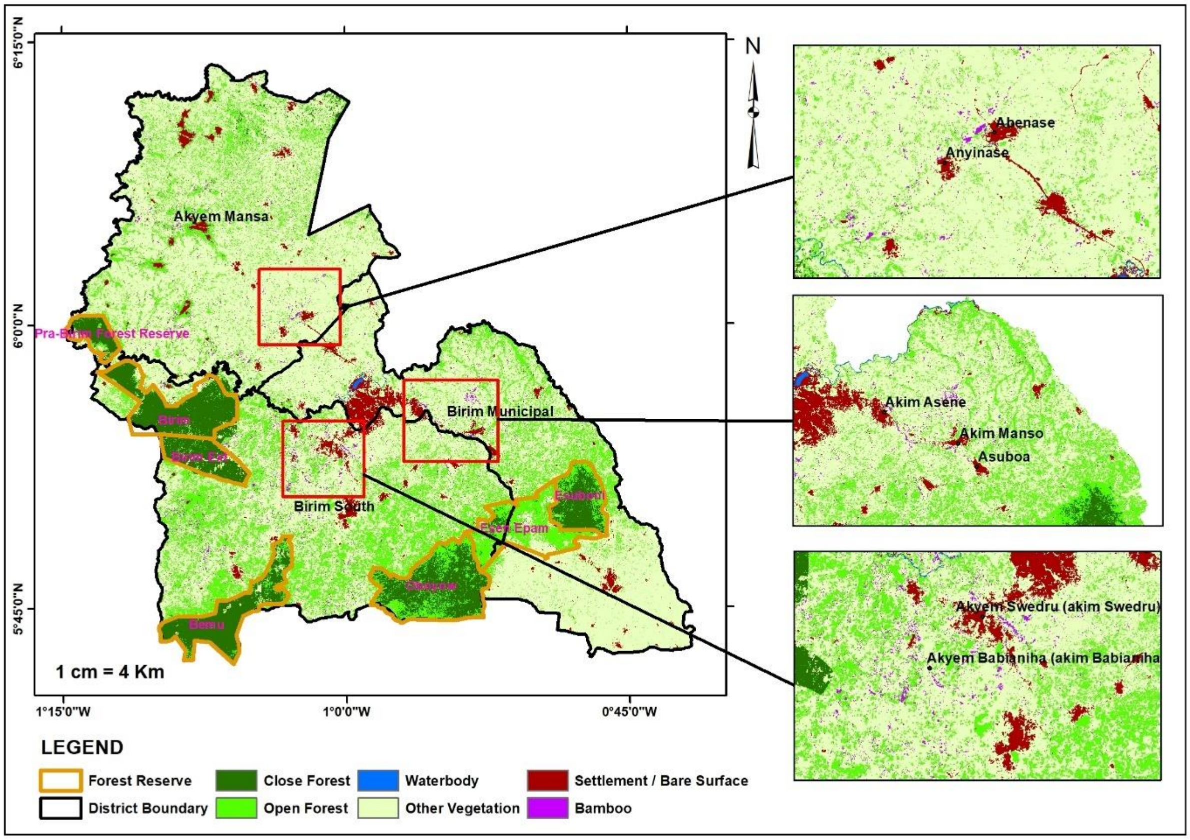
Appendix 9: Bamboo Distribution Map in Takoradi Forest District



