UNIVERSITY OF CAPE COAST

CARBON STOCK ASSESSMENT IN THE KAKUM AND AMANZULE ESTUARY MANGROVE FORESTS, GHANA

BY

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: …… Date: ……

Name: ……

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

Sustainable management of forests through enhancement of forest carbon stocks is a global effort aimed at creating incentives for developing countries to reduce emissions. Ghana's participation in carbon reduction initiatives such as REDD+ has brought about huge demand for data on carbon stocks. This pre-empted the need for carbon stock assessment in the Kakum and Amanzule mangrove forests. Above- and below-ground carbon pools in the two forests were assessed in order to evaluate the impact of environmental degradation on the ecosystems. Data on tree height and diameter, and soil were collected to estimate for carbon density. General allometric equations were used to estimate mangrove biomass and corresponding carbon density. One-way Analysis of Variance (ANOVA) with Tukey's *post hoc* test were conducted to test the effect of soil depth on soil carbon density, bulk density, salinity and pH at 95 % confidence level. Total carbon density in the Kakum forest was estimated as 465.9 MgC/ha and that in Amanzule at 5316.5 MgC/ha. The difference in carbon density could be attributed to the differences in tree stature in the two ecosystems. Whereas the Kakum forest comprised mainly of dwarf mangrove trees, the Amanzule forest has a mosaic of primary and secondary forest patches. The below-ground carbon density was higher than above-ground carbon density within the Kakum mangrove forest. The reverse was observed in the Amanzule forest. It is therefore recommended that forest carbon stock change evaluation be vigorously undertaken by establishing permanent plots since logging has a serious effect on the overall carbon stock density and ecosystem health of mangrove forests.

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DEDICATION

To Mr. Emmanuel. B. Adotey, my Father. Your relentless sacrifice saw me this far - I am overwhelmed.

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LIST OF ACRONYMS

ABG	above-ground
ANOVA	analysis of variance
BD	bulk density
BG	below-ground
CIFOR	Center for International Forestry Research
CO_2	carbon dioxide
CSLP	Coastal Sustainable Landscapes Project.
DBH	diameter at breast height
GHG	greenhouse gas
GtC	giga tonne of Carbon
Ha	hectare
IPCC	Intergovernmental Panel on Climate Change
MgC	mega gram of carbon
MRV	measurement, reporting and verification
REDD	reducing emissions from deforestation and forest degradation
REDD+	reducing emissions from deforestation and forest degradation, and enhancing forest carbon stocks in developing countries
SOC	soil organic carbon
TSP	temporal sampling plot
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USDA	United States Department of Agriculture

CHAPTER ONE

INTRODUCTION

Background of the study

The emergence of plants on earth has led to the conversion of existing carbon dioxide (CO_2) in the atmosphere and oceans into several inorganic and organic compounds on land and in the sea (Assefa, Mengistu, Getu & Zewdie, 2013). By far the greatest portion of carbon (39,000 GtC out of 48,000 GtC) is stored in the oceans, and fossil carbon which is the next largest stock accounts for only 6,000 GtC (Petrokofsky *et al*., 2012). Scharlemann, Tanner, Hiederer and Kapos (2014) reported that globally, approximately 2500 GtC is contained in terrestrial carbon pools (forests, trees and soils) whilst the atmosphere contains only 800 GtC. However, the natural exchange of carbon compounds between the atmosphere, oceans and terrestrial ecosystems is currently modified by human activities that release CO_2 from fossil fuel and through land use and land cover (LULCC) changes (Assefa *et al*., 2013). This has resulted in higher CO_2 concentration in the atmosphere with implicative greenhouse gas effects (Goetz *et al*., 2009; Murdiyarso *et al*., 2009; Köhl, Lister, Scott, Baldauf & Plugge, 2011; Hutchison, Manica, Swetnam, Balmford & Spalding, 2014).

These observations presented a challenge to international multilateral conventions and agreements, such as Convention on Biological Diversity (CBD), United Nations Convention to Combat Desertification (UNCCD), United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol to the UNFCCC, to identify and develop pragmatic, yet sustainable, measures to reduce anthropogenic emissions of GHGs, particularly

carbon dioxide (CO_2) (GOFC-GOLD, 2008). This is because, among the GHGs, CO_2 is the most abundant (Gevaña, Pulhin & Pampolina, 2008).

Proffered solutions to this challenge included tasking signatory countries to develop carbon measurement, reporting and verification (MRV) systems (GOFC-GOLD, 2009) pursuant to carbon accounting mechanisms. Inherent to this, the Ghana Forestry Commission has set out to establish transparent and verifiable methods, quantification of uncertainties and appropriate monitoring systems for carbon stocks in Ghana (Indufor, 2015). This follows adoption of REDD+ (Reducing emissions from deforestation and forest degradation, and enhancing forest carbon stocks) since 2008 (Forestry Commission, 2015).

According to Ribeiro *et al*. (2013) carbon stock assessment is an important step in carbon accounting and consideration of land use options and strategies to promote carbon sequestration. As such changes in carbon stock with the dynamics of land use changes may result in either carbon emission or sequestration. On this premise, forest ecosystems have been identified to play important roles in the climate change phenomena due to their ecological functions as both sources and sinks of atmospheric CO_2 (Gevaña *et al*., 2008; Forestry Commission, 2015). It has therefore become very necessary to estimate carbon stocks and changes in carbon stocks in various forest carbon pools in relation to carbon trading (Assefa *et al*., 2013).

Problem Statement

Mangroves have been identified to be among the most productive ecosystems in the world. These ecosystems have been reported to sequester the largest amount of carbon, estimated to be about 50 times more (Kathiresan,

2012) than other tropical forests. However, they can equally serve as huge sources of carbon emission, which potentially impedes initiatives to reduce anthropogenic emission of greenhouse gases (GHGs) (GOFC-GOLD, 2008). The foregoing does not augur well for climate change initiatives such as REDD and REDD+ (Agidee, 2011; Alemayehu *et al*., 2014; Forestry Commission, 2015) given that Ghana has been mandated to develop a greenhouse gas inventory for land-based emissions for UNFCCC reporting. The success of such initiatives are heavily dependent on sound information on carbon storage in various forests, and how much carbon may be released when these forests are converted for other land uses.

Interestingly, the current national mangrove cover assessment dates back to about seven years (see FAO, 2005; FAO, 2007). FAO (2007) identified five mangrove species (*Avicennia germinans, Laguncularia racemosa, Rhizophora harrisonii, Rhizophora racemosa* and *Conocarpus erectus*) and reported a total coverage of 13,729 hectares with an annual change of - 2.1 %. Meanwhile, there is increasing coastal urbanization and wetland encroachment with utilization of mangrove ecosystems for agriculture, aquaculture, firewood, salt production and residences (FAO, 2007; Mensah, 2013). These land-use and land-cover changes result in deforestation and degradation leading to large amounts of sequestered carbon being re-emitted into the atmosphere. The situation is further exacerbated by the fact that natural expansion of mangroves is rare (FAO, 2007) and coastal developments in Ghana are not properly regulated. While acknowledging the fact that local coastal communities are highly dependent on mangrove forests for commercial products such as food (Kathiresan, 2012), medicine (Alongi, 2009), fodder (Kathiresan, 2012)

firewood and timber for construction (Haruna, 2002; Gevaña *et al*., 2008), several of these activities and product extraction pose great threat to available mangrove ecosystems

In addition, there is a dearth in published studies, except preliminary assessment reports (e.g., Ajonina, 2011; Vallejo, 2013) on carbon stocks in Ghana's mangrove forests. These studies focused on the biomass, structure and ecology (see Haruna, 2002; Aheto *et al*., 2011; Mensah, 2013). Therefore, there is need to develop datasets to quantify carbon stocks by assessing mangrove carbon stocks of intact and modified forests. In the long term, filling these knowledge gaps will improve arguments for conservation of mangroves based on carbon stocks information.

Purpose of the Study

The aim of this research was to undertake carbon stock assessments in the Kakum and Amanzule mangrove forest systems of Ghana in order to evaluate the impact of environmental degradation on the ecosystems.

Research Objectives

The specific objectives were to:

i. estimate mangrove population parameters and total biomass of the mangrove trees comprising the above- and below-ground pools of both forests
ii. estimate the carbon density in the above- and below-ground pools of the ecosystems
iii. determine the soil particle size distribution in relation to carbon density in both locations

iv. assess the relationship between soil bulk density and particle size distribution
v. assess the implications of hydrographic factors (i.e. salinity and pH) on carbon density.

Significance of the Study

The findings of this study are expected to inform technical advisory services on mangrove conservation and fill in scientific gaps for policy making. The Forestry Commission, together with other relevant climate-related organisations and stakeholders, will find this study crucial to the development of the REDD+ program in Ghana as it contributes scientific information to the mangrove carbon stocks (blue carbon) database necessary to deepen ecological and policy discussion for mangrove forest management in Ghana.

Delimitations

The study was confined to the Central and Western regions of Ghana with focus on mangrove forests. A degraded mangrove forest at the Kakum River Estuary in the Central Region was compared against a non-degraded mangrove forest at Amanzule River Estuary in the Western Region.

Limitations

The major limitation in this study was the unavailability of site-specific wood density of the mangrove species. Mangrove wood densities could not be developed due to time and financial constraints. Thus, general species-specific wood densities were used with minimal consequences for biomass estimate errors.

Definition of Terms

Aboveground biomass (AGB): All woody stems, branches and leaves of living trees.

Allometric equation: Equations used for estimating tree weight from independent variables such as trunk diameter and height which are quantifiable in the field.

Belowground biomass (BG): It comprises living and dead roots, soil fauna and the microbial community.

Biomass: The mass of live or dead organic matter. It includes the total mass of living organisms in a given area or volume. The quantity of biomass is expressed as a dry weight.

Blue carbon: Carbon captured by oceans and coastal ecosystems and stored in the form of biomass and sediments from mangroves, salt marshes and sea grasses.

Bulk density: It refers to the dry weight per unit volume of undisturbed soil

Carbon: The term used for the C stored in terrestrial ecosystems, as living or dead plant biomass (aboveground and belowground) and in the soil.

Carbon pool: A system which has the capacity to accumulate or release carbon.

Carbon sequestration: The removal of carbon from the atmosphere and long-term storage in sinks, such as marine or terrestrial ecosystems.

Carbon sink: A carbon pool from which more carbon flows in than out

Carbon source: A carbon pool from which more carbon flows out than flows in

Carbon density/carbon stock: The mass of carbon contained in a carbon pool.

Climate change: A change in global or regional climate patterns due to increased levels of atmospheric carbon dioxide.

Soil organic matter (SOM): It comprises humus and other soil organic C pools in the mineral soil

Organisation of the Study

The work has been organized into six different chapters. The first chapter introduces the study, while bringing to light the purpose and objectives the study seeks to address.

Chapter two provides an in-depth review of earlier researches extracted from books, journals and other collected works relevant to the research topic with specific reference to the research objectives.

Chapter three outlines details of data collection procedure, organization and analysis of data obtained. It covers the varied techniques and tools used to collect and analyse data to obtain valid results.

Chapter four presents the research findings and analysis obtained through the methodology outlined in chapter three.

In chapter five, the results were adequately discussed taking cognizance of relevant literature reviewed in chapter two.

Finally, chapter six outlines a summary of findings, conclusions from the study and recommendations relevant for individuals and stakeholders of the research.

CHAPTER TWO

LITERATURE REVIEW

Introduction

According to Murdiyarso *et al*. (2009), the Center for International Forestry Research (CIFOR) and US Forest Services have developed a larger project in conjunction with United States Agency for International Development (USAID) with the overall goal of supporting the development of the international REDD+ mechanism in wetlands. The project aimed at producing maps for the tropics over four years. The project will adopt a regional approach, refining the methods at each stage and updating them with new developments in remote sensing technology. The project will also develop innovative statistical approaches to large-scale assessments of carbon stocks.

On a local scale, plans have been in place to establish local partnerships, and all field measurements in each target country will be carried out through local partners with supervision by CIFOR and the US Forest Service (USFS). This will contribute to building local capacity to undertake carbon assessments in wetland ecosystems (Murdiyarso *et al.,* 2009). The fulfilment of this goal was realized in Ghana by the implementation of the Coastal Sustainable Landscapes Project (CSLP) in the Western Region of Ghana as part of the broader Sustainable Landscape Initiative of the US Government.

It is important to note that in assessing eco-zones to be included in the National REDD+ strategy (Forestry Commission, 2015) and development of carbon MRV (Indufor, 2015) in Ghana, coastal forest systems such as mangrove ecosystems were not clearly defined in these guidelines. Meanwhile, principal drivers of deforestation and forest degradation have been identified as

agricultural expansion (50 %), wood harvesting (35 %), population and development pressures (10 %), and mining and mineral exploitation (5 %) (Forestry Commission, 2015). This places annual deforestation rate in Ghana at about 2 %, equivalent to 135,000 hectares per annum. Interestingly, mangrove systems are excluded from the gazetted forest reserves in the country despite facing threats of degradation arising from agriculture, population and coastal development.

Mangrove forests have been referenced in several studies (Gibbs, Brown, Niles & Foley, 2007; Kristensen, Bouillon, Dittmar & Marchand, 2008; Polidoro *et al*., 2010; Aheto, Aduomih and Obodai, 2011; Lovelock, Ruess & Feller, 2011; Pendleton *et al*., 2012; Kathiresan, 2012) to have huge potential to sequester vast amount of atmospheric CO_2 as a result of their high cost effectiveness, and associated environmental and social benefits.

Kauffman and Donato (2012) reported estimates of the worldwide extent of mangroves to range from 14 to 24 million hectares, sheltering tropical and sub-tropical coastlines between latitudes 30° N and 30° S (Hogarth, 2007). In Ghana, mangroves extend up to about 13,700 hectares (FAO, 2005). A report by UNEP (2007 as cited in Ajonina, Agardy, Lau, Agbogah & Gormey, 2014) indicated that mangroves in Ghana are limited to very narrow, non-continuous coastal areas around lagoons in the eastern and western part of the country. To the west, the most extensive stretches are between Cape Three Points and the border with la Côte d'Ivoire and on the fringes of the lower reaches of the Volta River delta in the eastern part of Ghana.

Despite representing only about 0.7 % of global tropical forests, mangroves are reported to collectively store as much as 22 million tonnes of

carbon annually (Giri *et al*., 2011). Mangrove forests are among the world's most productive ecosystems. They enrich coastal waters; yield commercial forest products; protect coastlines against storms and floods; and support coastal fisheries through the provision of habitats, breeding, spawning and nursery grounds for marine fisheries (Ellison, 2008; Kauffman & Donato, 2012; Kathiresan, 2012). However, several studies suggest that the least investigated, yet critically important, ecosystem service of mangroves is that of carbon storage. In view of this, some contemporary studies have focused on the ecological functions of mangrove ecosystems.

Jones *et al*. (2014) documented mangrove carbon pools to be among the highest of any forest type. The authors indicated that a large proportion of this pool is below-ground in organic-rich soils and are therefore highly susceptible to being released in significant volumes if disturbed by land-use, land cover changes or climate change. The foregoing factors contribute to deforestation and forest degradation accounting for up to 30 % of anthropogenic carbon emissions (Goetz *et al*., 2009). According to Kauffman and Donato (2012), carbon pools most vulnerable to changes in land-use and land-cover include above-ground biomass and below-ground pools up to 30 cm. This, however, poses an important issue of concern in Ghana and other developing countries. In Ghana, this is of grave concern because of the real and potential threats mangrove ecosystems are exposed to. These threats include increasing coastal urbanization, rapid changes in land-cover, and industrial pollution, all of which result in over- extraction of forest products, small- to industrial-scale conversion to agriculture and aquaculture, erosion, sedimentation and siltation from upstream intensive farming and terrestrial deforestation (Jones *et al*., 2014).

Against this background, mangrove ecosystems must be scientifically assessed for carbon stocks in order to estimate their carbon sequestration potential. Particularly in Ghana, such an assessment would contribute to the REDD+ strategy of the government of Ghana. This study will provide scientific data that will be useful for Ghana's evolving REDD+ programme.

Mangrove Ecology

Mangrove has been invariably defined throughout literature to mean individual trees (Hogarth, 2007; Gevaña *et al*., 2008) mangrove-related flora or entire ecosystems (Gevaña *et al*., 2008; Jones *et al.*, 2014). Mangroves generally refer to a group of halophytic trees and shrubs belonging to approximately 16 families, 20 genera and about 55 species (Hogarth, 2007). The term also refers to the complex of plant communities fringing sheltered tropical and sub-tropical coastlines between latitudes 30° N and 30° S (Hogarth, 2007) and the largest percentage of mangroves is found between 5° N and 5° S latitude (Giri *et al*., 2011). As an assortment of trees and shrubs, mangroves are thought to have adapted to the inhospitable coastal intertidal zone: the typical mangrove habitat is a muddy river estuary (Hogarth, 2007).

Of the mangrove species, there exist true mangroves as well as mangrove-associate species. In Ghana, a plethora of literature (e.g. Haruna, 2002; FAO, 2007; Aheto *et al*., 2011; Mensah, 2013; Vallejo, 2013) have documented the existence of a total of seven mangrove species. These include *Rhizophora mangle, Rhizophora harrisonii, Rhizophora racemosa, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus,* and *Acrostichum aureum.* These are true mangrove species with the exception of *Acrostichum aureum* (Kathiresan, 2012) and *Conocarpus erectus* (Haruna, 2002) which are

mangrove-associate species. Interestingly, in the FAO (2007) report on the types of mangrove species in Ghana, *Rhizophora mangle* was excluded although previous works have documented its existence. Since one objective of this study was to identify the mangrove species in the study areas attempts have been made to reconcile this anomaly.

Mangroves have special adaptations which allow them to survive variable flooding and salinity stress conditions imposed by the coastal environment (Kuenzer, Bluemel, Gebhardt, Quoc & Dech, 2011). For this reason, Khan (2011) opined that mangroves are defined by their ecology rather than their taxonomy. Mangroves have been reported to colonize protected areas along the coast such as deltas, estuaries, lagoons and islands. They, therefore, exhibit a high degree of ecological stability with regard to resilience (Kuenzer *et al*., 2011).

The major factors influencing mangrove distribution include climate, salinity, tidal fluctuations, sedimentation, wave energy (McKee, 1996) and soil characteristics (Hogarth, 2007). Khan (2011) however lumped all these factors into topography and hydrology as being key factors influencing mangrove ecotypes. Accordingly, Krauss *et al*. (2008) identified four of the most common mangrove ecotypes to include fringe, riverine, basin and scrub. A "fringe" forest borders protected shorelines, canals and lagoons and is inundated by daily tides. A "riverine" forest, on the other hand, flanks the estuarine reaches of a river channel and is periodically inundated by nutrient-rich fresh and brackish water.

The "basin" forest is usually found in the interior areas of a mangrove ecosystem characterized by stagnant or slow flowing water. "Scrub" forests

grow in areas where hydrology is restricted, resulting in conditions of high evaporation, high salinity, low temperature or low nutrient status. It is instructive to note that each of these mangrove ecotypes is characterized by different patterns of forest structure, productivity and biogeochemistry (Khan, 2011). Again, nutrient availability is an important factor influencing mangrove community structure. Conversely, Lovelock *et al*. (2005 as cited in Krauss *et al*., 2008) observed that many mangrove environments have extremely low nutrient availability due to infertility of upland soils in tropical regions and limited terrigenous input.

Land-use Changes and Mangrove Carbon Stocks

Mangroves have over the years experienced various degrees of threat (Diop *et al*., 2011; Ray *et al*., 2011). Changes in land-use are defined by Houghton (2003) to broadly include the clearing of lands for cultivation and pastures, the abandonment of these agricultural lands, the harvesting of wood, reforestation, afforestation and shifting cultivation. According to IPCC, (2007 as cited in Zhang, Xie, Zhao & YaJun, 2012) land-use change, one of the dominant components of global change, is estimated to be the second largest source of human-induced greenhouse gas emissions after fossil fuel combustion. Zhang *et al*. (2012) suggested that changes in soil organic carbon (SOC) upon land-use change may occur due to changes in the rates of accumulation, turnover and decomposition of soil organic carbon.

In the case of mangrove forests, Hutchison *et al*. (2014) noted that about one-third of total mangrove cover, over the last 50 years, has been lost primarily through conversion for aquaculture or agriculture. Given the rapid loss rates of mangrove ecosystems, in concert with high carbon values, mangroves have been

reported to contribute about 10 % of total global carbon emissions from deforestation (Kathiresan, 2012; Donato *et al*. 2011, cited in Hutchison *et al*., 2014). Conversely, Guo and Gifford (2002 cited in Söderström *et al*., 2014) reviewed data from 74 publications and found that soil carbon stocks increase after land-use changes from native forest to pasture (+8 %), cropland to pasture (+19 %), cropland to plantation forest (+18 %), and cropland to secondary forest (+53 %). However, data reviewed did not include those from mangrove environments. It is important to acknowledge that an increase in the soil carbon stock does not imply a decrease in the atmospheric carbon stock by the same amount. This is because techniques employed to achieve increased stocks of SOC may be using non-renewable energy which has the tendency to cause changes in the atmospheric carbon stock (Söderström *et al*., 2014). Thus, improved understanding of land-use impacts on the terrestrial carbon balance is a necessary part of global efforts to mitigate climate change (Zhang *et al*., 2012).

Carbon sequestration

According to FAO (2000), carbon exists in atmospheric gases, in dissolved ions of the hydrosphere, and in solids as a major component of organic matter and sedimentary rocks. However the major movement of carbon results from photosynthesis and respiration, with further exchange between the biosphere, atmosphere and hydrosphere. FAO (2000), in a working report, defined carbon sequestration as "the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere". This definition had a double intent: (a) to keep carbon emissions produced by human activities from reaching the atmosphere by capturing and diverting them to secure storage(s),

and (b) to remove carbon from the atmosphere by various means and store it. The context of this definition however failed to indicate what the storage(s) or sinks of carbon were.

Arguably, some works (e.g. Intergovernmental Panel on Climate Change [IPCC], 2005) believed the definition should be restrictive, in that it connotes "carbon retained for long periods within non-fuel products manufactured from fuels". The rationale borders on the fact that not all fuel supplied to an economy is burnt for heat energy. Part of this energy is used as raw material for the manufacture of products such as plastics or in a non-energy use (e.g. bitumen for road construction) which are all devoid of emission. This is however debatable.