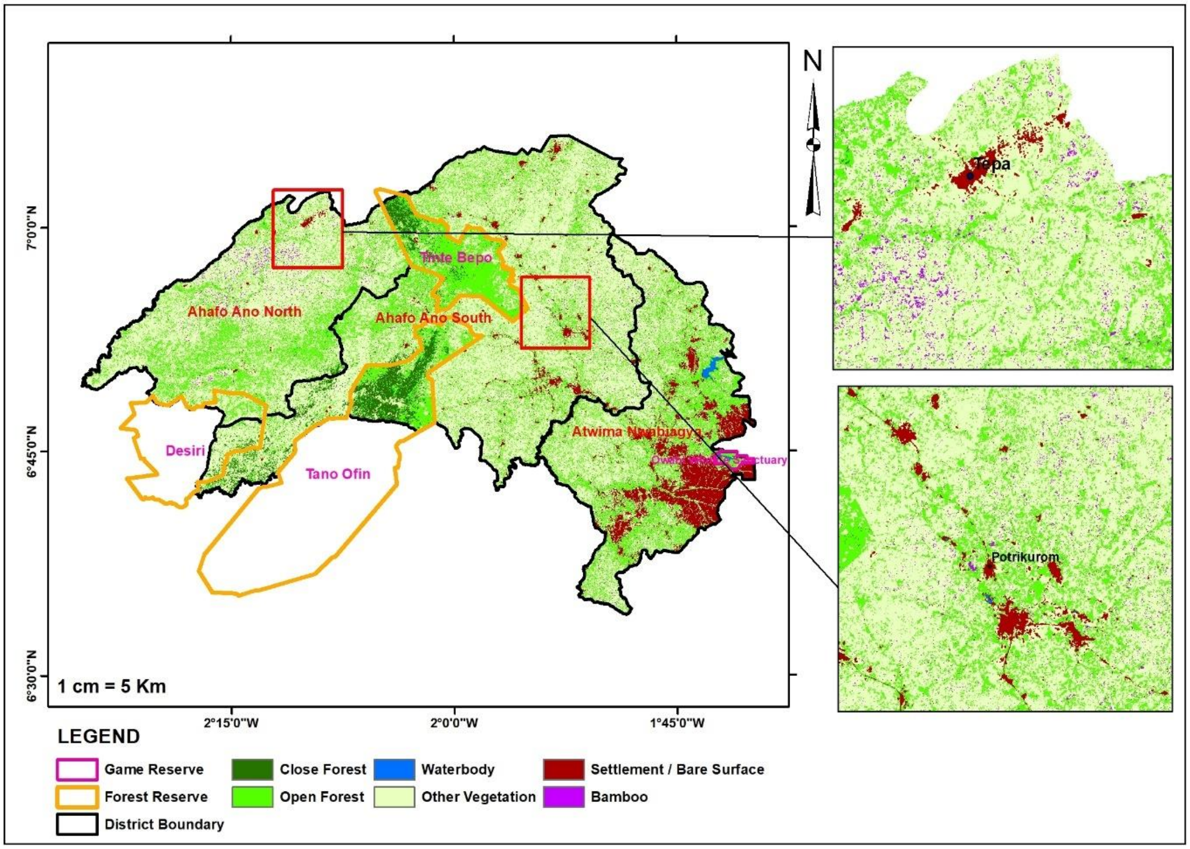
Appendix 10: Bamboo Distribution Map in Sefwi Wiawso Forest District



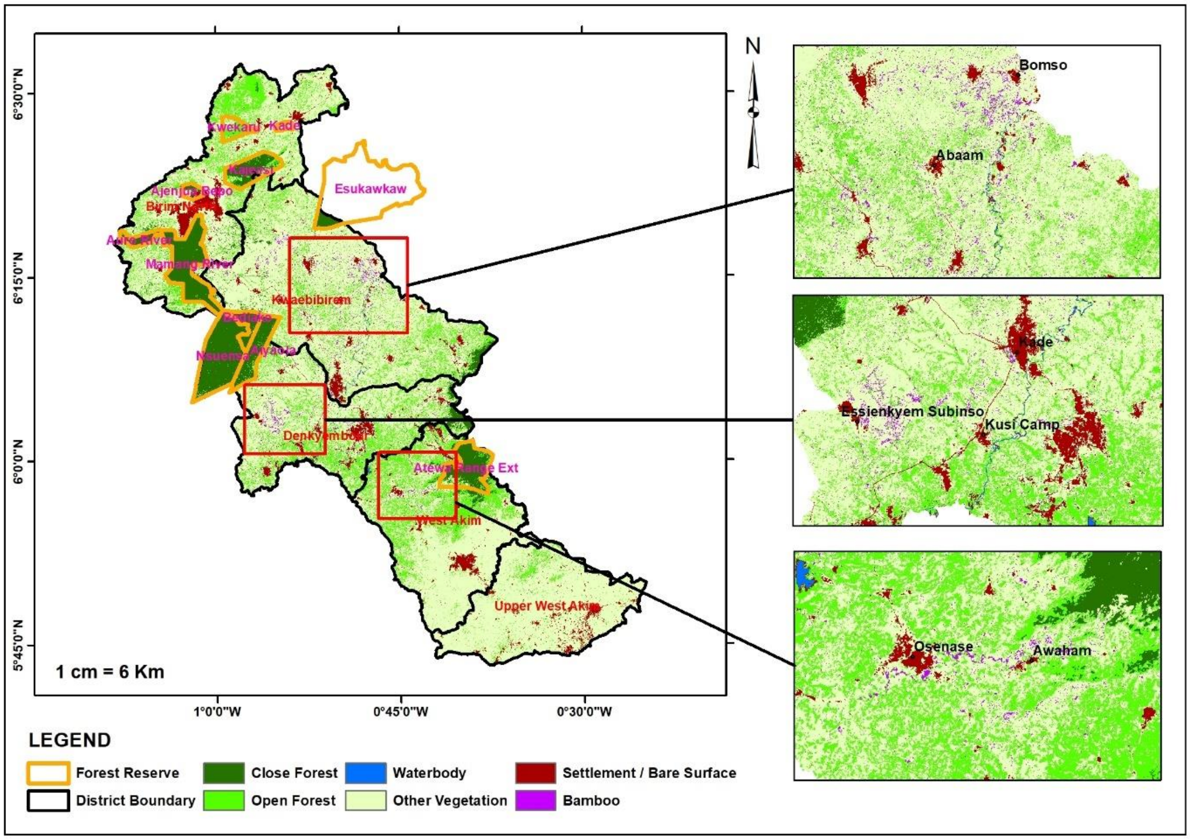
Appendix 11: Bamboo Distribution Map in Oda Forest District



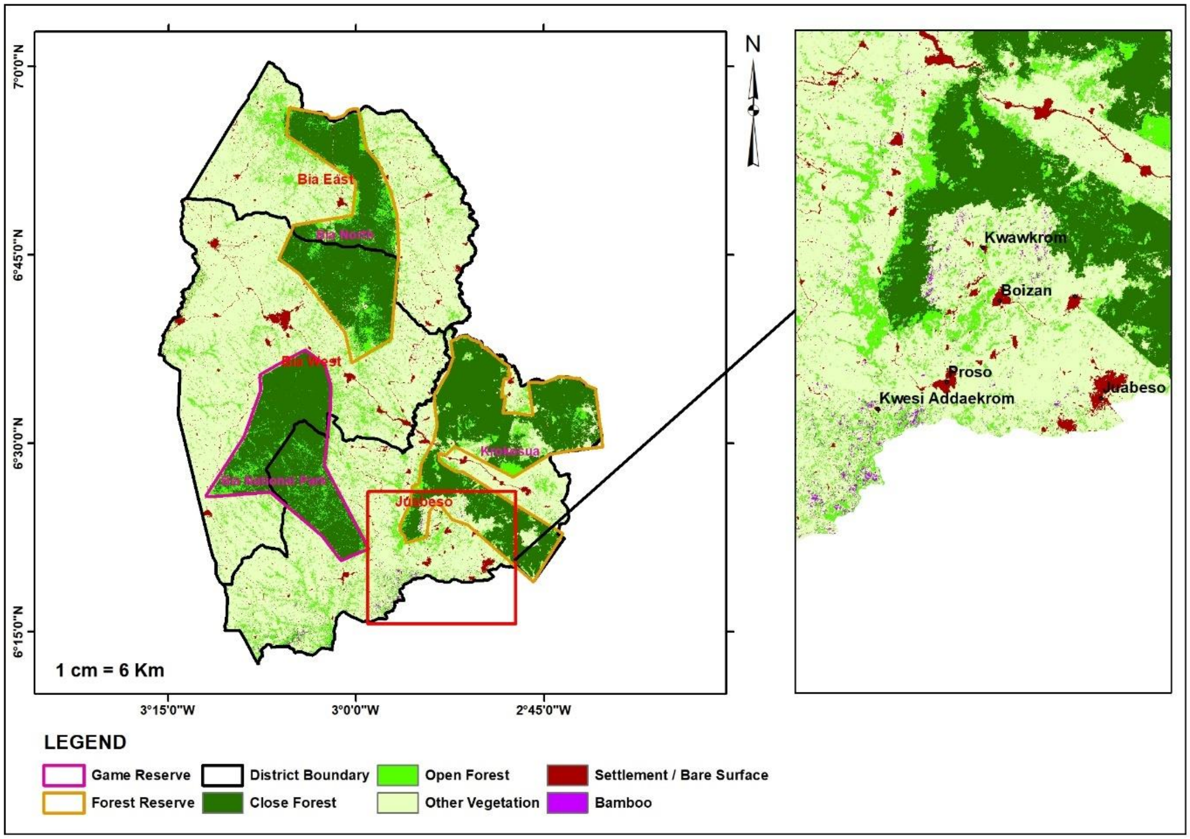
Appendix 12: Bamboo Distribution Map in Mankranso Forest District