Carbon sequestration occurs in several sites among which are biomass, forests, wetlands, and geologic formations and soils. Notable carbon sources and sinks within mangrove ecosystems include biomass, wetlands and soils. These comprise what is known as carbon pools (Assefa *et al*., 2013). According to Nellemann *et al*. (2009) mangroves, salt marshes and seagrasses constitute the ocean's vegetated habitats which in turn form the earth's blue carbon sinks accounting for more than 50 % of all carbon storage in ocean sediments.

Consequently, Jones *et al*. (2014) have reported higher stature closed-canopy mangroves (in Madagascar) to have high above-ground and SOC and as such sequester significantly larger amounts of atmospheric carbon relative to more open stands. In a similar study in the Phillipines, Camacho *et al*. (2011) observed that cultivated plantations produce greater amount of biomass and carbon stocks compared to natural stands; an observation which is attributable to high density planting and the practice of silvicultural management to improve

timber stock. Also, Gevaña *et al*. (2008) opined that some mangrove species sequester carbon better than others. This may be due to the varied capacities of mangrove species to trap sediment (Kathiresan, 2003) along with organic matter; and the probability that a greater portion of the carbon may be located in below-ground biomass or pools (Kauffman & Donato, 2012).

According to Schrumpf, Schulze, Kaiser and Schumacher (2011), soils contain more organic carbon relative to plant biomass and the atmosphere; thus they serve as the most important long-term organic carbon reservoir in terrestrial ecosystems. This storage is however heavily affected by changes in vegetation and plant growth, removal of biomass by harvest, and mechanical soil disturbances such as ploughing. To support this, Donato *et al*. (2011) pointed out that the quantity of carbon stored is primarily determined by size of stand, canopy height and stature, and soil depth. Hogarth (2007) further argued that carbon dioxide uptake by mangroves is reduced with high soil salinity.

Inherent to this understanding, Krauss and Ball (2013) noted that "…mangroves occurring within the upper intertidal influences of rivers often flourish in seemingly fresh water conditions". Nonetheless, in the interest of coastal urbanization, ecosystems and soils sensitive to such changes are heavily impacted by activities such as farming, creation of salt pans and aquaculture ponds and pollution.

Mangrove carbon flux

According to Houghton (2003) the most important factor influencing estimates of the current flux of carbon, globally, is the rate of deforestation in the tropics. Studies have estimated soil carbon emission to the atmosphere to be about 0.8 PgC yr^{-1} to 1.2 $PgCyr^{-1}$ (Söderström *et al*., 2014) while emissions

from mangrove deforestation alone was about 0.02 PgC yr^{-1} to 0.12 PgC yr^{-1} (Kathiresan, 2012). Several literature (e.g. Houghton, 2003; GOFC-GOLD, 2008; Divya *et al*., 2011; Söderström *et al*., 2014) have exhaustively documented activity data (e.g. forest degradation and deforestation) as the cause of organic carbon instability or flux.

On the contrary, studies have shown that mangrove environments are sites of intense carbon processing with a potentially high impact to the global carbon budget (Lacerda, Ittekkot & Patchineelam, 1995; Kristensen *et al*., 2008) given their rate of productivity. While acknowledging the role of mangrove productivity, which falls outside the scope of this study, a rudimentary review of mangrove organic matter is necessary to understand the dynamics of organic carbon in these systems.

Given that carbon is a derivative of organic matter, the fate of organic matter in mangrove ecosystems is usually three-fold as noted by Kristensen *et al*. (2008). First, the organic matter is quickly exported by tidal action to adjacent coastal waters, the reason for increased productivity in these ecosystems. On the other hand, organic matter which is not exported, enters in the sediment where it is consumed, degraded and chemically modified. A third and important pathway is where the organic matter is permanently buried within mangrove sediment or adjacent ecosystems. It must be stressed however that while some mangrove forests largely retain detritus (organic matter) within their sediments others lose a large fraction of it to adjacent coastal waters (Kristensen, 2007) through tidal action and outwelling. To corroborate this, Nellemann *et al*. (2009) highlighted the significant role oceans play in the global carbon cycle, in that about 93% of the earth's CO_2 is stored and cycled through the oceans.

Meanwhile, few works (e.g. Alongi, 1996; Kristensen *et al*., 2008) have highlighted the role of mangrove fauna [e.g. sesarmid crabs (Grapsidae) or the fiddler crab (ocypodidae)] and biogeochemical processes such as root respiration (Lovelock, Ruess & Feller, 2006) and sediment-water/air interactions (Kristensen, 2007) in mangrove carbon flux. Houghton's argument was given an alternative view by Kristensen *et al*. (2008) in that, recent measurements have shown that air-exposed pneumatophores and open crab burrows increase CO_2 emissions to the atmosphere considerably by efficient translocation of CO_2 gas from deeper sediments. Camilleri and Ribi (1986; Twilley *et al*., 1997 as reviewed in Kristensen *et al*., 2008) stressed that mangrove litter (source of organic carbon) removed by crabs was estimated to be about 30 % of total litter biomass. This provides an apparent organic carbon flux pathway; although this may be variable in different mangrove ecosystems. The authors further indicated that newly-fallen mangrove litter loses 20–40 % of the organic carbon by leaching when submerged in seawater for 10–14 days.

Inherent to this understanding, Kristensen *et al*. (2008) criticized the accuracy of global carbon budget basing their arguments on the fact that available global estimates of carbon accumulation are mainly calculated by difference using litter fall, export and consumption rates while ignoring the fact that net primary productivity is likely to be three to four-fold higher than the litter fall rates, leading to a significant underestimation of carbon burial rates. The authors further argued that significant fraction of the net carbon fixation through primary production is indeed exported to coastal waters as dissolved organic carbon (DOC).

Works by Nellemann *et al*. (2009) and Kathiresan (2012) emphasized that these exports are more than one order of magnitude higher in proportion to their net-primary production than any major river. Kristensen (2007) highlighted that mangrove waterways are often CO_2-supersaturated with respect to atmospheric equilibrium, hence providing a carbon loss to the atmosphere. Kristensen suggested that permanently water-covered creeks, which often account for more than 20 % of mangrove areas, be included in estimates of mangrove CO_2 emission.

In view of the foregoing, it is apparent that sediment carbon content of mangrove sites may be underestimated as a result of several pathways of carbon instability. Thus large data sets on sediment carbon content were necessary to confidently confirm or improve the global carbon estimates.

Carbon Stock Estimation

The biomass of mangrove forests varies with age, dominant species, and locality (Komiyama, Ongb & Poungparn, 2008). According to Tamooh *et al*. (2008) forest biomass is an indicator of atmospheric and soil pollution input and forest health. Therefore, Komiyama *et al*. (2008) further observed that the above-ground biomass in primary mangrove forests tends to be relatively low near the sea and increases inland. Similarly, Tam *et al*. (1995 cited in Soares & Schaeffer-Novelli, 2005) highlighted the tendency of mangrove biomass to increase towards low latitudes although Fatoyinbo, Simard, Washington-Allen and Shugart (2008) in their work in Mozambique did not find any relationship between latitude and biomass. In view of this, forest ecologists have, over the years, developed various methods to estimate the biomass of forests.

It is noteworthy that no existing method can yet directly measure forest carbon stocks across landscapes (Divya *et al*., 2011). The authors pointed out that the most direct way to quantify above-ground carbon stock is to harvest all trees in a known area, dry and weigh the biomass. Komiyama *et al*. (2008) therefore reviewed three main methods developed for estimating forest biomass: the harvest method, the mean-tree method, and the allometric method. The harvest method cannot be easily used in mature forests because it lacks reproducibility since all trees in a study site must be destructively harvested. Gibbs *et al*. (2007) emphasized that this technique is time-consuming, expensive and impractical for country-level analysis. The mean-tree method, on the other hand, can only be utilized in forests with a homogeneous tree size distribution (Fatoyinbo, 2010), such as plantations. This is however impossible in the case of mangrove ecosystems.

Divya *et al*. (2011) further suggested that an alternative method was to develop tools and models that can be utilized to extrapolate data points measured in the field or using remote-sensing instruments. Thus the allometric method is often used to estimate the whole or partial weight of a tree from measurable tree dimensions, including trunk diameter and height (Komiyama *et al*., 2008). This is the reason for which most projects are based on project-level or site-specific approaches. In the interest of conservation and reproducibility of methods, the allometric method of biomass estimation is preferred.

Allometric models

Komiyama *et al*. (2005 cited in Alemayehu, Richard, James & Wasonga, 2014) defined allometry as "a tool for estimating tree weight from independent variables such as trunk diameter and height that are quantifiable in the field". In

an earlier study by Chave *et al*. (2004), some errors associated with estimation of above-ground biomass were reviewed. The authors concluded that most important source of error is currently related to the choice of the allometric model. Tropical forest allometric models used for above-ground biomass estimation suffer from three important short-comings: (i) they are constructed from limited samples; (ii) they are sometimes applied beyond their valid diameter range; (iii) they rarely take into account available information on wood specific gravity. A previous study by Ketterings, Coe, Van Noordwijk, Ambagau and Palm (2001) reviewed the dynamics of allometric equations and stated that the most commonly used functions are polynomials and power models although the former has the disadvantage of presenting biologically unreasonable shapes. The power function is however widely used in biology and considers diameter at breast height (DBH) and stand height (H) as the most common variables used.

Consequently, Divya *et al*. (2011) suggest that measurements of DBH alone or in combination with tree height can be converted to estimates of forest carbon stocks using allometric relationships. This is because DBH alone explains more than 95 % of the variation in above-ground tropical forest carbon stocks. This supports earlier arguments by Chave *et al*. (2004) that above-ground biomass is strongly correlated with trunk diameter. Ketterings *et al*. (2001) suggested that inclusion of stand height (H) may be important when comparing sites, particularly secondary forests. The authors emphasized that site-specific wood density (ρ) and DBH versus H were two factors whose incorporation into allometric models could reduce estimate errors. Kauffman and Donato (2012) on the other hand, highlighted that accurate height

measurement in the field is difficult and thus not recommended as a parameter unless collected for other purposes.

On this premise, Comley and McGuinness (2005) observed that there is a dearth of literature on the allometric relationships between total tree biomass and DBH because few studies included the below-ground biomass portion. In this vein, Komiyama, Poungparnand and Katoin in 2005 developed allometric equations for below-ground biomass estimation. Later in 2012, Kathiresan in a meta-analysis highlighted that the ratio between above-ground biomass and below-ground biomass is about 2.5:1. In contrast, Hogarth (2007) stated that the ratio of below-ground to above-ground biomass varies with environmental conditions.

Gibbs *et al*. (2007) observed that species-specific or location specific allometric relationships are not needed to generate reliable estimates of forest carbon stocks, particularly when sample sizes are small (Chave *et al*., 2004). The rationale lies in the fact that species-specific models do not improve accuracy although they are occasionally warranted to validate allometric equations for specific locations. In view of this, this study exploited the application of generalized and species/location-specific equations for the purpose of comparison. Furthermore, it is instructive to note that when using allometric equations in biomass estimation, generalized equations for mangrove families impose similar estimation as species-specific or location-specific equations.

Role of Mangrove Carbon Stocks in REDD and REDD+

Climate policies and discussions, in recent times, have focused on mass and quantity of carbon or carbon dioxide sequestered or emitted into the

atmosphere (Donovan, 2013). In 2010, United Nations Framework Convention on Climate Change (UNFCCC) approved the inclusion of reducing emissions from deforestation and forest degradation (REDD) mechanism as an eligible action to prevent climate changes and global warming in post-2012 commitment periods of the Kyoto Protocol (Köhl *et al*., 2011). Five components of REDD have been agreed on by Parties to include reducing deforestation, reducing degradation, forest enhancement, sustainable management of forests, and forest conservation (Herold *et al*., 2011; Forestry Commission, 2015; Indufor, 2015). It is instructive to note that some other guidelines (e.g., Kauffman & Donato, 2012) cover information relating to carbon financing and carbon markets, which are beyond the scope of this review.

Although no financial value has been assigned to the carbon stored in forests, decisions about future land-use are driven by the potential income from alternative forms of land management (Alongi, 2011; Köhl *et al*., 2011; Kossoy & Guigon, 2012). As such, countries willing to adopt a REDD regime need to establish a national measurement, reporting and verification (MRV) system (Köhl *et al*., 2011) that provides information on forest carbon stocks and carbon stock change. These information are relevant for the development of carbon accounting in participating countries. It is relevant to note that carbon accounting has been particularly difficult in wetlands due to limited information on carbon stocks, carbon emissions and the removals of other GHGs (Murdiyarso *et al*., 2009; Henry, Maniatis, Gitz, Huberman & Valentini, 2011). Since the mangrove forests are treated as a unique forest category, Ghana as a developing country needs to focus on the carbon dynamics in these system in order to benefit economically.

As reviewed earlier under "Land-use changes and mangrove carbon stocks" real and potential threats to mangrove ecosystems warrant surveys to assess the ecosystem carbon pools. According to Kauffman and Donato (2012) due to the large carbon stocks of mangrove ecosystems, as well as the numerous other critical ecosystem services they provide, mangroves are potentially well suited to these climate change mitigation strategies. For instance, to participate in REDD+ programmes, the IPCC has established a tier system reflecting the degrees of certainty or accuracy of the carbon stock assessment (see GOFC-GOLD, 2009 for details). The focus of this review is on the Tier 2, which requires country-specific carbon data for key factors; and Tier 3 which requires highly specific inventory-type data on carbon stocks in different pools, and repeated measurements of key carbon stocks through time, which may also be supported by modelling (Kauffman & Donato 2012). On this premise, mangrove ecosystems in Ghana must be vigorously assessed for their carbon stocks as potential payment for ecosystem services.

CHAPTER THREE

MATERIALS AND METHODS

Study Areas

The study was conducted in the Kakum River estuary mangrove forest in the Central Region and the Amanzule River estuary mangrove forest in the Western Region of Ghana.

Kakum estuary mangrove forest

The Kakum estuary mangrove forest (hereafter referred to as Kakum forest) is located along the Cape Coast – Takoradi trunk road near the Cape Coast Metropolis in the Central Region of Ghana (5° 05′ 01.4″ N and 5° 03′ 56.3″ N and longitudes 1° 18′ 48.3″ W and 1° 19′ 19.9″ W) (Figure 1). The Kakum mangrove forest is fringed by two small communities, namely Iture and Abakam. The forest is drained by two rivers: the Kakum and Sweet (Sorowie) rivers and is inundated twice daily at high tide. However, the estuary is named after the Kakum River because it is relatively bigger. The catchment area of the estuary together with the Kakum and Sweet rivers are major locations of sand winning by the inhabitants of Iture and Abakam. Predominantly, the inhabitants in these communities are fisherfolks and farmers. There is no existing regulation on the cutting of mangrove trees in the Kakum mangrove forest. However, traditional laws prohibit mangrove cutting on Tuesdays only.

This site was selected because it has been reported to be the only single location in Ghana which contains six of the seven mangrove and mangrove-associated species found in Ghana (Haruna, 2002); thus a mangrove diversity hotspot. The study area is located in the dry equatorial zone of Ghana with

coastal savannah as the major vegetation type. The area experiences high rainfall with the wettest periods in May/June and September/October each year. There is a short dry season from December to March (Dzakpasu, 2012) which is occasioned by the south-east trade winds with slight harmattan conditions. The average annual rainfall is about 1,000 mm and the vegetation type is coastal savannah. The mean monthly temperature ranges from 24°C to 30 °C (Ajonina *et al.*, 2014). The topography of the Kakum forest is flat and the soil type is predominantly forest ochrosols (Anim-Kwapong & Frimpong, 2008). The Kakum forest is of the dwarf type (also known as mangle chaparro) (Figure 2a and 2b).

Amanzule estuary mangrove forest

The Amanzule wetlands occur in the Ellembelle District (4° 46' 31 ″N and 4° 53' 46 ″ N; and 2° 00‘ 19 ″ W and 2° 05‘ 39 ″ W) (Figure 1). The Amanzule estuary is formed by two arms of the Amanzule River which enters the sea at Azulenloanu (Figure 1).

The Amanzule estuary mangrove forest (hereafter referred to as Amanzule forest) is drained by the Amanzule River and is inundated twice daily at high tide. The Amanzule mangrove forest is a community-owned wetland system with no official conservation status in the eastern and western Nzema traditional areas of the Western Region of Ghana (Ajonina *et al*., 2014). However, mangroves cutting in the area is prohibited. While compiling customary laws and practices within the Ellembelle district, Adupong, Doku and Asiedu (2013) highlighted that customary laws contributed to the conservation of the wetlands (including the mangrove forests) because the wetlands are regarded as the dwelling place of their “gods”.

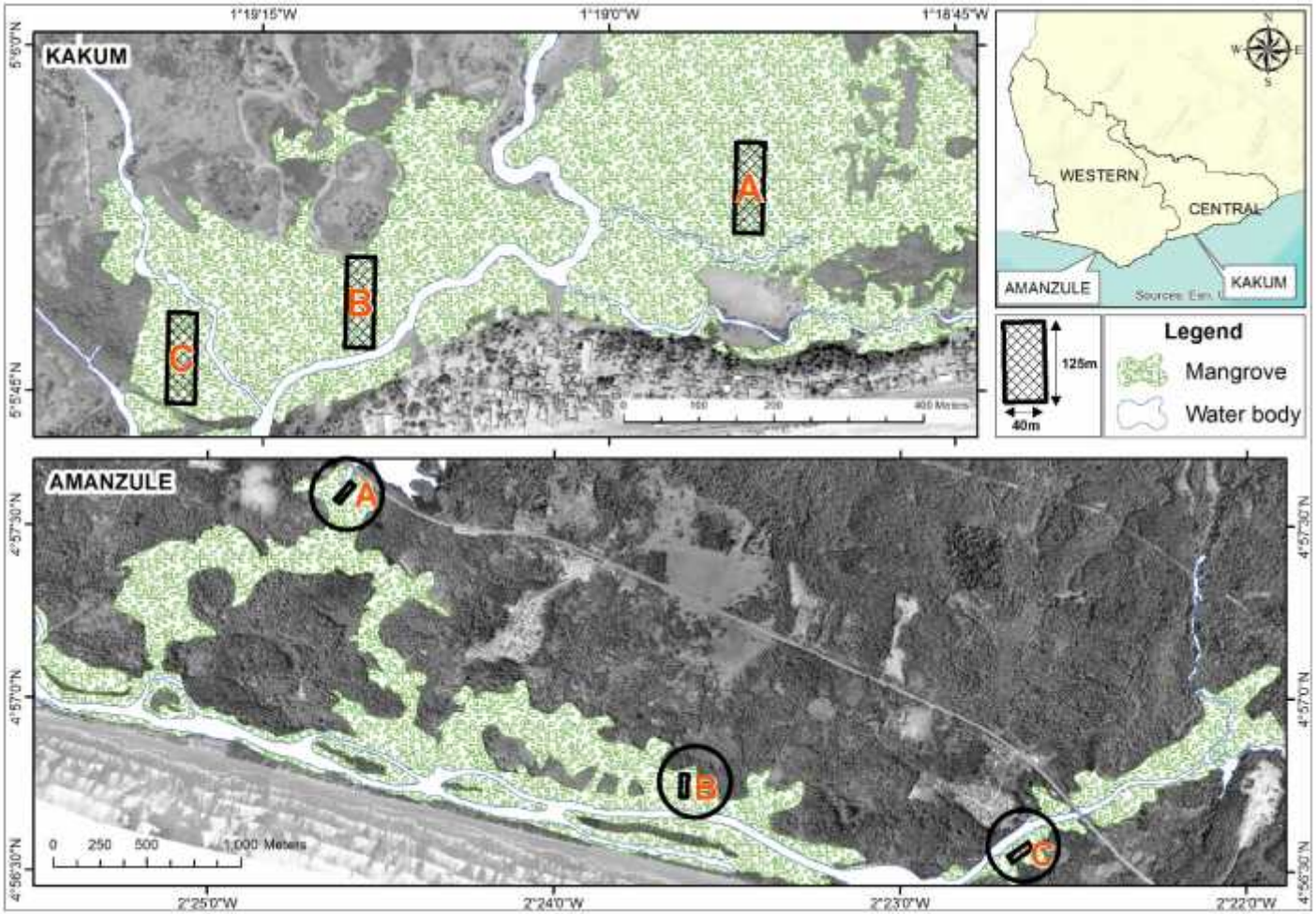

Figure 1: Study areas: Kakum estuary mangrove forest (top) and Amanzule estuary mangrove forest (below) showing the temporary sampling plots (TSPs) labelled A, B and C.

Figure 2: Mangrove stands around the Kakum estuary (a) and (b); (c) bare area resulting from wood harvesting; (d) and (e) freshly cut mangrove tree at the time of sampling; (f) mangrove woodlot ready to be transported to market centres.

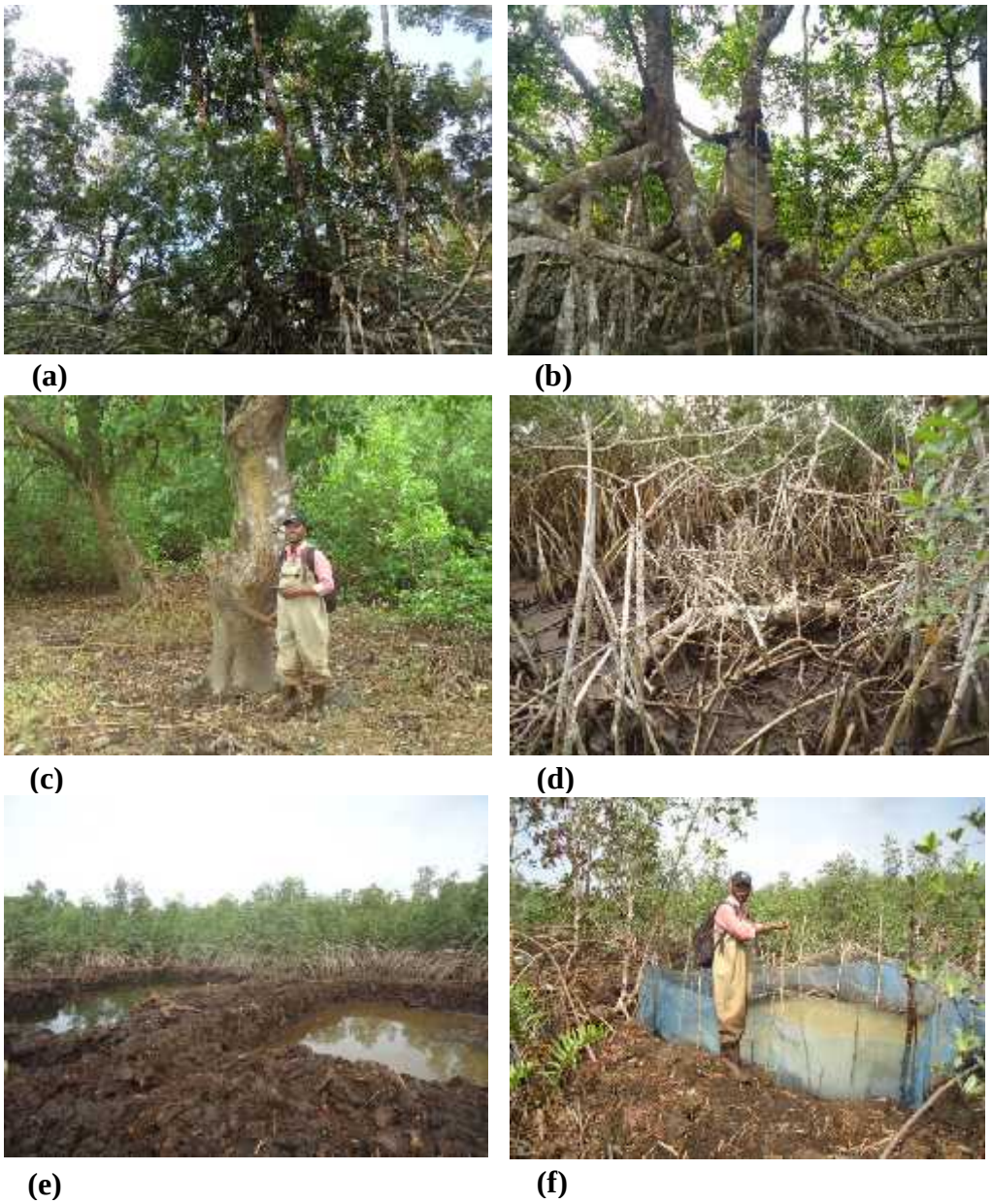

Figure 3: Mangrove stands at the Amanzule estuary (a) and (b); (c) disturbed area around an *Avicennia* tree; (d) down wood close to River Amanzule; (e) and (d) mangrove area converted for aquaculture.

They are thus required to be kept in a clean state. Some norms also prohibit certain persons, animals and items such as tenth child, women in their period of menstruation, goats, pigs and ducks from going near wetlands

(Adupong *et al*., 2013). However, in the advent of modern religious beliefs, formal education, and technology most of these norms are losing grounds in the communities. The inhabitants around this mangrove complex are mainly fisher folks and farmers while some engage in petty trading.

The Amanzule estuary mangrove forest was of interest because studies have shown that it has the most extensive stand of intact mangrove forests in Ghana (Mensah, 2013). Studies by Ajonina (2011) reported that over 1,000 ha of mostly estuarine mangrove forests exist in scattered pockets of less than 10 ha in the Amanzule area, representing about 10 % of national mangrove coverage of 13,700 ha. The study site has also been identified as an important bird area (IBA) (DeGraft-Johnson, Blay, Nunoo & Amankwah, 2010). The Amanzule forest comprised primary and secondary forest patches.

The Amanzule estuary mangrove forest is located in the equatorial climate zone, characterized by moderate temperatures. The area experiences high rainfall with a double maximum which peaks in May to June and October to November each year. The average annual rainfall is 1,600 mm with relative humidity of 87.5 %, and a mean annual temperature of 26 °C. A short dry season prevails from December to March during which cold south-westerly directional winds and harmattan conditions occur (Ajonina *et al*., 2014). The soil is predominantly forest oxysols and forest ochrosols-oxysols intergrades (Anim-Kwapong & Frimpong, 2008). The area has a flat topography.

Sampling Design

A sampling design adapted from Kauffman and Donato (2012) was used to describe forest composition, biomass and ecosystem carbon pools. In order to quantify carbon stocks, both mangrove ecosystems were divided into above-

ground and below-ground components (Donato *et al*., 2011). This study considered above-ground components to include mangrove trees with diameter at breast height (DBH) measuring ≥ 2 cm. The rationale is that trees which contain significant carbon pools measure ≥ 2.5 cm (Kauffman & Donato, 2012). In the case of the Kakum mangrove forest, which is dominated by dwarf mangroves, a large proportion of the trees have diameters at breast height or diameter at 30 cm above the highest prop root which is less than 2.5 cm. This was therefore to enable the inclusion of the dominant stem size of mangrove species found in the Kakum forest.

Stratified systematic sampling was used where parallel transects were laid perpendicular to the water's edge. A rectangular plot design was adopted unlike circular plots proposed by Kauffman and Donato (2012) in order to reduce heavy disturbances of the mangrove seedlings and sediments. Temporal sampling plots (TSPs) of dimension 125 m by 40 m (Figure 4) were established using a measuring tape and the boundaries marked with ribbons. Each study site had three TSPs and each plot contained eighteen subplots measuring 10 m by 10 m. Subplots were spaced 10 m perpendicular to the shoreline and 5 m parallel to the shoreline from each other (Figure 4). The sampling plots in the Kakum mangrove forest were located within coastal fringes and those in the Amanzule forest were located in coastal fringes (TSPs A and B) and an estuary (TSP C) (Figure 1).

The sampling plots and subplots were designed to encompass modified (degraded) and intact (non-degraded) areas as well as represent the main topography, land-uses and vegetation types within the range of vision. The rationale for this design was to provide a basis to assess stock-change estimates

across the mangrove forests. It is, however, instructive to note that the Kakum Estuary mangrove forest, at the time of sampling, was a highly modified ecosystem with large patches of the forest cover degraded. Forest degradation was recorded in each sampling plot. Conversely, the mangrove system at Amanzule had large patches of pristine primary forest. Ajonina *et al*. (2014) reported that about 70 % of the mangrove site is highly inaccessible, hence contributing to its pristine nature.

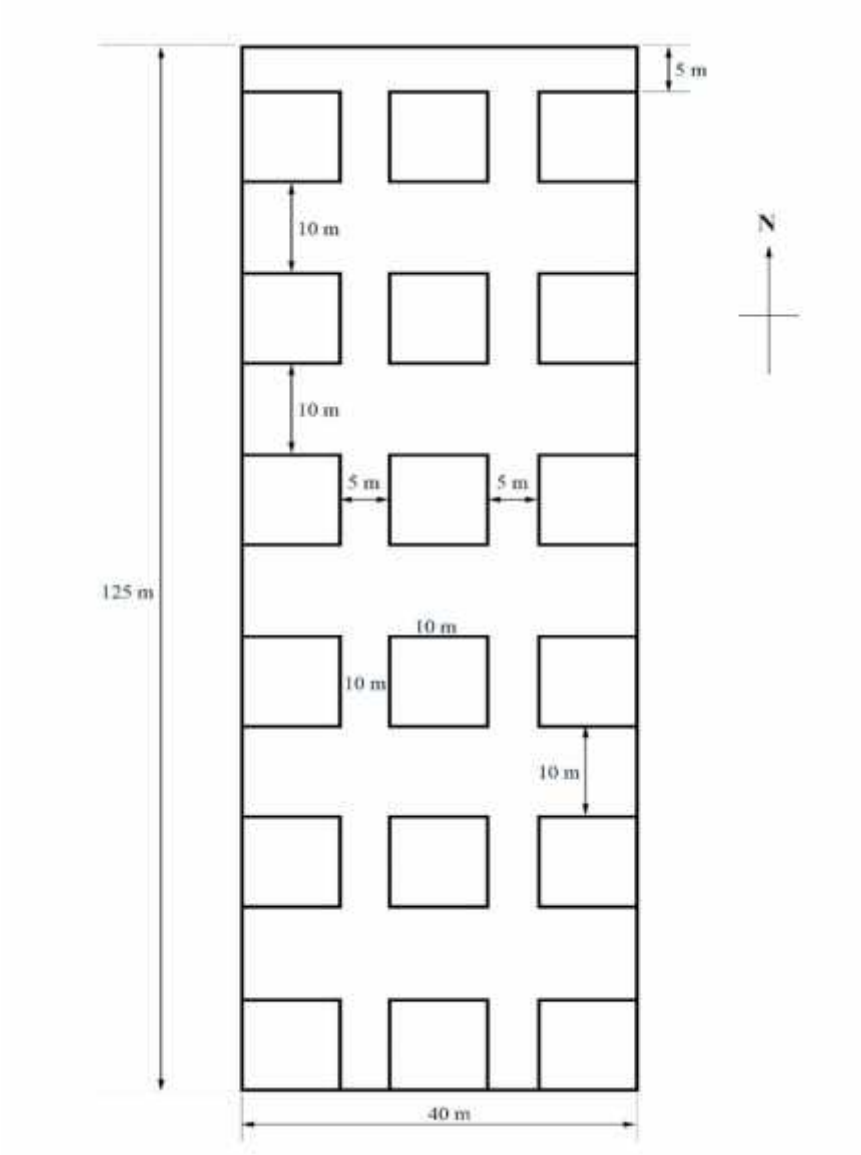

Figure 4: Schematic layout of TSP showing subplots

Data collection

Primary and secondary data were collected during the dry season from November 2014 to March 2015. Existing baseline aerial maps of the study areas, capturing total mangrove coverage, were acquired from Mensah (unpublished) to map out the sample plots. This provided a basis to account for total carbon stock at the two locations. A global positioning system (GPS) (Garmin rino 530HCx) was used to determine the coordinates of the sites, plots and soil sampling locations. Notes based on existing literature were made on land-use types, mangrove species and coverage and validated by field observation. Carbon pools measured comprised above-ground biomass and below-ground biomass and soil at different depths. The above-ground biomass included live and dead or fallen (down) trees whereas below-ground biomass comprised tree roots.

Above-ground biomass

Above-ground biomass refers to living and dead plant tissues above the surface of the soil. These include stems, stumps, branches, bark, seeds and foliage (Assefa *et al*., 2013). However, this study restricted above-ground biomass to tree stems ≥ 2 cm. Stilt roots of *Rhizophora spp*. were included as part of above-ground biomass rather than belowground following studies by Murdiyarso *et al*. (2009).

Mangrove species found were identified to species level using keys from available manuals (Irvine, 1961; Feller, 1995; McKee, 1996; Allen, 1998; Duke & Allen, 2006; Giesen, Wulffraat, Zieren & Scholten, 2007). It is important to note that due to dissenting views on the existence of *Rhizophora mangle* in Ghana, a systematic identification procedure was carried out to verify or

otherwise reject its existence. *Rhizophora spp.* and other mangrove species were collected and sent to the herbarium at the School of Biological Sciences, University of Cape Coast for identification using keys from the aforementioned manuals.

Data on trees within the plots and subplots included the species name, their height and diameter. Tree height was measured using graduated pole and the diameter at breast height (DBH) or 30 cm above the highest stilt root was measured using a tape measure and Vernier callipers where appropriate. Fallen trees (down wood) were measured using callipers (Kauffman & Donato, 2012).

The biomass of standing dead wood and live trees was calculated using published allometric equations following Komiyama *et al*. (2005) to predict total above-ground biomass of the mangrove trees. The principle was to use well-established, relevant computational techniques from the literature to obtain the most accurate carbon stock estimates possible (Komiyama *et al*., 2005; Kauffman & Donato, 2012).

The most frequently occurring species and the most dominant species based on diameter at breast height were determined to investigate their influence on the carbon storage in the mangrove forests.

Below-ground biomass

Below-ground biomass of trees which was defined to include live roots was calculated using a generalized equation developed by Komiyama *et al.* (2005).

Soil sampling

Soil depth was measured at three locations using a 3-m long graduated steel pole at the centre of each TSP (Jones *et al*., 2014). The pole with a sharpened end was thrust into the soil and pushed until the penetration met with resistance. The pole was then withdrawn and the depth read off. Soil samples were collected at six locations in each of the three TSPs at each study site. These locations were spaced at about 25 m intervals (10 m, 35 m, 60 m, 85 m, 110 m, and 135 m) along each transect from the water's edge. This transect distance allowed for the consistent sampling of both narrow and wide stands. Soil samples were extracted using an open-face (peat) auger at the six locations. The peat auger consisting of a semi-cylindrical chamber of 6.5 cm radius attached to a cross handle (Figure 5a). The peat auger was designed and manufactured locally following protocols from Kauffman and Donato (2012).

At the sampling locations, organic litter was removed from the soil surface. Then the auger was steadily inserted vertically into the soil until the top of the sampler was levelled with the soil surface (Figure 5b). Once at a depth of 100 cm, the auger was twisted in a clockwise direction a few times to cut through any remaining fine roots. The auger was then gently pulled out of the soil while continuing to twist it, in order to retrieve the soil sample (Figure 5c). Subsections of the soil profile were taken from depth classes 0 -15 cm, 15 - 30 cm, 30 - 50 cm, and 50 - 100 cm (Kauffman & Donato, 2012) using a hollow rectangular soil sampler measuring 120 cm^3 (Figure 5d). The samples were then placed in labelled plastic bags and transferred to the Department of Soil Science laboratory in the University of Cape Coast for analyses.

Figure 5: Soil sampling procedure: (a) Inserting the auger into the soil; (b) Auger is levelled with top of soil; (c) soil core extracted; (d) subsample collected using a pre-defined volume.

Laboratory analyses

The soil samples were analysed for bulk density, organic carbon density, soil particle size distribution, soil pH and salinity. A total of 72 soil samples were analysed from each study site.

Determination of soil bulk density

Bulk density refers to the dry weight per unit volume of undisturbed soil (Donovan, 2013). Thus in this study the same soil sample was used for bulk

density determination and carbon density estimation. Soil subsample of 120 cm^3 of soil from each depth class was collected and dried at 105 ^{0}C to constant mass. The samples were cooled in a desiccator and weighed to determine the bulk density which was computed as:

$$\text{Bulk Density} = \frac{[\text{Dry soil weight(g)}]}{[\text{Wet soil volume } (cm^3)]} \quad (1)$$

Values were expressed to the nearest whole number and used in computing the amount of carbon. Wet soil volume is the sampled wet soil (120 cm^3 in this study).

Determination of soil organic carbon density

A modified version of the wet oxidation (Walkley-Black) technique was used in determining the organic carbon concentration (Bajgai, Hulugalle, Kristiansen & Mchenry, 2013). After determining the bulk density, the samples were ground in a porcelain mortar, homogenized and sieved with a 0.5 mm mesh to remove root parts. Samples were tested for the presence of carbonate by adding drops of hydrogen chloride (HCl), which shows effervescence if carbonate is present (Schumacher, 2002). Samples were however found not to contain carbonates after testing.

Three replicates of 0.05 g ground soil from each depth were weighed into block digestor tubes and 10 ml of 0.5 N potassium dichromate ($K_2Cr_2O_7$) solution was added. This was followed by the addition of 10 ml of concentrated sulphuric acid (H_2SO_4). The tubes were then placed in a pre-heated digestor block (2012 Digestor- FOSS TECATOR) at 144 -150 °C and heated for 30 minutes in an ESCO fume hood (EFA – 5UDRVW-8). The samples were removed, allowed to cool and then transferred into 250 ml conical flasks. A

quantity of 10 ml orthophosphoric acid, followed by 0.2 g of sodium fluoride was added to the composition and gently swirled. The resultant solution was titrated against ferrous ammonium sulphate solution [$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$] using diphenylamine as indicator (Figure 6d) (Schumacher, 2002). The endpoint of the titration was a colour change from violet to dark green. Boiled and unboiled blanks, which contained no soil sample, were included for every set of sample analysed

Orthophosphoric acid and sodium fluoride were used as alternatives to *o*-Phenanthroline-ferrous complex used in the Walkley-Black procedure, and *N*-phenylanthranilic acid and sodium carbonate solution used in the modified Mebius procedure as reviewed by Nelson and Sommers (1982). The titre values were recorded and corrected for the blanks (Anderson & Ingram, 1993). The difference in titration values between blanks and the sample is equivalent to the amount of organic carbon in the soil (Nelson & Sommers, 1982). The higher the titre value, the lower the carbon content in the soil sediment.

Calculations:

Following the procedures of Nelson and Sommers (1982) percentage soil organic carbon was calculated using equations (2) and (3) as follows:

The blank minus titration (B – T) value was corrected for the amount of potassium dichromate consumed during boiling by titrating the unboiled blank and determining the normality of the ferrous ammonium sulphate [$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$] solution from this titration. The difference between titre values of the boiled and unboiled blanks was then divided by the amount

of ferrous ammonium sulphate solution required for the boiled blank, giving the corrected value.

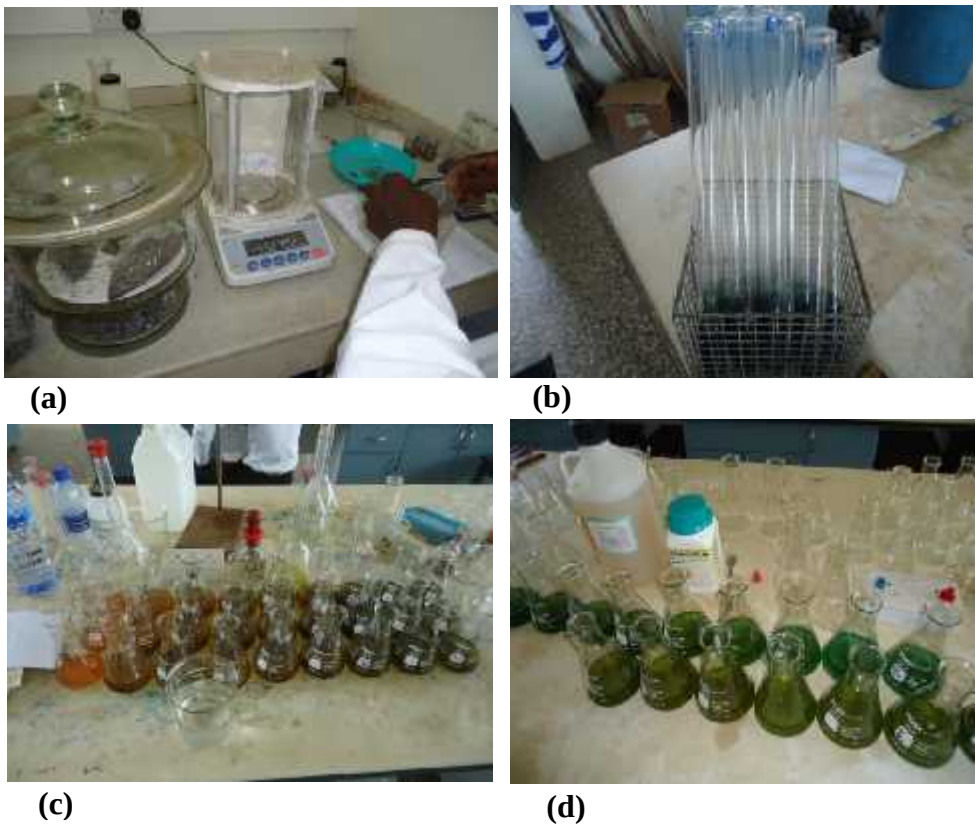

Figure 6: Dichromate oxidation procedure: (a) weighing of soil sample to be analysed; (b) samples after heating in digestor block; (c) samples prior to titrating with ferrous ammonium sulphate solution; (d) endpoint colour after all dichromate is used up.

$$A = \left[\left(ml_{BB} - ml_{sample}\right) x \left(\frac{\{ml_{UB} - ml_{BB}\}}{ml_{UB}}\right) + \left(ml_{BB} - ml_{sample}\right)\right] \quad (2)$$

where A is the corrected value for dichromate consumed during boiling, ml_{UB} is the titre value of the unboiled blank, ml_{BB} is the titre value of the boiled blank, and ml_{sample} is the titre value of the soil sample.

Percentage organic carbon was then calculated as follows:

$$\% \text{ organic C} = \frac{[\text{A x } N_{FAS} \text{ x } (0.003)]}{\text{weight of oven} - \text{dried soil } (g)} \text{ x } 100 \quad (3)$$

where A is the corrected value for dichromate consumed during boiling, N_{FAS} is the normality of ferrous ammonium sulphate solution, which in this study was 0.2.

Using the protocol of Kauffman and Donato (2012), the soil carbon mass (SOC) sampled at depth intervals was calculated as follows:

$$\text{SOC (Mg ha}^{-1}) = [\text{BD (g cm}^{-3})\text{x soil depth interval (cm)x \% OC}] \quad (4)$$

where SOC is soil organic carbon; Mg ha^{-1} is megagram per hectare; % OC is the percentage of carbon by weight in fine soil determined by laboratory testing and BD is bulk density.

Below-ground biomass was estimated using equation described in Komiyama *et al.* (2005) as follows:

$$W_R = 0.199p^{0.899}D^{2.22} \quad (5)$$

where W_R is below-ground biomass, *p* is specific wood density and D is diameter at breast height.

The above-ground biomass were calculated for each tree using allometric equations

$$W_{top} = 0.251pD^{2.46} \quad \text{Komiyama } et\ al. \text{ (2005)} \quad (6)$$

where W_{top} is above-ground biomass, *p* is specific wood density and D is diameter at breast height.

For this study, in order to standardize the results of the biomass estimations, mangrove trees species with DBH greater than 49.0 cm and 45.0 cm for above-ground and below-ground biomass respectively, were excluded from the analyses.

The biomass of trees in each plot (live, dead or fallen) were summed to obtain the total biomass in Mg per plot (1 Mg = 1 metric tonne). Biomass was then converted to the equivalent amount of carbon by multiplying the above-ground biomass by a factor of 0.46, the average carbon content value for tropical trees, and 0.39 as a conversion factor for below-ground tree biomass (Howard, Hoyt, Isensee, Telszewski & Pidgeon, 2014).

The total carbon stock (or density) was determined by adding all of the component pools according to protocols by (Kauffman & Donato, 2012).

Total carbon stock (Mg ha^{-1}) of plots = $C_{treeAG} + C_{treeBG} + C_{soil}$ (7)

where C_{treeAG} = above-ground carbon pools of trees; C_{treeBG} = below-ground tree carbon pool, C_{soil} is the total soil carbon pool.