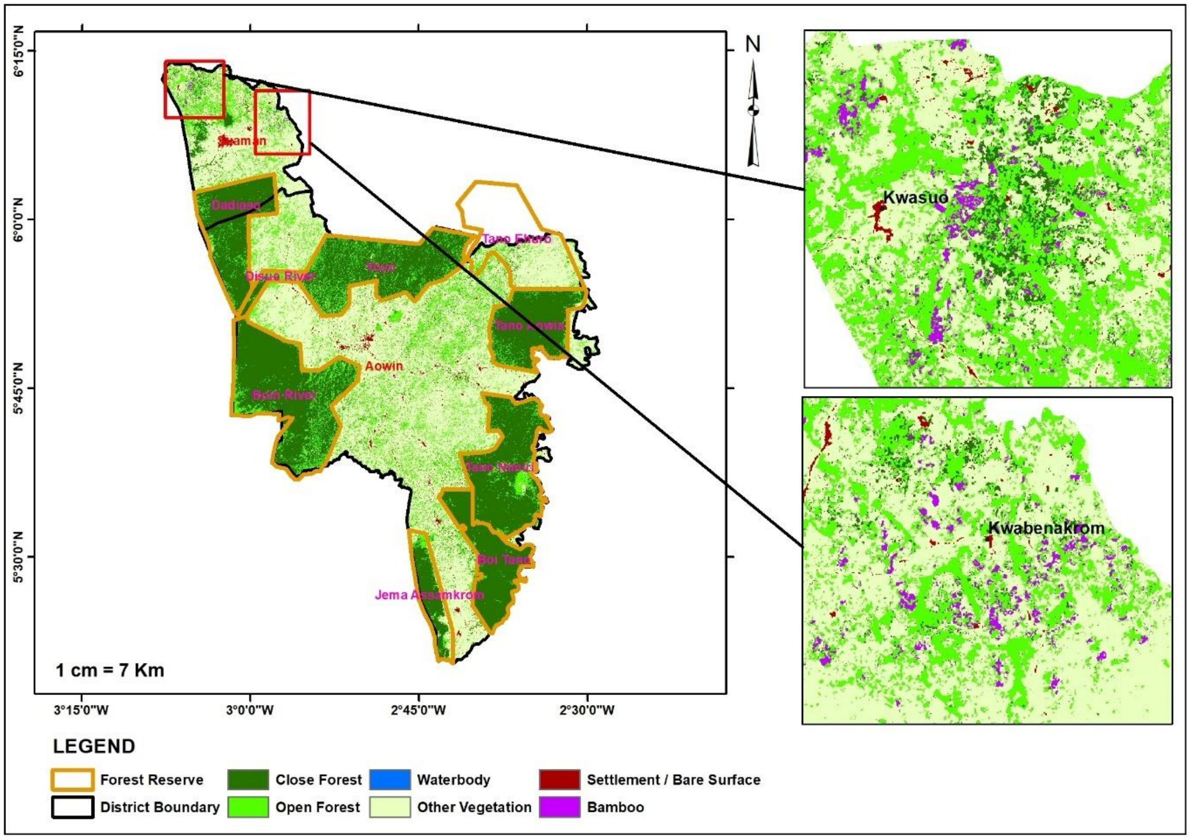
Appendix 13: Bamboo Distribution Map in Kade Forest District