The total carbon stock of the Kakum Estuary and the Amanzule Estuary mangrove forest was calculated as follows:

Total carbon density of project area (Mg) = TOC (Mg ha^{-1}) x Area (ha) (8)

where TOC is total mean organic carbon density of sampled area

The total carbon density was then converted to gaseous carbon dioxide (CO_2e) by multiplying carbon density by 3.67, the ratio of molecular weights of carbon dioxide to carbon (Kauffman & Donato, 2012).

Mangrove stand characteristics were estimated using equations 9 to 13 according to Aheto *et al*. (2011).

Density was measured species wise and totalled in each plot as follows:

$$\text{Density of each species } \left(\frac{\text{no}}{\text{ha}}\right) = \frac{\text{no. of individuals of a species}}{\text{area of plot (m}^2\text{)}} \text{ x } 10{,}000 \text{ m}^2 \quad (9)$$

Total density of all species = sum of all species densities

Basal area was measured species wise and totalled in each plot as follows:

$$\text{Basal area } (m^2) = \pi r^2 = \pi(DBH/2)^2$$

$$\text{Therefore BA} = \frac{\pi}{4} x\ (DBH)^2$$

But since DBH is in cm and basal area is usually expressed in square metres

$$\text{Therefore BA } \frac{\pi}{40000} x\ (DBH)^2$$

$$\text{Basal area (m}^2\text{) of each species} = 0.00007854 \text{ x (DBH)}^2 \quad (10)$$

$$\text{Total basal area of all species (m}^2 \text{ ha}^{-1}\text{)} = \frac{\text{sum of all species basal area}}{\text{area of plot (m}^2\text{)}} \text{ x } 10{,}000 \text{ m}^2 \quad (11)$$

$$\text{Relative density} = \frac{\text{no. of individuals of a species}}{\text{total no. of individuals of all species}} \text{ x } 100 \quad (12)$$

$$\text{Relative dominance} = \frac{\text{total basal area of a species}}{\text{basal area of all species}} \text{ x } 100 \quad (13)$$

Soil pH and soil salinity

Mangrove soil pH and salinity were determined to find out if there was any correlation with soil carbon density. 10.0 g of soil sample from the pre-determined depths from each study site was weighed into centrifuge tube and 25 ml of distilled water was added. The sample was capped and placed on a mechanical shaker for 20 minutes (FAO, 2008). The suspension was allowed to settle for 30 minutes and the pH recorded with a pH meter. The pH meter was rinsed with distilled water and wiped with tissue before each reading. The pH values were then compared against the soil pH ratings by FAO (2008) to determine the level of soil acidity. Soil salinity was recorded using a salinity probe after pH was recorded for each sample.

Soil particle size distribution

Soil samples obtained from the two sites were analysed for particle size distribution in order to inform the soil types and their possible effect on the distribution of organic matter across soil profiles from sample plots. Soil texture, as defined by Kettler, Doran and Gilbert (2001) refers to the relative size distribution of the primary particles in a soil. The particle size, using the U.S. Department of Agriculture (USDA) classification scheme, is divided into three major size classifications: sand (2.0–0.05 mm), silt (0.05– 0.002 mm), and clay (< 0.002 mm) (Fitzpatrick, 1986).

The standard pipette method (without sieving) was used to analyse soil particle size as described by Rowell (1994). 10 g of < 2 mm sieved soil (initial soil sample) was weighed into a 500 ml beaker. A reasonable amount of distilled water was added to the soil sample, followed by 15 ml of hydrogen peroxide (H_2O_2) solution, to decompose the organic matter present. Presence of organic

matter in soils to be analysed binds mineral particles together; thus hindering dispersion of the mineral particles (Rowell, 1994; Arriaga, Lowery & Mays, 2006). The H_2O_2 was added in stages of 5 ml at a time. This was due to the violent rapid frothing of soil samples as a result of high amount of organic matter present in them. Amyl alcohol was used to reduce frothing of the samples. The composition was then boiled to complete the decomposition of organic matter and allowed to cool.

A dispersing agent was prepared as described in Rowell (1994) by dissolving 50 g of sodium hexametaphosphate and 7 g of anhydrous sodium carbonate in water and made up to 1 litre. This contains 0.57 g of total reagent per 10 ml of solution. The mass of the sodium hexametaphosphate was checked by pipetting 10 ml of the solution into a dry weighed beaker and evaporated to dryness in an oven at 105 °C. The beaker was cooled in a desiccator and re-weighed.

The peroxide-treated soil was transferred into a plastic shaking bottle about 500 ml. The bottle was half-filled for effective shaking. Approximately 10 ml of the dispersing agent was added to the samples in each plastic bottle and shaken on a mechanical shaker for about 15 hours. After dispersing the soil, the content of the shaking bottle was transferred (Figure 7a) into a 500 ml measuring cylinder and made up to 500 ml with distilled water (Figure 7b).

The suspension was thoroughly mixed for about a minute and allowed to settle for 40 seconds. A pipette was inserted 10 cm below the surface of the suspension and approximately 25 ml of the suspension was pipetted and transferred into a weighed beaker (Figure 7c) and dried at 105 °C to constant weight (Figure 7c). The beaker and content was cooled in a desiccator and re-

weighed. The weight of the silty-clay soil particles was determined as difference in weight of the empty beaker and the beaker with dried soil

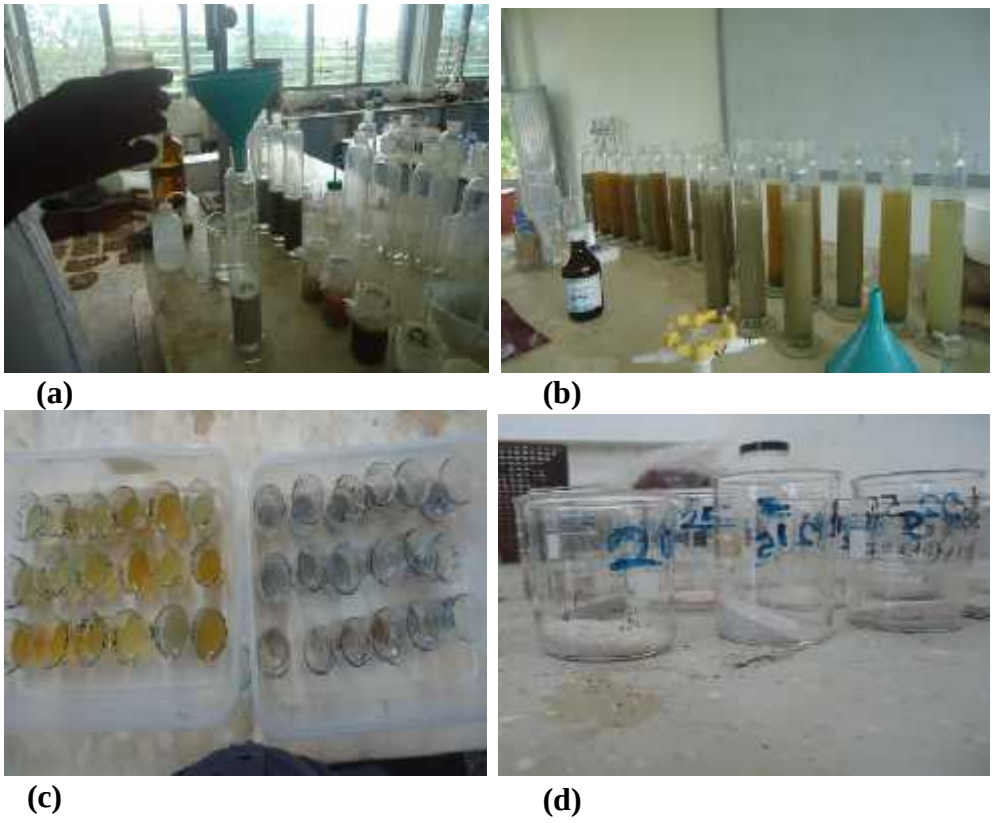

Figure 7: Particle size analysis: (a) Transfer of sample into measuring cylinders after shaking mechanically for 15 hours; (b) Sedimentation after recording for silt; (c) samples of clay and sand prior to drying in oven; (d) sand crystals after drying and weighing.

After pipetting 25 ml of solution for the silt content determination, the suspension was thoroughly mixed again and allowed to settle for 5 hours. Determination of clay content in soil sample was done following the same procedure as used in sampling the silt (above). The 25 ml of the suspension was dried to give the weight of the clay.

After the 5 hours of sedimentation all of the sand (and some amount of the silt and clay remained at the bottom of the cylinder. Most of the supernatant was gently decanted and the sediment was transferred into a 500 ml beaker which was marked at 10 cm above the base. Water was added to the sediment up to the 10 cm mark. The sediment was stirred, allowed to settle for 40 seconds and carefully decanted. Stirring, settling and decanting was repeated until the supernatant was clear, given that all the silt and clay had been washed out of the sand. The sand was transferred into a weighed beaker and dried at 105 °C to constant weight. The beaker and content was cooled in a desiccator and reweighed to obtain the mass of the sand. The procedure was repeated for soil sampled at the respective depths at each study site.

Calculations:

Equations 14 to 19 following Rowell (1994) were used in the estimation of the respective soil textural classes and presented in percentages.

$$\text{Total mass of silt in the soil sample} = \text{mass of silt in 25 ml} \times \frac{500}{25} \qquad (14)$$

where 25 ml is the volume of suspension pipetted, 500 ml is the volume of the cylinder containing soil sample.

$$\text{Total mass of clay in the soil sample} = \text{mass of clay in 25 ml} \times \frac{500}{25} \qquad (15)$$

where 25 ml is the volume of suspension pipetted, 500 ml is the volume of the cylinder containing soil sample.

$$\text{Percentage silt} = \frac{\text{total silt}}{\text{mass of soil}} \times 100 \qquad (16)$$

$$\text{Percentage clay} = \frac{\text{total clay}}{\text{mass of soil}} \times 100 \qquad (17)$$

The sand fraction in the soil sample was determined as:

$$\text{Percentage sand} = \frac{\text{mass of sand}}{\text{mass of soil}} \text{ x } 100 \qquad (18)$$

Mass of soil in grams was obtained as the sum of total mass of silt, total mass of clay and total mass of sand

Data analyses

The textural class was determined following the guide provided by USDA (2008) (see Appendix 20) where the texture triangle was employed using the particle size percentages determined as described earlier. The sand, silt and clay percentages were traced along the texture triangle and the points where these percentage values converged were accepted as the texture description of each soil.

One-way Analysis of Variance (ANOVA) with Tukey's *post hoc* test was conducted to test the effect of soil depth on soil carbon density, bulk density, salinity and pH at 95 % confidence level. T-test was conducted to compare the mean height and mean DBH of mangrove trees, and total mean carbon density for the two study sites. Levene's *post hoc* tests were conducted when necessary to determine to degree of significance.

CHAPTER FOUR

RESULTS

The findings of this study are presented in three sections: mangrove population characteristics, mangrove biomass and carbon density, and hydrographic factors.

Mangrove Population Characteristics

Identification of *Rhizophora mangle*

In this study, collected mangrove samples were taken through systematic identification procedures to confirm the occurrence of *R. mangle* species in Ghana, particularly in the Kakum mangrove forest.

The leaves of *R. mangle* are opposite, simple, bright green, obovate, leathery with a curved surface. The margins revolute, with obtuse blunt apex, and a minute lip folded under (Duke & Allen, 2006). Flowers are borne in axillary clusters, which have been characterized as simple cymes. Mature buds and flowers are located at 1–2 nodes down from the apical shoot. The calyx is typically waxy yellow to creamy white and green at maturity, with four lobes (Figure 8a) (Allen, 1998).

Buds elongate to ovate, green when immature to lighter colours as they mature. Dimensions of the buds are 1–2 cm long and about 0.5 cm wide (Duke & Allen, 2006). The petals, usually four, are lanceolate to linear, creamy white, with woolly to sparsely hairy margins. The petals are about 12 mm long and 4 mm wide. Stamens number eight and are pale yellow to golden brown at maturity (Allen, 1998). The style is pale green, filiform and 0.5–4 mm above ovary base; it is 1.5–3 mm wide, pale yellow and has dichotomous tip. Peduncle is 3–4 cm long, and about 0.3 cm wide (Duke & Allen, 2006).

Hypocotyls are narrowly cylindrical, elongate, green, smooth with irregular small brown lenticels, distal half wider, distal tip pointed (Figure 8b) (Irvine, 1961). *Rhizophora spp.* samples collected from the field (Figure 8a and 8b), exhibited these characteristics and hence were confirmed as *R. mangle*.

(a) **(b)**

Figure 8: *Rhizophora mangle*: (a) downwardly curved petals with bell-shaped, leathery, persistent, pale yellow sepals; (b) propagule showing elongated hypocotyl with distinctive distal ending.

Species density, dominance and basal area

Mangrove species encountered in the Kakum and Amanzule mangrove forests were *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa*.

A. germinans was present in the three sampling plots in the Kakum forest (Table 1). Inherently, *A. germinans* recorded the highest total density of 3627.7 ind./ha while *R. mangle* and *L. racemosa* had marginally low densities of 213 ind./ha and 331.5 ind./ha respectively (Table 1).

Table 1: Species density (no/ha) at Kakum and Amanzule mangrove forests

Plots	Kakum			Amanzule		
	R. mangle	***A. germinans***	***L. racemosa***	***R. mangle***	***A. germinans***	***L. racemosa***
A	-	1208	-	524	-	-
B	106	1116	178	474	362	26
C	124	1594	46	1398	-	-
Total	**213**	**3627.7**	**331.5**	**2396**	**362**	**26**

The situation was different in the Amanzule forest where *R. mangle* dominated all three plots thus showing the highest total density of 2396 ind./ha followed by *A. germinans* with 362 ind./ha and *L. racemosa* with the lowest density 26 ind./ha (Table 1). Comparatively, *R. mangle* and *A. germinans* were the species with the highest total densities in the Amanzule and Kakum forest respectively. *L. racemosa* had the least density in both the Kakum and Amanzule forests. On the whole, the total density of all mangrove species was higher in the Kakum forest than in the Amanzule forest (Table 1).

Table 2: Relative dominance, relative density and basal area of mangrove species at Kakum forest

Species	Relative density (%)	Relative dominance (%)	Total basal area (m^2ha^{-1})
R. mangle	5.10	3.23	0.05
A. germinans	89.62	89.94	1.45
L. racemosa	7.95	6.83	0.11

Table 2 shows the relative density relative dominance and total basal area of the three mangrove species encountered in the three sampling plots in the Kakum forest. Based on the density values, *A. germinans* showed the highest

relative density (89.62 %), dominance (89.94 %) and total basal area (1.45 m^2 ha^{-1}). This was followed by *L. racemosa* with a higher relative dominance and total basal area. In the Kakum forest, *R. mangle* recorded the lowest relative density and relative dominance (Table 2). The foregoing observation is a reflection of total species density recorded with sampling plots (Table 1).

Table 3: Relative dominance, relative density and basal area of mangrove species at Amanzule forest

Species	Relative density (%)	Relative dominance (%)	Total basal area (m^2ha^{-1})
R. mangle	86.06	93.39	20.64
A. germinans	13.00	6.52	1.44
L. racemosa	0.93	0.08	0.02

R. mangle was observed to show the highest relative density (86.06 %), relative dominance (93.39 %) and total basal area of 20.64 m^2ha^{-1} in the Amanzule forest (Table 3). This was followed by *A. germinans* and then *L. racemosa*. The data further indicate that *L. racemosa* was insignificant relative to the other two species with regards to density, dominance and total basal area. The total number of individuals used in the estimation of these parameters accounted for this observation (Table 3).

Mean height and diameter

The mean height and diameter at breast height (DBH) of mangrove species encountered in the sampling plots in the Kakum and Amanzule forests are presented in Table 4. Given the variation in tree form of the various species, height and diameter at breast height were presented for individual species.

Table 4: Mean height and diameter at breast height (DBH) of species at Kakum and Amanzule mangrove forest

Species	Kakum			Amanzule		
	Height (m) (± S.E)	**DBH (cm) (± S.E)**	**No. of trees**	**Height (m) (± S.E)**	**DBH (cm) (± S.E)**	**No. of trees**
R. mangle	2.89 ± 0.05[a]	2.94 ± 0.06[a]	115	8.22 ± 0.08[a]	11.04 ± 0.29[a]	1198
A. germinans	2.74 ± 0.01[b]	2.97 ± 0.02[a]	1959	5.77 ± 0.14[b]	7.98 ± 0.46[b]	181
L. racemosa	2.26 ± 0.05[c]	2.73 ± 0.05[b]	179	3.65 ± 0.17[c]	4.13 ± 0.25[c]	13
Mean (all species)	**2.71 ± 0.01**	**2.95 ± 0.01**	**2 253**	**7.86 ± 0.07**	**10.58 ± 0.25**	**1 392**

Figures with different superscript in the same column are statistically different

Kakum forest

Although the mean height value of each mangrove species in Kakum was below 3 metres, ANOVA results indicated significant differences among the mean heights of the species (Appendix 18). Levene's test further showed that *R. mangle* and *L. racemosa* showed the highest (2.89 ± 0.05 m) and lowest (2.26 ± 0.05) mean heights respectively (Table 4). It was observed as indicated by Levene's test that *R. mangle* and *A. germinans* recorded mean DBH of similar magnitude (Table 4). The difference in stem size of the two species was not significant across all sampling plots. However, *L. racemosa* obtained the lowest mean DBH value (2.73 ± 0.05 cm), across the sampling plots (Table 4). Therefore, the values are reflective of the fact that *L. racemosa* had secured the position of being the species with the smallest tree form in the Kakum mangrove forest.

Amanzule forest

Variations were prominent in both mean height and mean DBH of mangrove species in the Amanzule forest. *R. mangle* and *L. racemosa* obtained the mean highest and mean lowest height of 8.22 ± 0.08 m and 3.65 ± 0.17 m respectively (Table 4). Again, *R. mangle* and *L. racemosa* recorded the mean highest and mean lowest DBH of 11.04 ± 0.29 cm and 4.13 ± 0.25 cm respectively. In effect, *L. racemosa* had the smallest tree form in this ecosystem.

Height

For *R. mangle*, the mean height was 2.89 ± 0.05 m in the Kakum forest whereas the Amanzule forest showed a higher value of 8.22 ± 0.08 m. The mean height for *A. germinans* in the Kakum forest was 2.74 ± 0.01 m while that of the

Amanzule forest was 5.77 ± 0.14 m (Table 4). Observations were similar for *L. racemosa* which had a mean height of 2.26 ± 0.05 in the Kakum forest and 4.13 ± 0.25 in the Amanzule forest (Table 4). From the data presented in the Table 4, the mean heights of the respective species were higher, ranging from 3.6 m to 8. 2 m, in the Amanzule forest compared to values for the Kakum forest where the individual species had mean height less than 3 m. Species-wise, *R. mangle* was observed to obtain the highest mean height in both locations (Table 4).

Diameter at breast height

The diameter at breast height of mangrove species in both forests displayed the same trend as the mean height. In the Kakum forest, *R. mangle* showed a mean DBH of 2.94 ± 0.06 cm but 11.04 ± 0.29 cm in Amanzule forest (Table 4). For *A. germinans*, mean DBH in the Kakum forest was 2.74 ± 0.01 cm while in the Amanzule forest, it was 7.98 ± 0.46 cm. *L. racemosa* recorded a mean DBH of 2.26 ± 0.05 cm in Kakum and a relatively higher value of 4.13 ± 0.25 cm in the Amanzule forest. Generally, mangrove species recorded lower DBH values (< 3 cm) in the Kakum forest but higher DBH values ranging from 4 cm to 11 cm in the Amanzule forest (Table 4). There was significant difference in mean DBH of species sampled from the two forests. Species-wise, *R. mangle* and *A. germinans* recorded the highest mean DBH values of 2.94 ± 0.06 cm and 2.97 ± 0.02 cm, respectively in the Kakum forest whereas in the Amanzule forest, *R. mangle* was observed to obtain the highest mean DBH value of 11.04 ± 0.29 cm.

Diameter classes

Stem size classes of *R. mangle, A. germinans and L. racemosa* were computed using the total number of individual trees to determine the dominant diameter sizes present in both Kakum and Amanzule mangrove forests.

In Kakum forest, the dominant stem size class of *R. mangle* was 2 – 5 cm with approximately 114 trees and only a single tree in 5 – 10 cm diameter class. No tree counts of *R. mangle* were recorded in the other diameter classes (Figure 9a).

In Amanzule forest, the diameter class of 5 – 10 cm was dominant, recording 702 stems of *R. mangle.* This was followed by 10 – 30 cm with 265 stems and then 2 – 5 cm with approximately 164 stems. For the diameter class of 30 – 50 cm, only 59 stems were recorded (Figure 9a). Generally, the stems of *R. mangle* in the Amanzule forest were bigger than *R. mangle* trees encountered in the Kakum forest. It can be deduced from the figure that the distribution of species sampled from the Kakum forest was negatively skewed while species from Amanzule displayed a normal distribution.

Figure 9b shows stem size classes of *A. germinans.* The stem size classes were computed using total number of individual trees to determine the dominant diameter sizes of *A. germinans* present in both Kakum and Amanzule mangrove forests.

In Kakum majority of the trees (1,921 stems) ranged from 2 – 5 cm while only 38 stems were found within the diameter class of 5 – 10 cm (Figure 9c). There were no trees recorded in the other diameter classes. On the contrary, in the Amanzule forest, *R. mangle* was encountered in all the diameter classes: 2 –

5 cm (81 stems), 5 – 10 cm (58 stems), 10 – 30 cm (40 stems) and 30 – 50 cm (2 stems) (Figure 9b).

Despite having higher stem numbers in the Kakum forest, stems of *A. germinans* ranged between 2 cm to 10 cm, with majority occupying the 2 – 5 cm diameter class. (Figure 9b). Other the other hand species of *A. germinans* encountered in the Amanzule forest fell within all the diameter classes, indicating that *A. germinans* species were relatively larger in the Amanzule forest than those in the Kakum forest. The distribution of diameter classes of species sampled from both ecosystems is negatively skewed.

Figure 9c shows diameter classes of *L. racemosa* as observed in both Kakum and Amanzule mangrove forests. In the Kakum forest, stem numbers reaching 179 fell within the 2 – 5 cm diameter class. No trees were recorded in the other stem size classes. Conversely, in the Amanzule forest, 10 stems and 3 stems were found in the 2 – 5 cm and 5 – 10 cm diameter classes respectively. No trees in this forest were recorded in the other diameter classes as shown in Figure 9c. The distribution of diameter classes of *L. racemosa* sampled from both forests was negatively skewed.

All mangrove species encountered in both Kakum and Amanzule forests were pooled and their diameter classes were determined as shown in Figure 10. In the Kakum forest, all three species were observed to obtain only diameter classes of 2 – 5 cm and 5 – 10 cm with approximately 2214 stems and 39 stems respectively. This means majority of the three species had smaller stem sizes. None of the three species had stems recorded in the other diameter classes (Figure 10).

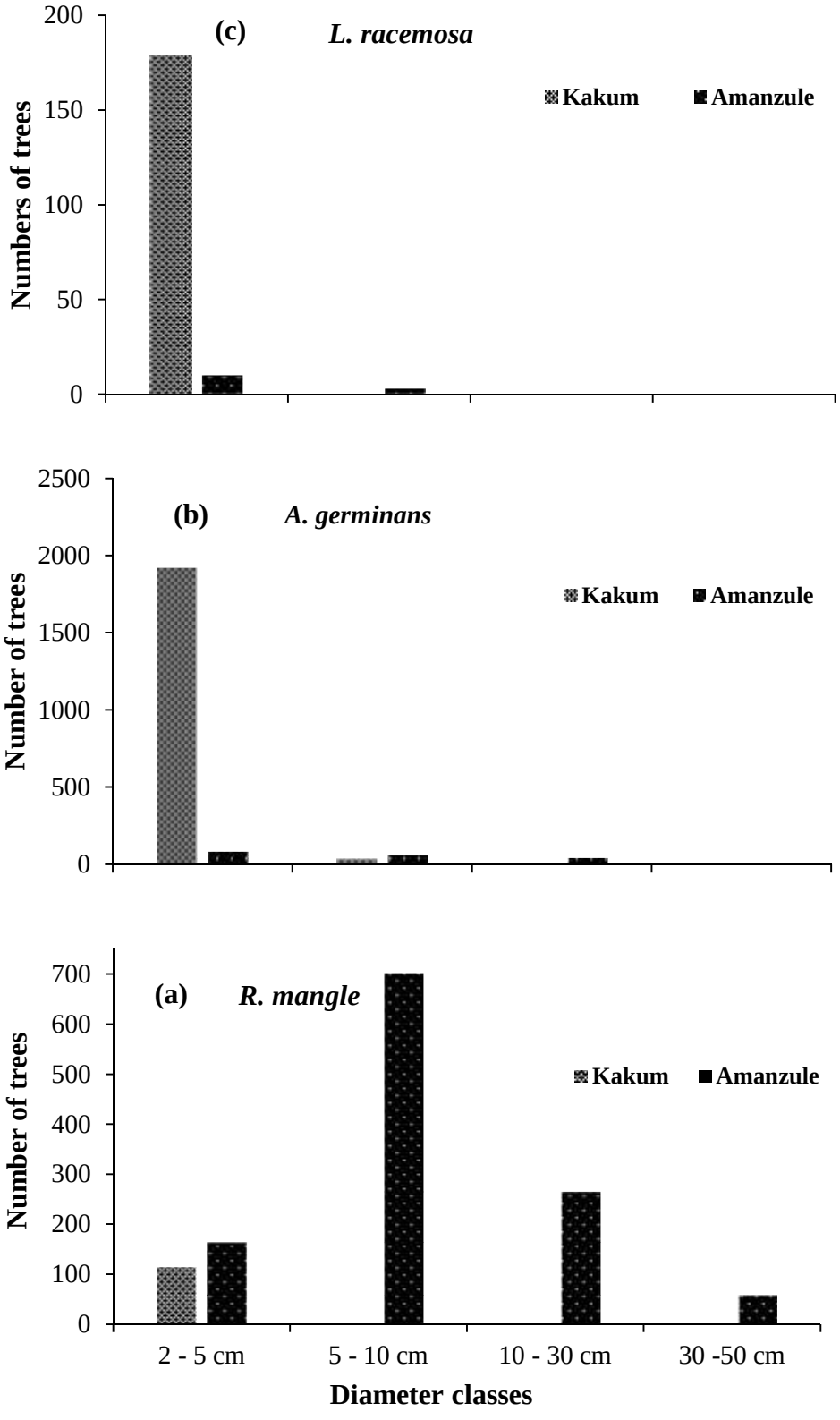

Figure 9: Stem size classes of (a) *R. mangle* (b) *A. germinans* and (c) *L. racemosa* in Kakum and Amanzule mangrove forests.

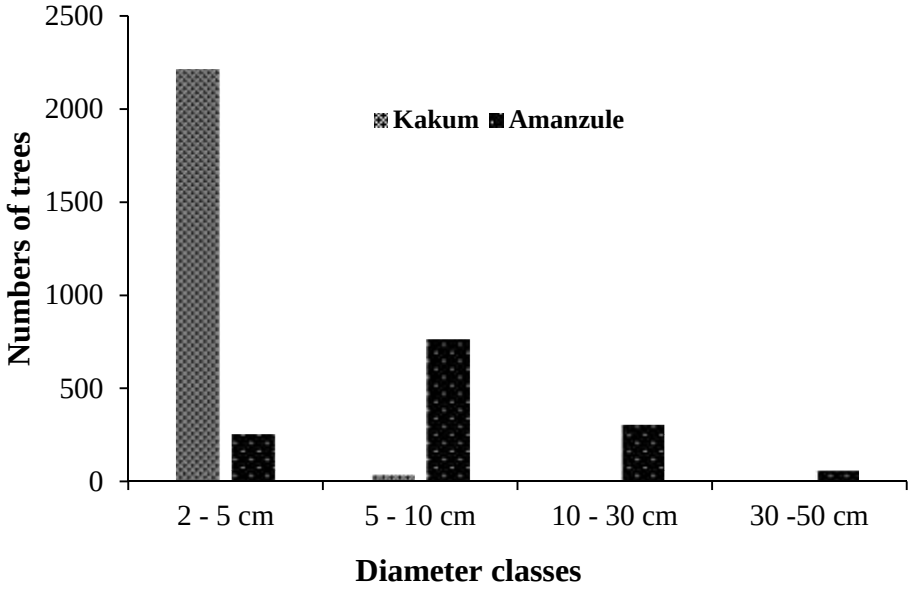

Figure 10: Stem size (diameter) classes of all mangrove species at Kakum and Amanzule forests

Conversely, mangrove species sampled from the Amanzule forest occurred within all diameter classes. As shown in Figure 10, the dominant diameter class for the three mangrove species was 5 – 10 cm (763 stems). The next diameter class occupied by the species was 10 – 30 cm (305 stems), followed by stem size class of 2 – 5 cm (225 stems) and the least dominant diameter class being 30 – 50 cm with 61 stems. It can be deduced that the distribution of mangrove species sampled from the Kakum forest are negatively skewed while species from Amanzule displayed a normal distribution (Figure 10).

Carbon Density

Biomass estimation

The biomass of mangrove species sampled from the Kakum and Amanzule mangrove forests was estimated and individual species were pooled

based on sampling plots in each study site and presented as shown in Figure 11. As displayed in the figure, the sampling plots in Amanzule forest recorded relatively higher biomass as compared to the plots in Kakum.

On site basis, sampling plot C in the Kakum forest recorded the highest biomass of 468.9 kg followed by plot B with 294.4 kg while plot A recorded the least biomass with approximately 247.2 kg (Figure 11).

In the Amanzule forest, sampling plot A recorded the highest biomass of 23,221 kg, followed by plot C with 3482.4 kg while plot B recorded the least biomass of 2713.6 kg (Figure 11). The biomass values recorded are functions of stem density and stem diameters encountered in the respective sampling plots at the two study sites. However, the vast difference in biomass values for plots in Kakum and Amanzule is accounted for by stem sizes of the mangrove trees (Figure 11).

Tree carbon density

Figure 12 shows the total carbon density of mangrove species based on the total biomass estimated in the Kakum and Amanzule mangrove forests.

Kakum forest

The above-ground carbon density of live tree was higher than below-ground carbon density, for all species. On species basis, *A. germinans* was observed to attain the highest above-ground and below-ground carbon densities of 269 MgC/ha and 121 MgC/ha respectively. This was followed by *R. mangle* with 18 MgC/ha and 8.2 MgC/ha. *L. racemosa* had the least above-ground and below-ground carbon densities of 16.2 MgC/ha and 7.5 MgC/ha respectively (Figure 12b). A deduction made from the figure indicates that there is a wide

disparity between values recorded by *A. germinans* and values recorded by *R. mangle* and *L. racemosa* for above-ground and below-ground carbon densities, respectively (Figure 12b).

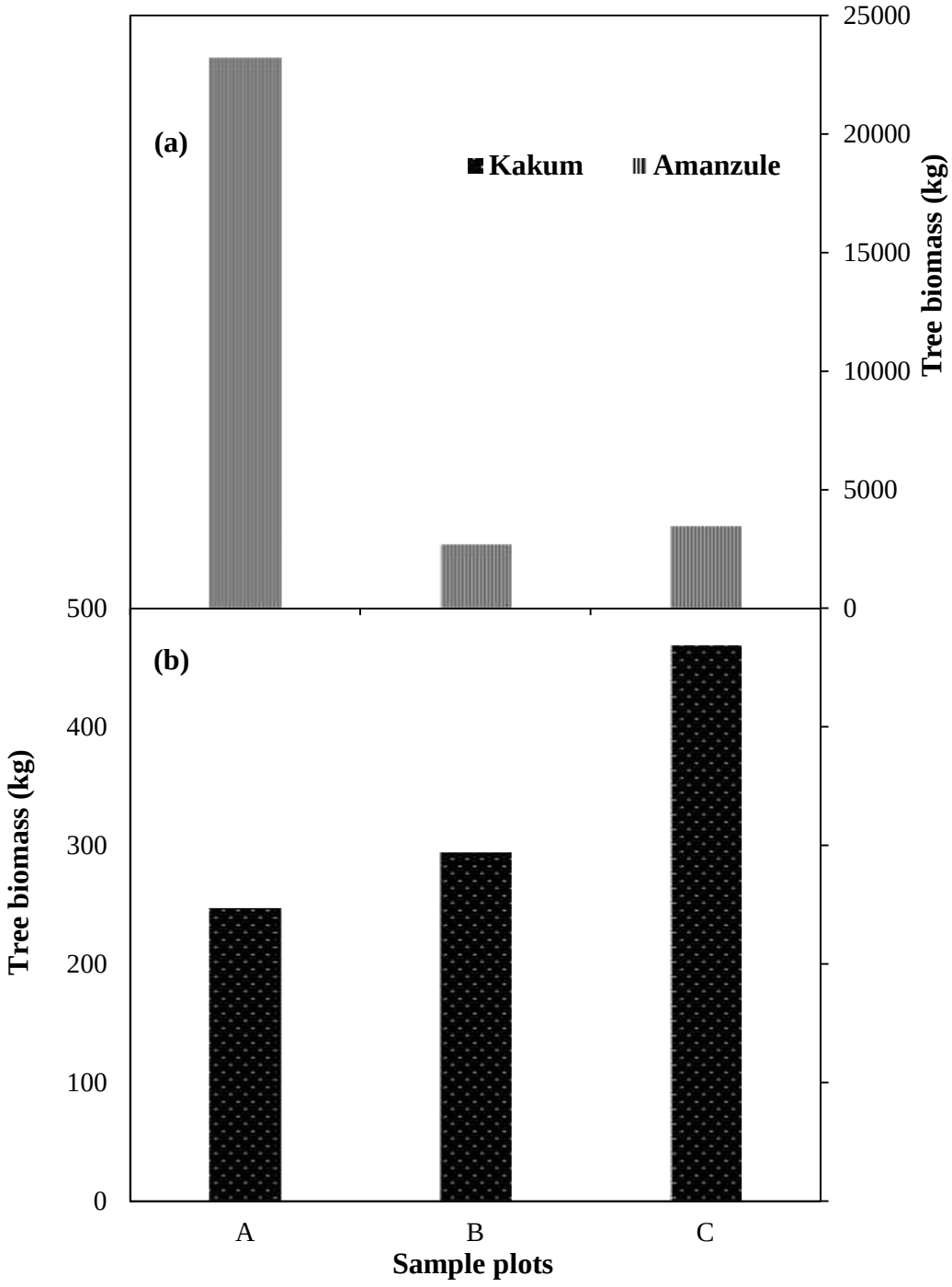

Figure 11: Total tree biomass per sample plot at (a) Amanzule and (b) Kakum mangrove forests

Amanzule forest

The above-ground and below-ground carbon densities of mangrove species from sampling plots in the Amanzule forest were estimated as shown in Figure 12a. Among all species, the above-ground carbon densities were higher than below-ground densities. However, on species basis, *R. mangle* was observed to record the highest above-ground and below-ground carbon densities respectively (Figure 12a). This was followed by *A. germinans* and *L. racemosa*, in that order.

The carbon densities of all mangrove species (live plant) with respect to sampling plots in Kakum and Amanzule mangrove forests are shown in Figure 13. The focus is to compare plant carbon density, excluding soil organic carbon density, for the two forests.

In the Kakum forest, sampling plot C showed the highest tree carbon density of 204.3 MgC/ha while plot A had the least carbon density of 107.7 MgC/ha. However, sampling plot A in the Amanzule forest recorded the highest carbon density of 10682 MgC/ha whereas plot B recorded the lowest tree carbon density of 1195.8 MgC/ha (Figure 13).

Results from pooled species indicate that sampling plots in the Amanzule forest recorded higher carbon densities relative to plots in the Kakum forest (Figure 13). This finding stems from the biomass estimated (Figure 11) in the respective sampling plots at both study sites.

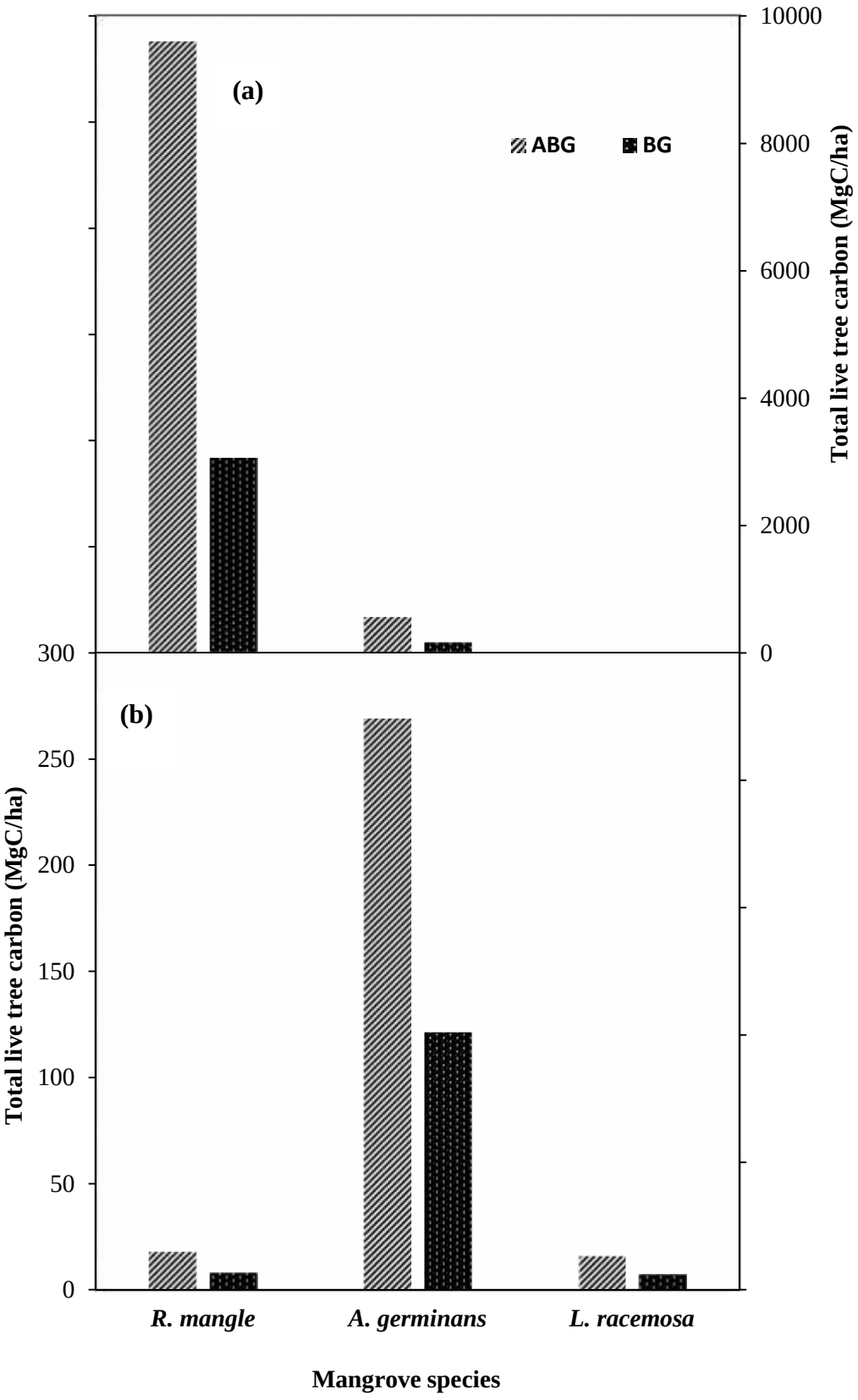

Figure 12: Total live tree carbon density of mangrove species at (a) Amanzule and (b) Kakum mangrove forests

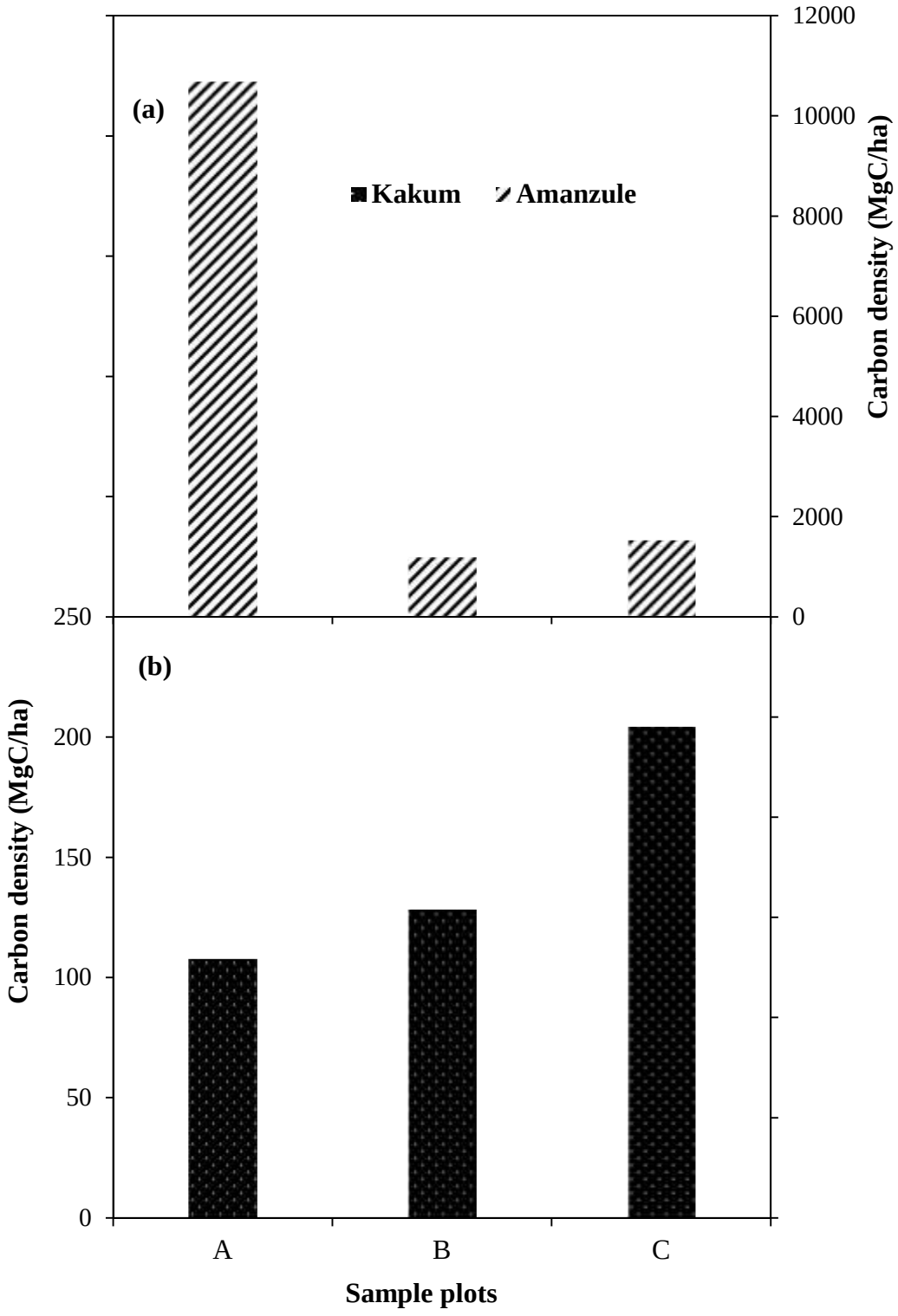

Figure 13: Total carbon density of live tree per sample plot at study areas at (a) Amanzule and (b) Kakum mangrove forests

Soil organic carbon (SOC) density

The mean SOC density with respect to depth for each sampling plot was estimated as shown in Figure 14 below.

Kakum forest

Spatially, variations in mean carbon density with respect to depth were not prominent because values were similar across sampling plots as confirmed by ANOVA results (P = 0.43) (Appendix 3). However, vertical variations in carbon density among the sampling plots were distinct (Appendix 2). It was observed that mean soil carbon density increased with depth in all three sampling plots (Figure 14a). Plot C displayed the most prominent variation as carbon density increased from 22.7 MgC/ha at the surface to 33.9 MgC/ha at 100 cm depth. This was followed by plot A which increased from 19.6 MgC/ha at 15 cm depth to 29.7 MgC/ha at 100 cm depth. Plot C also increased from 22 MgC/ha at 15 cm depth to a mean value of 27.6 MgC/ha at 100 cm depth (Figure 14a). Tukey's *post hoc* analysis however indicated that soil organic carbon density did not vary significantly below depths of 15 cm across the three sampling plots (Appendix 2B).