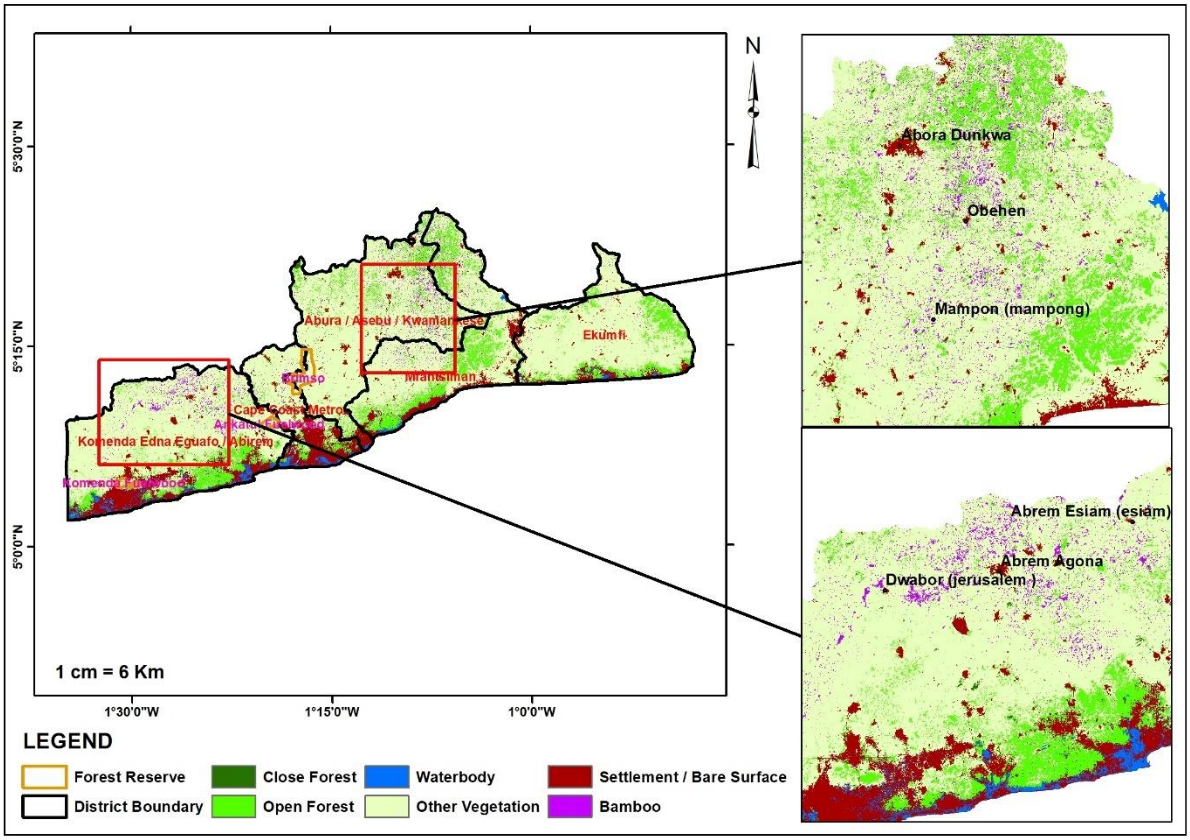
Appendix 14: Bamboo Distribution Map in Juabeso Forest District