Amanzule forest

Sampling plots in the Amanzule forest displayed distinct spatial variations in mean soil carbon density (Appendix 5). Sampling plot B recorded the highest carbon density at all depth intervals. This was followed by plot A, while plot C recorded the least carbon density at respective depth intervals (Figure 14b). This was confirmed Tukey's *post hoc* test (Appendix 5B). Generally, the trend depicts an increase in carbon density with increasing depth

(Figure 14b) although the variations are were not statistically significant (see Appendix 4).

Figure 15 below shows the mean soil organic carbon densities estimated for each sampling plot within the Kakum and Amanzule mangrove forests. As shown in the figure, soil organic carbon density was highest in plot B in both Kakum and Amanzule forests. Sampling plots C and A had lower and lowest carbon densities respectively, in both forests. In the Kakum forest, there were no significant variations in mean soil carbon densities among the sampling plots. The trend however showed plot A recording 96.4 MgC/ha, plot B with 112.8 MgC/ha and plot C had 101.7 MgC/ha. The Amanzule forest however displayed statistically significant variations in soil carbon density values among sampling plots. Plot A had 112 MgC/ha which increased to 155.3 MgC/ha in plot B and finally decreased to 85 MgC/ha in plot C.

On the whole, all three sampling plots, except plot C, in the Amanzule forest displayed higher mean soil organic carbon densities compared to corresponding sampling plots in the Kakum forest (Figure 15).

Table 5 below presents total carbon density with respect to plant biomass and soil organic carbon (SOC). The Kakum forest recorded a lower carbon density of 155.1 MgC/ha for live tree biomass as against higher SOC density of 310.9 MgC/ha. In contrast, the Amanzule forest recorded a higher live tree carbon density of 4964.3 MgC/ha whereas SOC was only 352.2 MgC/ha. However, comparing sediment carbon for both sites, the Amanzule forest had higher carbon density of 352.2 MgC/ha relative to values for Kakum forest (310.9 MgC/ha) (Table 5).

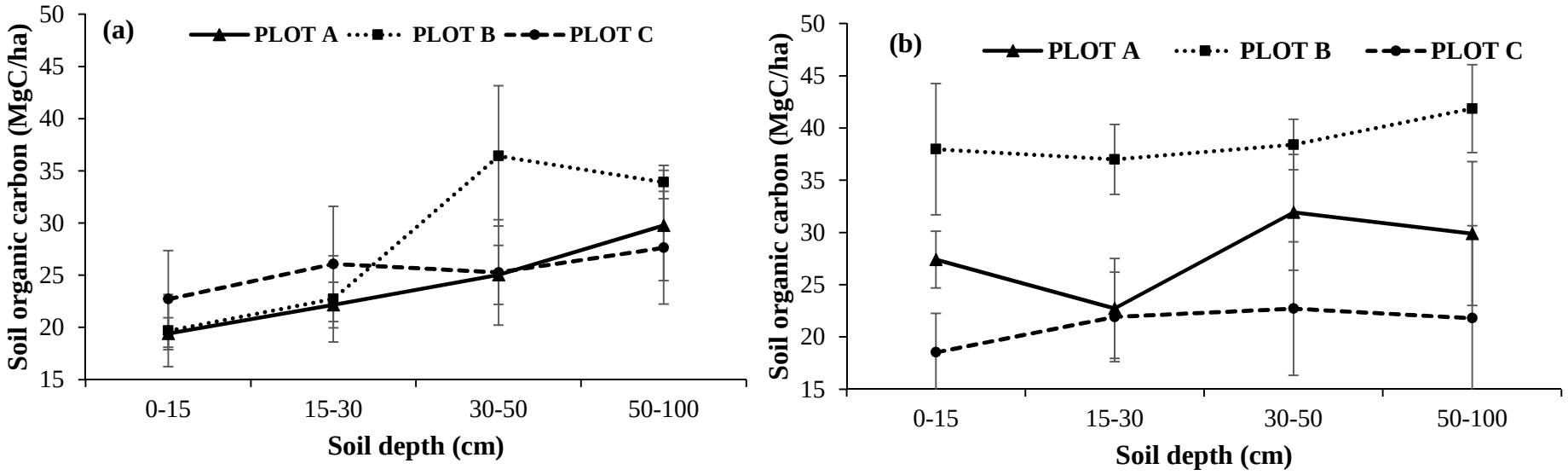

Figure 14: Variations in mean soil organic carbon density at (a) Kakum and (b) Amanzule mangrove forests (vertical bars indicate standard errors of the mean)

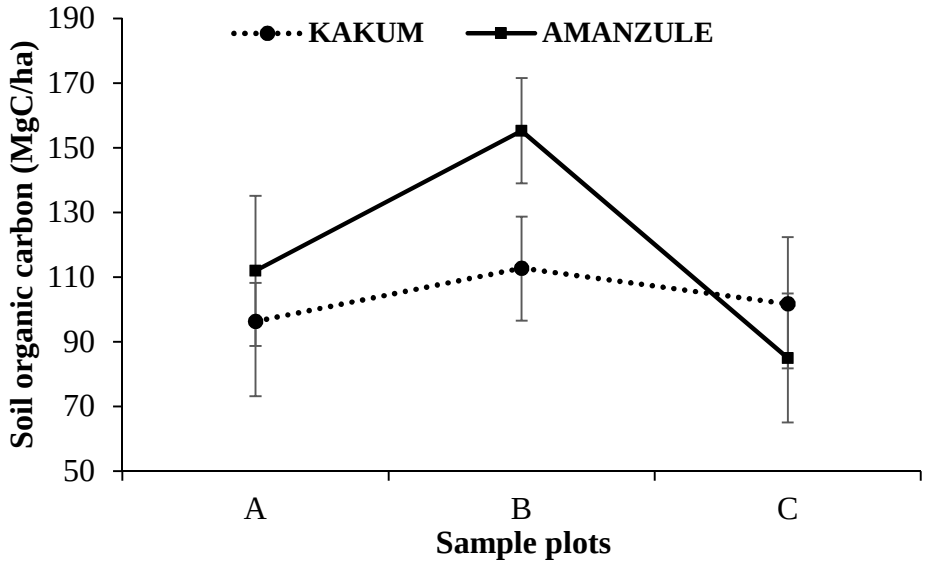

Figure 15: Total mean soil organic carbon density per sampling plot in Kakum and Amanzule mangrove forests.

Table 5: Total carbon density in Kakum and Amanzule mangrove forests

Site	Carbon density						
	Live tree (MgC/ha)	**ABG (MgC/ha)**	**BG (MgC/ha)**	**SOC (MgC/ha)**	**Total (MgC/ha)**	**Total organic matter (kg/ha)**	**Total CO_2 equivalent (Mg/ha)**
Kakum	155.1	106.8	48.3	310.9	465.9	801.5	1709.9
Amanzule	4964.3	3770.9	1193.4	352.2	5316.5	9144.4	19511.6

Comparing above- and below-ground carbon pools, the Kakum forest recorded higher below ground carbon density. The reverse was observed in the Amanzule forest where above-ground carbon density was higher (Table 5).

Given the sediment carbon densities of both sites, the total organic matter, which is a product of the SOC and a factor of 1.72, was evidently higher for the Amanzule forest as compared to the Kakum forest. Apparently, the carbon dioxide equivalent (a product of the carbon density and a factor of 3.67) for both sites reflect the total amount of carbon stored in these ecosystems (Table 5).

Table 6 below shows the total carbon stock in Kakum and Amanzule mangrove forests based on the total mangrove coverage of the two forests. The total mean carbon density comprised the means of soil carbon and tree carbon densities.

Table 6: Total carbon stock in Kakum and Amanzule mangrove forests per coverage

Stratum	**Total mean carbon ± S.D. (MgC/ha)**	**Total carbon stock ± S.D. (MgC/ha)**
Kakum	373.8 ± 73.6	15 923.9 ± 3135.4
Amanzule	3033.7 ± 2074.9	1 365 165 ± 933705

From a secondary data, the Kakum mangrove forest covered approximately 42.6 hectares (Mensah, unpublished) whereas the Amanzule mangrove forest covered about 450 hectares (Mensah, 2013). Considering the fact that the total organic carbon density of Amanzule forest was higher than that of Kakum forest, the large difference in total carbon stock was invariably

accounted for by the size of the forests. Data on area cover suggest that the Amanzule mangrove forest was ten times bigger than Kakum forest.

Soil Bulk Density

Kakum forest

Figure 15a shows variations in soil bulk density among sampling plots in the Kakum forest. Spatially, soil samples from plot A had lower bulk density values while samples from plots B and C showed the highest and higher bulk densities respectively, across all depths. The difference in the mean bulk density values are significant and a *post hoc* analysis categorized them into descending order of magnitude as follows: plot B, plot C, and plot A (Appendix 15B). It therefore means that sediments in sampling plots B and C were heavier relative to sediments in plot A.

Vertically, bulk density showed no significant variation with increasing depth in the three sampling plots (Appendix 14). Contrary to this observation sampling plot C showed slight increase (from 0.91 g/cm^3 to 1.2 g/cm^3) in bulk density as depth increased (Figure 16a).

Amanzule forest

Figure 16b presents the trend in soil bulk density as encountered in the Amanzule mangrove forest. Spatially, variations in soil bulk density among sampling plots were significant (Appendix 17). Plot B generally recorded a relatively lower bulk density while plots A and C displayed higher bulk densities of similar magnitude as indicated by Tukey's test (Appendix 17B).

As indicated in Figure 16b only sampling plot A displayed distinct vertical variations as bulk density was observed to increase with depth from 0.41

g/cm^3 to 0.77 g/cm^3. Plot C also experienced slight increase in bulk density with increasing depth although the differences in these variations were not significant (Appendix 16). On the reverse, sampling plot B recorded a decrease (from 0.39 g/cm^3 to 0.29 g/cm^3) in bulk density as depth increased.

Comparing bulk densities for both sites, the data for sampling plots in the Kakum mangrove forest showed higher values than values for the Amanzule forest. This means that mangrove soils in the Kakum forest contained more mineral particles and were therefore heavier than mangrove soils in the Amanzule forest.

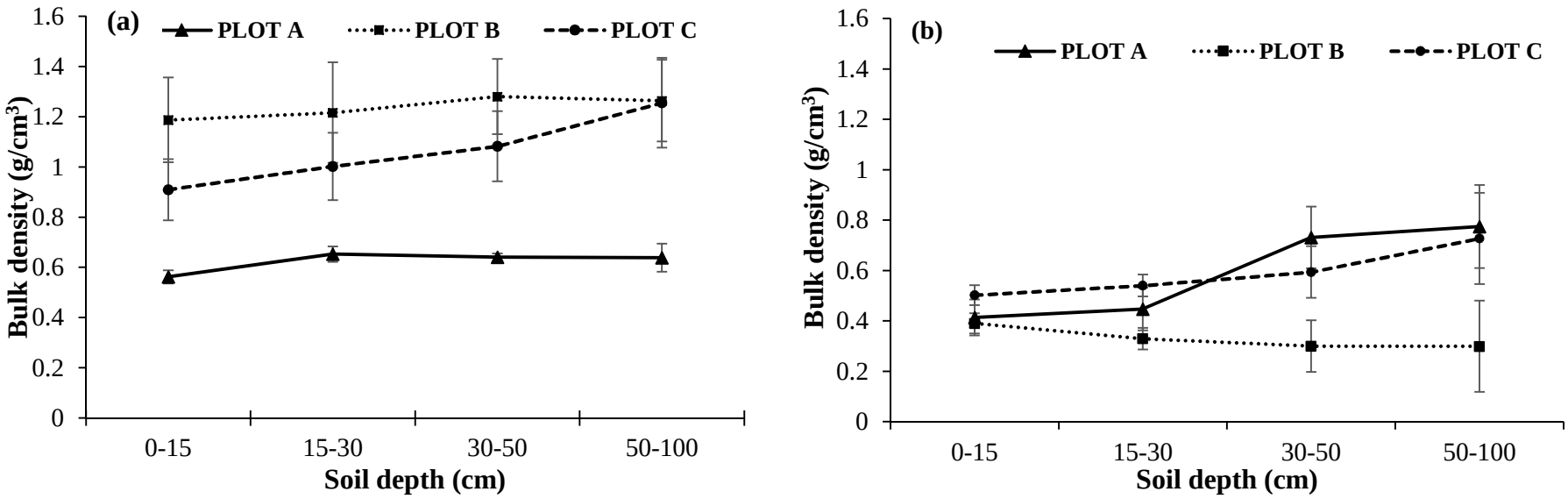

Figure 16: Variations in soil bulk density at (a) Kakum and (b) Amanzule mangrove forests

Soil Texture Distribution

The soil textural class of study areas were determined and presented in Tables 7 and 8 below.

Table 7: Soil texture distribution in the Kakum

TSP	Depth (cm)	Silt (%) (± S.E)	Clay (%) (± S.E)	Sand (%) (± S.E)	Textural class
A	0-15	54.2 (2.4)	18.2 (0.7)	27.5 (1.7)	Silt loam
	15-30	54.7 (1.4)	18.6 (1.1)	26.7 (1.7)	Silt loam
	30-50	52.4 (3.3)	25.7 (3.5)	21.8 (1.5)	Silt loam
	50-100	38.2 (4.1)	35.3 (2.5)	26.5 (4.8)	Clay loam
B	0-15	9.4 (4.3)	15.6 (1.7)	75.0 (5.4)	Sandy loam
	15-30	4.1 (1.0)	16.3 (1.9)	79.6 (2.9)	Sandy loam
	30-50	4.0 (1.2)	18.1 (2.8)	77.9 (3.9)	Sandy loam
	50-100	3.4 (1.3)	16.4 (2.8)	80.1 (4.1)	Sandy loam
C	0-15	8.0 (1.2)	24.3 (0.2)	67.6 (1.3)	Sandy clay loam
	15-30	7.5 (2.0)	23.7 (1.8)	68.7 (3.6)	Sandy clay loam
	30-50	8.9 (1.0)	21.2 (0.7)	70.0 (1.2)	Sandy clay loam
	50-100	13.8 (1.7)	18.3 (1.9)	67.9 (0.3)	Sandy clay loam

Table 7 above shows the mean soil textural composition as encountered in Kakum mangrove forest. Soil samples obtained had proportions of sand, loam, silt and clay. Generally, spatial variation was observed in soil texture distribution across the sampling plots while vertical variations with respect to depth were minimal or non-existent.

At sampling plot A, the vertical distribution of soil was silty-loam up to a depth of 50 cm. Depth interval of 50 cm – 100 cm was composed mainly of clayey-loam. Sampling plot B displayed a relatively uniform soil textural class with increasing depth. The main soil composition were sand and loam. Plot C also had a homogenous distribution of soil texture as depth increased with the main textural compositions being sand, clay and loam as shown in Table 7. Inherent to the foregoing observation, it is evident that mangrove soils up to 100 cm depth were heaviest in sampling plot C followed by sediments in plot B and then plot A (Table 7).

In the Amanzule mangrove forest, sediments were analysed for the mean soil texture distribution across sampling plots, as shown in Table 8. As indicated in the table, spatial variations were minimal with only sampling plot B showing variation in soil textural distribution. Textural classes were similar for plots A and C. With respect to depth, vertical variation was recorded in sampling plot B only. All other plots displayed homogenous textural class with increasing depth. The soil textural classes of plots A and C were sand, clay and loam. Sampling plot B inclined towards a more clayey soil composition with increasing depth. Therefore, mangrove soils in sampling plots A and C are expected to be heavier relative to soils from plot B.

Table 8: Soil texture distribution in the Amanzule

TSP	Depth (cm)	Silt (%) (± S.E)	Clay (%) (± S.E)	Sand (%) (± S.E)	Textural class
A	0-15	15.9 (3.0)	28.8 (0.9)	55.4 (3.9)	Sandy clay loam
	15-30	19.7 (2.0)	27.8 (3.9)	52.5 (5.0)	Sandy clay loam
	30-50	11.7 (1.7)	26.2 (0.3)	62.1 (1.6)	Sandy clay loam
	50-100	18.2 (3.8)	28.4 (3.5)	53.4 (7.0)	Sandy clay loam
B	0-15	13.5 (2.6)	29.4 (1.3)	57.0 (3.6)	Sandy clay loam
	15-30	16.4 (1.6)	37.5 (2.7)	46.1 (4.3)	Sandy clay
	30-50	25.3 (4.8)	44.2 (7.6)	30.5 (8.9)	Clay
	50-100	15.6 (2.7)	53.4 (9.1)	31.0 (11.4)	Clay
C	0-15	9.4 (2.6)	27.0 (5.2)	62.6 (7.8)	Sandy clay loam
	15-30	13.8 (4.1)	29.0 (4.2)	57.1 (8.3)	Sandy clay loam
	30-50	12.4 (5.1)	27.4 (3.6)	60.2 (8.6)	Sandy clay loam
	50-100	15.3 (3.8)	28.4 (2.9)	56.0 (6.8)	Sandy clay loam

Hydrographic Factors

Soil salinity

Kakum forest

On a spatial scale, there were very minimal variations in soil salinity among sampling plots. Relatively, plot A displayed higher salinity values. Vertically, soil salinity was relatively homogenous for sampling plots B and C at all depths as indicated by the error bars. Sampling plot A however experienced an increase from 14.6 ‰ to 23.4 ‰ across the 100 cm depth range

(Figure 17a). Thus plot A recorded the highest salinity range. Further analysis of variance conducted for all sampling plots indicated that there was no significant difference in salinity with respect to depth as well as among the various plots (Appendices 8 and 9).

Amanzule forest

Spatially, sampling plots were observed to experience distinct variation in soil salinity. Plot C recorded the highest salinity value across all depth ranges while plot B recorded the least salinity values (Figure 17b). Confirming this, ANOVA results reported a statistically significant difference in mean salinity values. Tukey's *post hoc* test further highlighted plots A and B having similar values while plot C obtained a higher value compared to the other two plots (Appendix 11B).

On the contrary, vertical variations in soil salinity were not distinct among the three sampling plots (Figure 18b), as indicated by one-way ANOVA. The figure however shows that soil salinity decreased with depth in all plots except sampling plot B (Figure 17b). Therefore among the sampling plots, plot C recorded the highest salinity range of 21.1 ‰ at the surface to 16.6 ‰ at 100 cm depth.

In comparison, Kakum forest recorded higher soil salinity values relative to the Amanzule forest. The lowest mean and highest mean salinity values for soils across the sampling plots in the Kakum forest were 11.8 ‰ and 23.4 ‰ respectively (Figure 17a). Meanwhile the lowest mean and highest mean salinity values for the Amanzule forest plots were 4.1 ‰ and 21.1 ‰ respectively (Figure 17b). Therefore soil salinity was higher in sampling plots in the Kakum forest.

Soil pH

Kakum forest

Generally, mangrove soils in this forest were acidic. On the spatial scale, there are statistically significant differences among sampling plots where plot A recorded the highest pH values, indicating low acidity levels; whereas plot B displayed higher acidity levels given its lower pH values (Figure 18a). Tukey's *post hoc* test grouped plots B and C into the same category as being more acidic while plot A was classified as being less acidic (see Appendix 7B).

Vertically, the pH in the respective sampling plots decreased with increasing depth in the Kakum forest (Figure 18a). Vertical variations in pH in plots A and B were significant. The pH values for plot A decreased from 5.6 to 3.0 while those of plot B decreased from 4.1 to 2.3. Sampling plot C showed slight decrease in pH from 3.8 to 2.9. The top 15 cm recorded pH values ranging between 3.8 to 5.7, whereas depth range of 50 cm -100 cm displayed pH ranging between 2.8 to 3.0, across the three sampling plots. In effect, pH was relatively higher at the surface as compared to deeper portions of the ecosystem. Lower portions were thus observed to be extremely acidic while acidity levels in the upper portions of the mangrove sediment ranged from moderately acidic to extremely acidic. Tukey's *post hoc* test confirmed this, classifying depth class of 50 – 100 cm to be more acidic while upper portions maintained similar acidity levels across sampling plots in the Kakum forest (Appendix 6B).

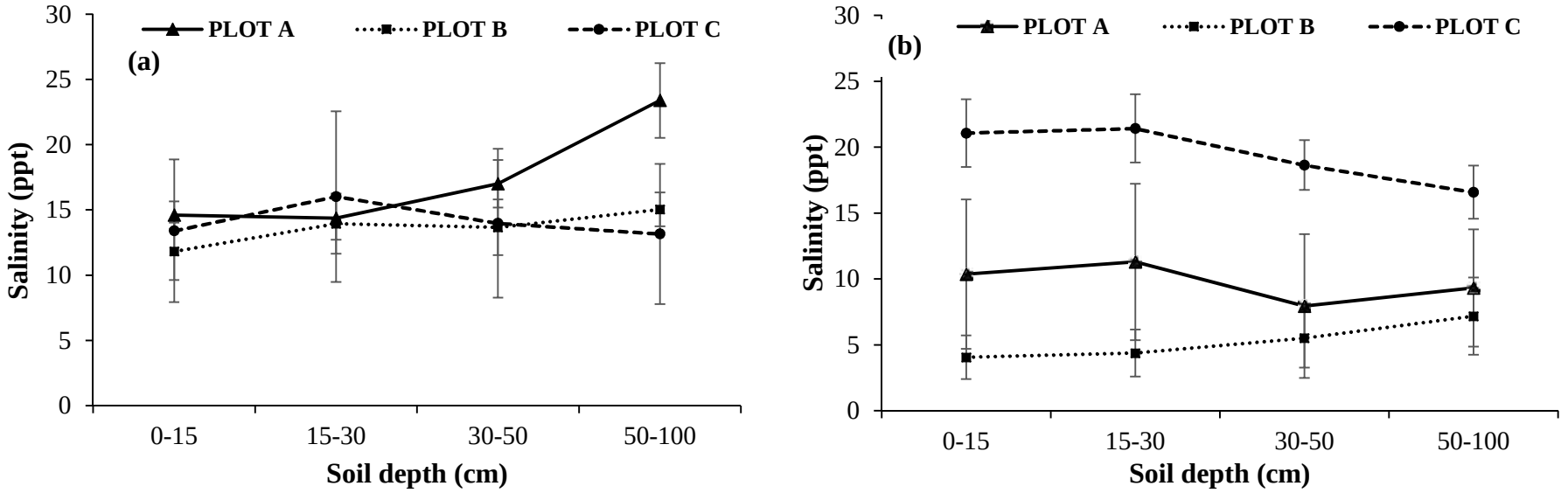

Figure 17: Variations in salinity with depth at (a) Kakum and (b) Amanzule mangrove forests (vertical bars indicate standard error of means)

Amanzule forest

In this stratum, spatial variations in pH among plots were statistically significant (Appendix 11). Plot A recorded the highest pH values while plots B and C displayed similar pH levels as indicated by the *post hoc* test (Appendix 11B).

Vertically, there were no significant differences in variations in pH (Appendix 10) in the three sampling plots. However, plot B recorded an upward trend in pH, from 2.6 to 3.2, with increasing depth (Figure 18b). Soils sampled from this forest were observed to be extremely acidic.

In general, sampling plots in the Kakum forest recorded higher pH values compared to plots in the Amanzule forest. This indicates that soils at Amanzule were more acidic relative to soils sampled from the Kakum forest. The highest pH value recorded at Kakum was 5.7 (Figure 18a) at a depth < 15 cm while Amanzule recorded 3.8 (Figure 18b) at the same depth.

Correlation Analysis of Environmental Parameters and Soil Organic Carbon (SOC) Density

Using Pearson's Moment correlation, only parameters with significant correlation coefficient ($P < 0.05$) were considered (thus $r \geq \pm 0.60$).

Table 9 shows the correlation matrix of environmental factors and SOC in plot A at the Kakum mangrove forest. Salinity and pH were negatively correlated while salinity and SOC had a strong positive correlation. Table 10 shows the correlation matrix of environmental factors and SOC in plot B at the Kakum forest. A strong negative correlation was observed between salinity and bulk density.

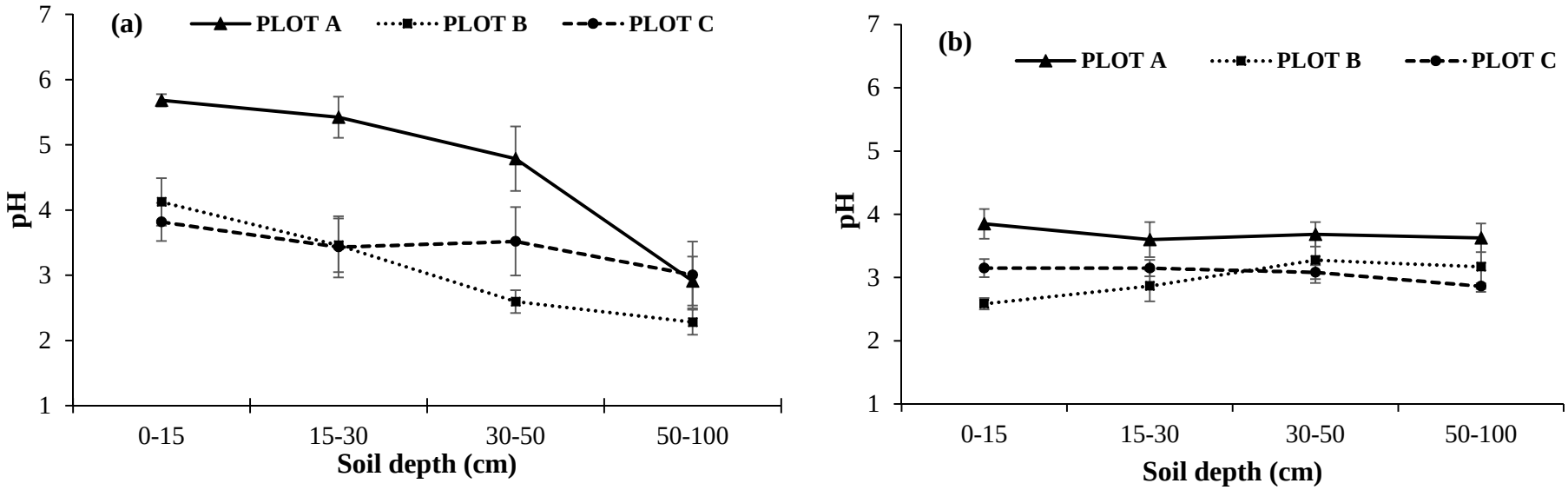

Figure 18: Variations in soil pH at (a) Kakum and (b) Amanzule mangrove forests

The correlation matrix of environmental factors and SOC in plot C at the Kakum forest is present in Table 11. A strong negative correlation was observed between salinity and bulk density.

In Table 12 correlation matrix of environmental factors and SOC for all plots at the Kakum forest is presented. It was observed that salinity and bulk density were negatively correlated across the stratum. No other parameter correlated in any way.

Table 9: Correlation matrix of environmental factors and SOC in plot A at the Kakum forest.

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	-0.68*	1		
Bulk density (g/cm^3)	-0.35	-0.09	1	
SOC (MgC/ha)	0.71*	-0.45	-0.34	1

*Significant correlation coefficient

Table 10: Correlation matrix of environmental factors and SOC in plot B at the Kakum forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	-0.31	1		
Bulk density (g/cm^3)	-0.86*	-0.08	1	
SOC (MgC/ha)	-0.05	-0.30	0.15	1

*Significant correlation coefficient

Table 11: Correlation matrix of environmental factors and SOC in plot C at the Kakum forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	0.04	1		
Bulk density (g/cm^3)	-0.79*	-0.14	1	
SOC (MgC/ha)	0.14	-0.07	0.20	1

*Significant correlation coefficient

Table 12: Correlation matrix of environmental factors and SOC for all plots in the Kakum forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	-0.09	1		
Bulk density (g/cm^3)	-0.64*	-0.39	1	
SOC (MgC/ha)	0.16	-0.29	0.19	1

*Significant correlation coefficient

Table 13 shows the correlation matrix of environmental factors and SOC in plot A at the Amanzule mangrove forest. Only salinity and bulk density had a strong negative correlation.

In Table 14, the correlation matrix of environmental factors and SOC in plot A at the Amanzule forest shows that salinity and bulk density had a strong negative correlation. It was also observed that pH and bulk density were negatively correlated.

The trend was not different in plot C as salinity and bulk density were negatively correlated based on the correlation matrix of environmental factors and SOC presented in Table 15.

Table 13: Correlation matrix of environmental factors and SOC at plot A in the Amanzule forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	-0.58	1		
Bulk density (g/cm^3)	-0.64*	0.09	1	
SOC (MgC/ha)	-0.29	0.14	0.48	1

*Significant correlation coefficient

Table 14: Correlation matrix of environmental factors and SOC at plot B in the Amanzule forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	0.46	1		
Bulk density (g/cm^3)	-0.91*	-0.60*	1	
SOC (MgC/ha)	-0.16	0.12	0.16	1

*Significant correlation coefficient

Table 15: Correlation matrix of environmental factors and SOC at plot C in the Amanzule forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	0.07	1		
Bulk density (g/cm^3)	-0.71*	-0.14	1	
SOC (MgC/ha)	-0.27	0.25	0.49	1

*Significant correlation coefficient

Table 16: Correlation matrix of environmental factors and SOC for all plots in the Amanzule forest

	Salinity (ppt)	**pH**	**Bulk density (g/cm^3)**	**SOC (MgC/ha)**
Salinity (ppt)	1			
pH	-0.17	1		
Bulk density (g/cm^3)	-0.62*	0.03	1	
SOC (MgC/ha)	-0.09	0.05	0.11	1

*Significant correlation coefficient

Conducting a comprehensive analysis for all sampling plots in the Amanzule forest as shown in Table 16 indicated that only a negative correlation existed between salinity and bulk density. None of the other factors correlated in any way.

CHAPTER FIVE

DISCUSSION

Findings of this study are discussed to primarily cover the mangrove population characteristics, mangrove biomass and carbon density, and hydrographic factors in the Kakum and Amanzule mangrove forests, and interlinked where appropriate to explain observed trends.

Mangrove carbon stock takes into consideration all existing carbon pools in a defined ecosystem. This often includes above- and below-ground carbon pools and soil carbon pool. The above-ground pool comprise all live and dead or down (fallen) mangrove trees. The below-ground pool considers tree roots. It is instructive to note that due to time and budget constraints, this study focused on only standing live or dead mangrove trees with stem sizes above 2 cm in sampling plots at both study sites.

Given the difficulty associated with data collection for carbon stock analysis, a rectangular sampling design was used in this study as opposed circular protocols recommended by Murdiyarso *et al*. (2009; Kauffman & Donato, 2012). By this procedure, trampling was reduced, accessibility was enhanced and sampling was consistent in both ecosystems irrespective of the species composition.

Mangrove Stand Characteristics

The total mangrove cover of the Kakum forest obtained from secondary data was reported to be 42.6 ha (Mensah, unpublished) whereas the Amanzule mangrove forest covered approximately 450 hectares (Mensah, 2013). A total of 2253 and 1392 individual trees were counted, identified and measured in

designated sampling plots in the Kakum and Amanzule mangrove forests respectively. Although some studies have reported the existence of six (6) mangrove species in the Kakum forest, only three species (i.e. *Rhizophora mangle*, *Avicennia germinans* and *Lagucularia racemosa*) were encountered during this study. In the Amanzule forest, a reconnaissance study confirmed the presence of *Conocarpus erectus* (a mangrove-associated species) but was not encountered in the sampling plots during this study.

Again, the existence of *R. mangle* in Ghana was confirmed during this study through a systematic identification procedure contrary to an earlier report by FAO (2007) which failed to account for the existence of the species in Ghana. The occurrence of *R. mangle* has been validated by studies such as Ellison, Farnsworth and Moore (2015). In differentiating *R. mangle* from other species in the same family, it can be observed that *R. mangle* mostly has 0–3 inflorescence joints. These are distinguished from *R. racemosa* and *R. harrisonii,* which have 3–8 inflorescence joints. For the purpose of further clarification, *R. mangle* has mature buds and flowers are located at 1–2 nodes down from the apical shoot. The case is different for *R. harrisonii,* and *R. racemosa* which have their mature buds and flowers are located at 3–5 and 7–9 nodes down from the apical shoot, respectively. The hybrid character of *R. harrisonii* is shown where it has characters intermediate between *R. racemosa* and *R. mangle* (Duke & Allen, 2006). The *Rhizophora* species encountered in both study sites conform to the above descriptions for *R. mangle* and are hence confirmed as such.

Standing dead trees in the Kakum forest were very rare and were included as live trees when present. This is because mangrove trees in this forest

were extensively harvested (see Figure 2c, 2d, 2e and 2f). It was observed that *A. germinans* dominated all sampling plots, particularly areas further from the shore or mid-portion of the estuary. This was not uncommon as different mangrove species inhabit different locations landward (Washington, Kathiresan & Bingham, 2001). In the Amanzule forest, however, a number of standing dead trees and down woods were encountered during the feasibility studies but were minimal or totally absent in sampling plots. This observation may be as a result of the rectangular sampling design used. The skipped portions of the forest was likely to contain standing dead and downed trees. *R. mangle* dominated the sampling plots in the Amanzule forest as was seen presented in Table 3.

In the Kakum forest, diversity of mangrove species was not even in the respective sampling plots. For instance plot A was highly dominated by *A. germinans* with no trees of *R. mangle* and *L. racemosa* were recorded. Conversely, plots B and C recorded all three species. The absence of *R. mangle* in sampling plot A (see Figure 1) confirms observations by McKee (1996) that *R. mangle* are commonly dominant in lower intertidal zones but not in the highest intertidal zones. On the contrary, species such as *A. germinans* displays "double distribution" and are therefore dominant in two different zones in an ecosystem (McKee, 1996). This pattern was observed in all plots in the Kakum forest and in plot B in the Amanzule forest. Tables 2 and 3 therefore show *A. germinans* and *R. mangle* as the dominant species at Kakum and Amanzule respectively. Studies have indicated that *Rhizophora* species are high value firewood in Ghana (Haruna, 2002). They are preferred for the smoking of fish because it is believed that they give the fish a better flavour. This explains the density of the species in the Kakum forest since they are substantially exploited

for fuel by the indigenous people (Aheto *et al*., 2011). Rhizophora species in the Amanzule forest did not suffer much exploitation for firewood probably because of the huge stem sizes which will require chain saw to cut, and also because of the traditional conservation status.

Findings indicate that Kakum forest was inhabited mainly by mangrove trees of low stature; what some may refer to as dwarf mangrove or mangle chaparro. It was therefore not uncommon to record mean height and mean DBH of all three species encountered to be 2.71 ± 0.01 m and 2.95 ± 0.01 cm respectively. This was contrasted by higher mean height and DBH values of 7.86 ± 0.07 and 10.58 ± 0.25 cm respectively for mangrove species in the Amanzule forest. It could therefore be deduced from the mean height values that the mangrove stand in the Kakum forest was relatively homogenous (see Figure 2a). The tree density in the Kakum forest is reflective of the open nature of the forest canopy. The trees are generally short and as such seedlings receive adequate warmth for growth. The maximum tree height of mangrove trees recorded in the Kakum forest over a decade ago by Haruna (2002) was 4.7 m. The height and diameter of trees in the Kakum mangrove forest suggest they are stunted. This is as a result of excessive logging of mangrove trees (see Figure 2d, 2e and 2f) by adjoining communities.

Furthermore, the soil type in the Cape Coast metropolis within which the forest is located explains the nature of mangrove stands. The soil type, which is classified as ochrosols, has low resistance to degradation, low nutrient levels and contain toxic concentration of aluminium as reported by Yu (1997). These conditions, in concert with high bulk density (more mineral particles), do not provide the best conditions for mangrove growth performance.

Irrespective of the presence of the three species in the Kakum forest, *A. germinans* recorded the highest relative density with corresponding total basal area. It is therefore expected that species density should influence total basal area of the species. As shown in Table 1, while disregarding the dominant species, the density of all species in Kakum forest was relatively higher compared to values recorded for species in the Amanzule forest. The foregoing observation confirms reports by McKee (1996) that areas characterized by high rainfall typically have tall canopies, high basal areas, and low tree densities. These attributes were characteristic of the Amanzule mangrove forest as shown in Tables 4 and 5, and Figure 11. In Figure 10, the diameter classes of all species determined for both locations showed Amanzule forest to be dominated by stem sizes ranging between 5 cm and 30 cm. Meanwhile, about 98 % of trees in the Kakum forest had stem sizes ranging between 2 cm and 5 cm.

Unlike the Kakum forest, the Amanzule forest is characterized by high tree canopy with little chance for the survival of seedlings. The Amanzule forest can therefore be described to comprise patches of primary and secondary mangrove stands. According to Tamooh *et al*. (2008) forest biomass is an indicator of atmospheric and soil pollution input and forest health. Inherent to this assertion, the Amanzule mangrove forest can be said to be healthier than the Kakum mangrove forest. Again, it is possible that the traditional knowledge of conservation practised by communities bordering the Amanzule forest accounts for its relatively pristine nature.

Carbon Density

The total tree biomass estimated showed that sampling plot C and A in Kakum and Amanzule forests, respectively recorded the highest values. Interestingly, plot C in the Kakum forest fringed the estuary and the Sweet River, and had a higher number of *R. mangle* and *L. racemosa* trees compared to plots A and B. Sampling plot C in the Kakum forest also recorded trees with stem sizes bigger than 3 cm as opposed to stem sizes in other plots. In the Amanzule forest, plot A fell within a basin-type forest close to the Ebi River (see Figure 1), and was inhabited by the tallest mangrove trees with larger stem sizes relative to other plots. A common feature of plots A and C in the Amanzule and Kakum forests, respectively, is drainage- either riverine in the case of Amanzule forest or estuarine in the case of Kakum forest. The conditions encountered in plot A in the Amanzule forest agree with observations by Krauss and Ball (2013) that mangroves occurring within the upper intertidal influences of rivers often flourish in seemingly fresh water conditions. In the case of the Kakum forest however, the high tree carbon density observed may be due to the high tree density of mangrove species encountered in plot C.

High carbon density is a function of high tree stature and stem sizes. Contrary to reports by Camacho *et al*. (2011), the occurrence of more trees within a defined area, as observed in the Kakum forest, does not necessarily translate into more biomass vis-à-vis higher carbon density. Tree biomass and corresponding carbon density were lower in the Kakum forest, given that majority of trees sampled had stem sizes below 3 cm, with a mean DBH of 2.95 cm (Table 4). The foregoing may be accounted for by the pressure mounted on the ecosystem by adjoining communities (i.e. Iture and Abakam). Rampant

destructive harvesting of mangrove trees for fuel wood and other subsistence uses have resulted in the occurrence of very few large trees remaining in the stand. An earlier work by Aheto *et al.* (2011) reported similar development pressure on the ecosystem. According to Kauffman and Donato (2012) tree species with stem sizes below 2.5 cm do not contain significant carbon density. The biomass and carbon density values for the Amanzule forest therefore validate the assumption that mangrove species in the Amanzule forest are more developed and as such have higher tree stature.

It is important to note that allometric equations used in estimating tree biomass are heavily dependent on the stem sizes with less focus on other parameters. On this basis, tree parameters such as height are often ignored in the development of allometric equations. Reasons are attributable to the difficulty encountered in accurate measurement of the height of trees (Kauffman & Donato 2012) in well-developed, high stature mangrove forests. This was observed particularly in the Amanzule forest which had high tree canopies. At best, height measurements were estimates.

An earlier report by Ketterings *et al*. (2001) suggested the inclusion of height variable particularly when comparing sites. However due to paucity of appropriate local allometric models which take in consideration height variable, global wood densities (see Appendix 1) obtained from Howard *et al.* (2014) were used to compensate for the height variable. This is because the inclusion of both wood density and height or either one has the tendency of reducing estimate errors. Also, as indicated by Divya *et al*. (2011), DBH alone explains more than 95 % of the variation in above-ground tropical forest carbon stocks. In the interest of generating national carbon data to feed into carbon accounting

for REDD+ it is suggested that specific wood density should be developed for local species across the country. At the time of reviewing literature for this study local information on specific wood density were not available.

In this study, general allometric equations 5 and 6 developed by Komiyama *et al*. (2005) were used to estimate above-ground and below-ground mangrove biomass, respectively. To eliminate possible biases of overestimating mangrove biomass, DBH was restricted to stem sizes ≤ 49 cm and ≤ 45 cm for above-ground and below-ground tree biomass estimation respectively. This did not affect tree biomass outcome because except for a few *R. mangle* and *A. germinans* tree species in the Amanzule forest, all trees had DBH below 50 cm.

Total tree carbon density estimated for both sites indicate that above-ground component contained more carbon compared to below-ground pool (excluding soil component) for all species. Although the total carbon density recorded by *R. mangle,* in Amanzule forest, exceeded the carbon density of all species combined in both locations, it is however difficult to propose that *R. mangle* contain higher carbon density relative to other species. This is because the coverage of species are not the same to warrant such comparison. Also, standing dead and down (fallen) trees were insignificant in number compared to the live trees. Thus they were added to make up for the live tree above-ground biomass.

Soil carbon formed an important component of this study due to the paucity of data in this area, particularly in the Kakum forest. Soil has been reported to be the largest pool of terrestrial organic carbon in the biosphere, storing more carbon than plants and the atmosphere combined (Jobbágy & Jackson, 2000). The soil organic carbon density trend displayed in Figure 15

highlights the effect of zonation on mangrove soil carbon concentration. Arguably, the figure depicts a similar trend in carbon density for both Kakum and Amanzule forests. Sampling plot B in either forest had the highest carbon density followed by in plot C. sampling plot A had the lowest carbon density in both forests.

According to Alongi (2014) mangrove carbon lost to adjacent waterways account for up to 40 % of annual primary production. Alongi's argument conforms to observation by Kristensen *et al*. (2008) in that newly-fallen mangrove litter loses 20–40 % of the organic carbon by leaching when submerged in seawater for 10–14 days. This culminates into the exportation of about 10 -11 % of particulate terrestrial carbon to the ocean. The locations and conditions of sampling plots A and C in the Kakum and Amanzule forest may have influenced to soil carbon storage and flux. In the Kakum forest, plot A had streams of water channels, mostly caused by tidal action, running through it, while plot C was drained by the Sweet River and the estuary itself. The situation in the Amanzule forest was not different as plot A was drained by the Amanzule River with large tidal incursion at high tides, while plot C fringed the Ebi River. Sampling plot B, on the other hand, had less or minimal drainage or tidal incursion in both forests. The presence of water in plots A and C may have contributed to the loss of particulate carbon as reported by Kristensen *et al*. (2008) and Alongi (2014).

In consolidating soil carbon and tree carbon densities, the Kakum forest recorded higher below-ground carbon density relative to above-ground carbon density. The reverse was observed in the Amanzule forest where above-ground

tree carbon density of 3770.9 MgC/ha was higher than below-ground (roots and soil) carbon density of 1545.6 MgC/ha.

The total soil carbon density of 352.2 MgC/ha was ten times lower compared to 3770.9 MgC/ha as carbon density for tree biomass in the Amanzule forest (Table 6). This observation for the SOC in Amanzule is consistent with views by Scharlemann, Tanner, Hiederer and Kapos (2014) that soil organic carbon is the largest component of total carbon stock, particularly in regions that are not naturally forested or have lost their natural vegetation. Evidence gathered during field survey confirm that the Amanzule forest comprised intact patches of primary and secondary forest where anthropogenic disturbance was non-existent or largely minimal in sampled plots.

Arguably, the stature of mangrove trees in the Amanzule forest influenced the high carbon density values (Figure 3a and 3b). Considering the total carbon stock estimated for the two forests, values for Amanzule forest far exceeded values for Kakum forest, thereby supporting views by Donato *et al*. (2011) that the quantity of carbon stored is primarily determined by size of stand, canopy height and stature. There were instances the DBH of mangrove trees were measured to be around 80 cm, although these were not included in biomass estimation. Assefa *et al*. (2013) reported that carbon stored in the above-ground living biomass of trees is typically the largest pool whereas below-ground carbon pool is variable. Given these reasons it is expected that, these old trees contain huge amounts of carbon as biomass.

Also, there is a high possibility that a greater pool of soil carbon in the Amanzule forest may be stored at greater depths beyond sampling range. In this study, sampling was conducted up to only one-metre depth in both locations.

Another factor may be the size of plots sampled for above-ground biomass. In each location, a total of 5400 m^2 of mangrove cover was sampled, where all trees with stem size above 2 cm counted, identified and measured. This area is the sum of a total of 54 subplots measuring 10 m^2 each which were established in the three sampling plots in each study site.

Results indicate that soil organic carbon (SOC) density was similar across the sampling plots in the Kakum forest. Since the lack of spatial variation in SOC could not be explained by spatial variations in bulk density, other factors may be responsible for this discrepancy.