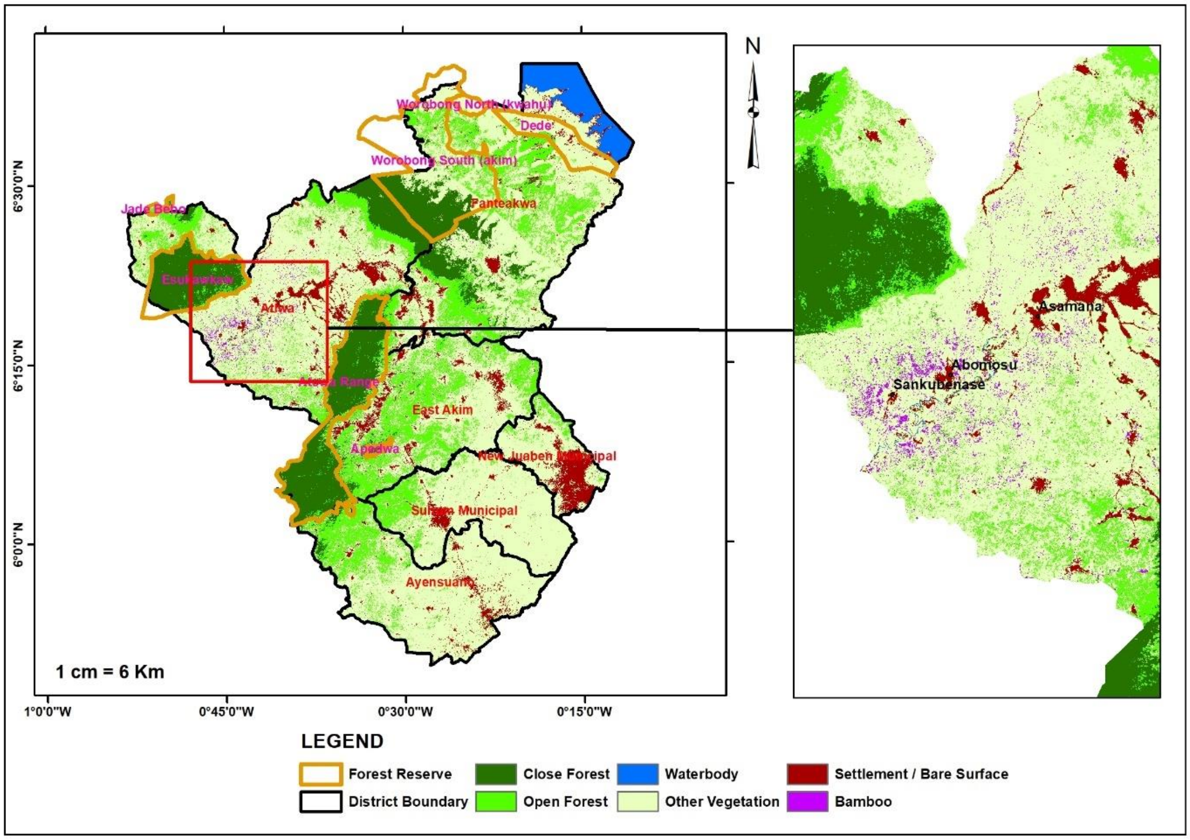
Appendix 15: Bamboo Distribution Map in Enchi Forest District



Appendix 16: Bamboo Distribution Map in Cape Coast Forest District



Appendix 17: Bamboo Distribution Map in Begoro Forest District



INTERNATIONAL BAMBOO
AND RATTAN ORGANISATION

www.inbar.int

@INBAROfficial