Vertically variation in carbon density occurred among the sampling plots in the Kakum forest, where SOC increased with depth. However, there was no significant variation in mean carbon density below 15 cm depth as verified by Tukey's *post hoc* test. Deductions suggest that amount of carbon stored at 30 cm may be similar to carbon quantity at 100 cm depth. Also, in Amanzule, SOC did not vary with depth for all three plots. This is consistent with reports of peat and soil carbon densities sampled to one-metre depth in Indonesia by Murdiyarso *et al*. (2009). A similar study by Asante and Jengre (2012) implied the foregoing. However, studies by researchers such as Yang, Fang, Guo, Ji and Ma (2010) and Shi *et al*. (2012) in China; Kauffman and Donato (2012) in Indo-Pacific; and Patricio (2014) using agricultural soils in Philippines contradict findings in this study. The discrepancy may be due to vegetation-related conditions. Results of Patricio, particularly, showed SOC to reduce with increasing depth in a rubber plantation. Arguably, several years of carbon sequestration, devoid of intensive tillage, in the Kakum and Amanzule

mangrove forests may have stored carbon at greater depths in equal proportions, thus accounting for the lack of vertical variation.

A negative relationship exists between spatial variations in SOC and bulk density in the Amanzule forest. Plot B had the highest SOC with correspondingly low bulk density. Lack of vertical variation in SOC may be explained by the relative homogeneity of pH across depth classes in all sampling plots. This is because acidification inhibits SOC decomposition. Mangrove soils in the Amanzule forest were however found to be highly acidic at all depth classes. Soil organic carbon density was higher (352.2 MgC/ha) in Amanzule than in Kakum (310.9 MgC/ha). Besides the stature of trees, acidification may be responsible for this difference since pH was lower in the Amanzule forest than in the Kakum forest. Furthermore, the high organic matter loading in the Amanzule forest resulting in the high soil carbon density may be contributed to by the dominance of *R. mangle*. The much-branched lower ends of the stilt roots effectively trap the surface litter transported by receding tidal floods.

A post-graduate study by (Nti, 2012) in Wet Evergreen forests and agroforestry project sites in the Western region of Ghana reported tree carbon densities of 1.9 Mg ha^{-1} to 13.8 Mg ha^{-1} in pure and agroforestry plantations, respectively. This included fast growing trees like *Ceiba pentandra, Milicia excelsa, Terminalia superba and Terminalia ivorensis*. The carbon values were, however, far lower than values estimated for both Kakum and Amanzule mangrove forests. It is imperative to acknowledge that soil organic carbon values estimated in each site were higher than the IPCC estimated default value of 260 MgC/ha (Climate Investment Funds, 2012) for undisturbed tropical rainforests found in Ghana. Soil carbon stocks in the high forest zone and

savannah zone range from 110 – 340 MgC/ha and from 100 – 125 MgC/ha, respectively. In the cultivated areas within the high forest zone soil carbon stocks range from about 100 – 260 MgC/ha, while the respective estimates in the savannah zone range from 70 – 160 MgC/ha. The Climate Investment Funds further estimated the highest upland total carbon stock to be 731 MgC/ha as contained in forest reserves. These values validate several reports, including this study, that mangrove ecosystems contain higher carbon densities compared to terrestrial forest systems. This is, therefore, implicative of the carbon sequestration potential of mangrove ecosystems. Again this calls for a review in the estimated default values to allow for accurate carbon stock estimation in countries willing to participate in carbon initiatives such as REDD.

Although the sampled areas in the Amanzule forest have fairly intact mangrove vegetation, human pressure for exploitation is nonetheless evident (Figure 3c and 3d). Most degraded mangrove areas were located in more accessible areas since they were closer to settlements (Figure 3e and 3f). According to Asante and Jengre (2012) mangrove stems harvested are often small to medium sized diameters (8 – 15 cm) because the major tool for cutting was the cutlass. Active logging of mangrove trees were not encountered in the sampling plots.

Following the offshore oil drilling operations in the Western Region, a gas pipeline has been laid extending from the Tano Deepwater and West Cape Three Points development blocks through farmlands and mangrove forests in the Amanzule region. Following a stakeholders' meeting organized to discuss compensation packages for those affected by the project, it was discovered that affected persons demanded compensation for destroyed farmlands but not for

degraded portions of mangrove forests (N. B. Jengre, personal communication, February 9, 2015). The knowledge of the rights and privileges of these stakeholders inform the values individuals or communities attach to these ecosystems.

Hydrographic Factors

Salinity

The locations of sampling plots in the Kakum forest did not significantly influence variations in salinity values. The same trend was observed for changes with respect to depth. It can be deduced that tidal action is great in the estuary. Another reason may be the sampling points of soil samples, as they were located within tidal incursion catchment areas.

In the Amanzule forest, sampling plots had distinct salinity ranges. Although plot B had the least mean salinity value, it may not necessarily have influenced the high SOC recorded. Sampling plot A recorded the highest salinity range although it was located in basin-type forest, close to a river. Minimal tidal incursion and little river discharge may explain such occurrence. It can be inferred that mangrove species in this location have adapted to the prevailing conditions. As noted by McKee (1996) mangroves reach their greatest development in low-lying areas and large tidal ranges. These environments must be depositional with low wave energy. The foregoing explains the mangrove stature and the corresponding diameter classes, biomass and carbon density encountered in sampling plot A in the Amanzule forest. In effect salinity regimes did not significantly influence carbon density in both forests.

Soil pH

According to Fitzpatrick (1986), pH for soils ranges from 3 to 9. However, very low pH values are associated with drained coastal marshes and swamps which contain oxidised pyrite, thus forming sulphuric acid. Alternatively, extremely high pH values ranging from 7.4 to 8.2 (Schumacher, 2002) result from the presence of sodium carbonate, Nonetheless large amounts of organic matter induce acidity.

Soils sampled for the determination of pH were free of carbonates because pH values across sampling plots on both locations were lower than 7.4. A possible reason accounting for this observation may be the depth at which soils were sampled. Carbonates are characteristic of mineral soils which are often located at depths beyond one metre, particularly in mangrove ecosystems. The low pH values are attributable to oxidation of sulphides in the mangrove soils, particularly during low tides. Consequent formation of sulphuric acids could result in the high acidity of mangrove soils (Anim-Kwapong & Frimpong, 2008).

The trend of pH values shown in Figure 18 indicates that soils sampled from Amanzule forest were more acidic compared to soils sampled from the Kakum mangrove forest. Amanzule displayed no distinct vertical variations in pH. Similar concentration of organic matter at all depth classes explains this trend. Thus, mean carbon density in the Amanzule forest did not significantly increase with depth. A weak negative relationship exists between pH and SOC in Kakum forest. The decrease in pH with depth is explained by the increase in SOC with depth. According to Shi *et al*. (2012) acidification inhibits SOC decomposition which tends to reduce loss of carbon at lower depths. This is

consistent with findings by Asante and Jengre (2012) in the Ankobra and Amanzule wetlands in Ghana. The pH ranges recorded for Amanzule were similar to those observed by Asante and Jengre (2012).

The high acidity recorded in the Amanzule forest compared to low acidity levels in the Kakum forest could therefore be due to the fact that the soils in Amanzule are forest oxysols, which are inherently acidic. For instance, Sackey *et al*. (1993 cited in Haruna, 2002) reported a low pH of 3.5 for mangrove soils at Takoradi. However, decomposition and mineralisation of organic materials in the top 15 cm in Amanzule mangrove soils could have reduced the acidity, resulting in the higher pH values in the top 15 cm.

Since most of the potential acidity of soils is due to hydrogen ions held on the clay and organic particles, fine-textured soils which are high in clay and organic matter, such as those found in Amanzule, are expected to have a higher total acidity than sandy soils of low clay and organic content (Allaway, 1957). Ideally, soil with extremely low pH such as the one found in Amanzule may be detrimental to plant growth. The solubility and availability to plants of many important nutrients is closely related to the pH of the soil. According to Tisdale, Nelson, Beaton and Havlin (1993), at a low pH, beneficial elements such as molybdenum (Mo), phosphorus (P), magnesium (Mg) and calcium (Ca) become less available to plants. Other elements such as aluminium (Al), iron (Fe) and manganese (Mn) may become more available and Al and Mn may reach levels that are toxic to plants. However within the pH of 3 – 4, exchangeable iron and aluminium phosphates have minimum solubility (Brady, 1990), thereby making phosphorus less available to plants due to complexation reaction with phosphate ions.

Joshi and Ghose (2003) confirmed that Al toxicity is the most important growth-limiting factor in many acid soils, such as the Amanzule soils, which have pH < 5.0. Excess Al interferes with cell division in plant roots, decreases root respiration and interferes with uptake, transport and use of nutrients and water by plants As such mangrove trees in the Amanzule forest are expected not to attain the high stature observed. This deviation is explained by the fact that mangroves are species that tolerate wide ranges of pH. This is evident in the dominance exhibited by *R. mangle* in the Amanzule forest.

According to McKee, Mendelssohn and Hester (1988) concentrations of hydrogen sulphide accumulate under reduced conditions leading to a build-up of other metallic sulphides in the soil. This can be observed in the darker colouration of soils found in old mangrove stands. However, aerial stilt roots of *Rhizophora* species have the ability to oxidize the hydrogen sulphide around them, thereby resulting in high acidic soils.

Although the correlation matrix revealed no strong correlation between pH and SOC in the respective plots, there was negative correlation in all plots in Kakum (see Table 12) while plots in Amanzule correlated positively (see Table 16). This means pH influenced increase in mean SOC with depth in the Kakum forest. However, the naturally acidic condition of soils in Amanzule did not affect the carbon density as SOC did not increase significantly with depth. Decomposition of organic residues and root respiration increases CO_2 in soil air (Tisdale *et al*., 1993). Since mangrove systems contain enormous amount of organic carbon, CO_2 concentration is expected to be higher than any upland forest.

Soil Bulk Density and Texture Dynamics

Bulk density is influenced by the dominant soil textural composition (i.e. sand, silt and clay). Bulk density varies from about 2.65 g/cm^3 for mineral particles to 0.2 g/cm^3 for organic matter (Fitzpatrick, 1986). It is however possible that a loose porous soil will have smaller bulk density than a compact soil even though the density of individual particles in both soils may be the same. It is important to determine the textural class of mangrove soils because species composition and growth of mangroves are directly affected by the physical composition of mangrove soils (Kristensen, 2007). It is therefore common to find riverine and basin type mangrove forests usually rich in organic matter, and composed largely of silt and clay, whereas more exposed fringe and over-wash forests typically have organic-poor sediments with higher sand content. Accordingly, Kettler *et al*. (2001) observed that soil textural composition dictates soil-water retention characteristics, leaching and erosion potential, plant nutrient storage, organic-matter dynamics, and carbon sequestration capability.

The bulk density range of 0.56 – 1.28 g/cm^3 and 0.29 – 0.77 g/cm^3 for Kakum and Amanzule respectively falls within the ambits of bulk density for organic soils. It can therefore be postulated that Kakum forest contained more mineral particles compared to Amanzule forest. According to USDA (2008) high bulk density is an indication of low soil porosity and soil compaction; it may cause restrictions in root growth, and poor movement of air and water through the soil. This may be a factor contributing to the stature of mangrove trees observed in the Kakum forest.

The spatial variation in bulk density in Kakum (Figure 15a) may be as a result of the location of the sampling plots. Plots B and C were closer to the

estuary and as such experienced heavy deposition of sand particles. This is confirmed by the textural class analysis, where plots B and C were composed of sandy loam and sandy clay loam respectively (Table 8). The high sand content in plots B and C may be due to sand particles brought in by tidal action. Sampling plot A, on the other hand, was located in a basin-type forest, close to Kakum River (see Figure 1) and contained only silt loam as textural class. This follows arguments by Kristensen (2007) in that more exposed fringe and over-wash forests typically have organic-poor sediments with higher sand content. Soil textural classes recorded in the Kakum forest corroborate earlier studies by Haruna (2002) where particle size composition was mainly sandy loam.

In Amanzule, an isolated case of spatial variation in bulk density was observed in plot B which was located in a coastal fringe-type forest. The variation in bulk density is explained by the dominant clay particles recorded from 15 – 100 cm beneath the surface. Plots A and C had sandy clay loam as dominant textural classes.

The increase in bulk density with increasing depth in Amanzule is consistent with reports by Donato *et al.* (2011) in the Indo-pacific and Asante and Jengre (2012) in Ankobra-Amanzule wetlands in Ghana. The deviation observed in sampling plot B where bulk density decreased with depth is an indication of the presence of higher organic matter at lower depths. Therefore plot B recorded relatively low bulk density when spatial analysis was conducted for all plots. Accordingly, soil organic carbon was highest at plot B (Figure 14b). Sampling plots A and C had higher bulk density values of similar magnitude since they had sandy clay loam as dominant textural classes.

Results of correlation between bulk density and soil carbon density did not conform to findings by Asante and Jengre (2012) in the Ankobra and Amanzule wetlands where a strong positive correlation existed between the two variables. Contrary to studies in 12 permanent sites in Europe by Schrumpf *et al*. (2011) where bulk density correlated negatively with soil organic carbon, correlation matrix from this study shows that bulk density had a weak positive correlation with SOC. This observation is accounted for by dominant textural class of sampled soils at pre-defined and sampling plots. Soil texture distribution generally lacked vertical variation in both Kakum and Amanzule forests (Tables 7 and 8). Since bulk density is influenced by the dominant soil textural composition (i.e. sand, silt and clay) of any soil sample, this was reflected in the bulk density determination as there was no significant increase with depth (Figure 16).

Furthermore, considering the weight (about 0.05 g) of soil used in determining percentage organic carbon (Equation 3) soil mass used may contain high amount of organic matter which may not be a true reflection of the soil sample used in determining bulk density. However, on plot-basis, there exists a negative correlation between bulk density and SOC for soils in the Amanzule forest (Figures 8 and 10).

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

This study sought to undertake carbon stock assessments in the Kakum and Amanzule mangrove forest systems of Ghana in order to evaluate the impact of environmental degradation on the ecosystems. To achieve the foregoing, mangrove population parameters and total biomass of the mangrove trees of both forests were estimated leading to the derivation of carbon density estimation of both ecosystems. Soil particle size distribution in relation to carbon density in both locations was determined while the implications of hydrographic factors (i.e. salinity and pH) on carbon density were also assessed. Finally, the relationship between soil bulk density and particle size distribution was assessed. Allometric equations were used to estimate tree carbon density while soil carbon was estimated using dichromate oxidation technique.

Despite the existence of seven mangrove species (true and associated species) in Ghana, only three species were encountered in the designated sampling plots in both Kakum and Amanzule mangrove forests. These three species include *Rhizophora mangle*, *Avicennia germinans* and *Lagucularia racemosa*.

The height and DBH of mangrove trees in Amanzule were greater than those measured in the Kakum forest although tree density was higher in the Kakum forest. The mean height and DBH of mangrove species in the Kakum forest imply the existence of homogeneity in the mangrove system. Kakum forest comprise mainly dwarf mangrove stands while the Amanzule is a mosaic of primary and secondary mangrove stands.

In comparison, Kakum forest recorded higher soil salinity values relative to the Amanzule forest. The location of sampling plots in Kakum did not significantly influence variations in salinity values. The same trend was observed for salinity differences with respect to depth. Spatial variations were experienced in the Amanzule forest but vertical salinity variations were insignificant. In effect, salinity regimes did not significantly influence carbon density in both ecosystems. In a correlation analysis, salinity and bulk density had significant negative relationship in both Kakum and Amanzule mangrove forests.

Soils sampled from both Kakum and Amanzule mangrove forest did not contain carbonates because pH values remained lower than the standard range of 7.4 to 8.2, which indicates the presence of carbonates in any soil. However, pH values were lower for Amanzule than for Kakum, indicating higher acidity levels in the Amanzule forest soils. This is characteristic of the high organic matter content and the forest oxysols – ochrosols intergrade dominating the Amanzule forest.

Bulk density values of mangrove soils indicated that soil samples from Kakum forest contained more mineral particles and were therefore heavier than the soils sampled from the Amanzule forest. It was however difficult to estimate soil textural class for the entire ecosystem. Nonetheless, bulk density and textural class in respective plots do correlate positively.

Below-ground carbon density (roots and soil) in the Kakum forest was higher than above-ground carbon density. The reverse occurred in the Amanzule forest where above-ground carbon pool was higher than below-ground pool. Factors accounting for this may include the stature of mangrove trees in the

ecosystem which influenced the high carbon density values. This particular finding in the Amanzule mangrove forest oppose reports by Asante and Jengre (2012) where below-ground carbon was higher than above-ground carbon density.

Analysis for only soil organic carbon showed that Amanzule forest had higher carbon density than the Kakum forest. On plot-basis, sampling plot B in both forest contained more soil organic carbon compared to the other plots.

Conclusions

Total carbon stocks for Kakum and Amanzule mangrove forests were above the IPCC estimated default values of 260 MgC/ha for undisturbed tropical rainforest such as those found in Ghana. This confirms the high carbon sequestration potential of mangrove ecosystems.

At the time of this study, there were no available conservation measures in place for the Kakum forest. On the other hand, the mangrove forest in Amanzule is traditionally protected, where inhabitants are prohibited from cutting mangroves in the area. There is however laxity in the conservation status in the Kakum forest where individuals are banned from cutting mangrove trees only on Tuesdays.

The study highlights the fact that non-degraded mangrove forests provide valuable service in capturing carbon and therefore their destruction has negative implications on their carbon sequestration capacity. This is because in degraded forests, stored carbon is released and contributes to increasing levels of greenhouse gases in the atmosphere. As a result, degraded coastal ecosystems such as mangroves are converted from being net carbon sinks to net carbon sources. For instance, the results suggest that above-ground biomass is an

important factor for attaining significantly high carbon stock from mangrove forests. Thus, non-degraded Amanzule mangrove forests contained about ten times more carbon pools compared to the degraded Kakum mangrove forests. This observation points to the serious effect of logging as an environmental disturbance on the overall carbon stock density and ecosystem health of mangrove forests.

Therefore, carbon offsets based on the protection and restoration of mangroves could be far more cost effective than current approaches focused on other trees. This situation brings enormous ad-on benefits to fisheries and potentially limit coastal erosion through the conservation of blue carbon.

The study has revealed that mangroves store an enormous amount of carbon and therefore carbon sequestration is a significant incentive to be accrued from non-degraded mangrove systems which could provide added benefits to the REDD+ strategy for Ghana only if there can be policy review to include mangrove and swamp forest habitats in the forest definition in Ghana. Policy review is necessary because presently, mangrove systems are excluded from the gazetted forest reserves in the country despite facing threats of degradation arising from agriculture, population and the development of the coastal environment.

Recommendations

Based on the findings and challenges arising from this study the following recommendations are made:

It is important that a carbon stock change evaluation be undertaken by establishing permanent plots, particularly in the Amanzule mangrove forest. This is because the extensive nature of mangrove stands in this ecosystem holds

the potential to contribute to REDD+ policies on carbon accounting. Again, it is important that conservation measures for the Kakum mangrove forest be strengthened given its role as a mangrove biodiversity hotspot.

It is further recommended that a nation-wide carbon accounting in mangrove forests should be vigorously carried out. Therefore, further research could be carried out nation-wide to estimate mangrove forest structure, composition and fragmentation. This will require a review of policy to include mangrove ecosystems in the forest definition of gazetted areas for REDD+ initiatives.

There is also the need to develop local allometric models which take into account below-ground mangrove biomass, as well as development of specific wood density for local species across the country.

Embarking on district-level campaigns for extensive mangrove afforestation projects, including aspects of seedling regeneration, in the affected areas should be prioritized. At community levels where adequate sivilculture practices can not be proven, a complete ban on mangrove wood harvesting should be legislated.

It is recommended that proper land use planning and re-zoning of the mangrove ecosystems be done in collaboration with chiefs, district assemblies and other interest groups. In this regard, local traditional authorities should be encouraged to introduce regulations regarding the use of the mangrove forests since there are no known or defined laws to this effect.

To achieve the overarching goal of high carbon storage, it is imperative to create incentives to encourage stakeholders to conserve carbon in the same landscapes in which they are entitled to exploit timber. This, therefore,

necessitates further research to explore the potential for sustainable exploitation of the mangrove trees. This can be done by investigating user profiles in line with deforestation and forest degradation. The introduction of additional livelihood options for rural coastal communities is strongly recommended.

Furthermore, emission reduction from deforestation must be simultaneous with efforts to increase yields in non-forested lands to satisfy demands for agricultural products. Therefore, policies aimed at agricultural production should be intensified by providing greater yields per hectare and avoiding substantial land-use changes.

On a broader scope, there is the need to assess the feasibility of introducing “closed areas” in mangrove ecosystems across the country. This may form the basis for the gazetting and legally enforcing the conservation of these threatened ecosystems.

There is also the urgent need to reinforce knowledge and understanding surrounding mangrove benefits to local communities and policy makers alike by strengthening country or regional networks of mangrove conservation practitioners, strengthen dialogues on policy, research and practice around mangroves and climate change issues as well as take lessons from sustainable management projects in mangroves.

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APPENDICES

Appendix 1: Global average wood density of mangrove species

Species	Average wood density (± S.E)
R. mangle	0.87± 0.04
A. germinans	0.72 ± 0.01
L. racemosa	0.60 ± 0.02

Appendix 2: One-way ANOVA for mean soil carbon density with respect to depth for Kakum mangrove forest

Source	DF	SS	MS	F	P
Treatment	3	1129	376	3.41	0.022
Error	68	7510	110		
Total	71	8639			

2B: Tukey's HSD Post hoc test for mean carbon density at Kakum mangrove forest

Depth	Carbon Density
0-15	20.61^{b}
15-30	23.66^{a}
30-50	28.91^{a}
50-100	30.44^{a}

Similar exponent indicate no significance

Appendix 3: One-way ANOVA for mean soil carbon density with respect to sampling plots for Kakum mangrove forest

Source	DF	SS	MS	F	P
Treatment	2	210	105	0.86	0.427
Error	69	8428	122		
Total	71	8639			

Appendix 4: One-way ANOVA for mean soil carbon density with respect to depth for Amanzule mangrove forest

Source	DF	SS	MS	F	P
Treatment	3	227	76	0.37	0.776
Error	68	13969	205		
Total	71	14196			

Appendix 5: One-way ANOVA for mean soil carbon density with respect to sampling plots for Amanzule mangrove forest

Source	DF	SS	MS	F	P
Treatment	2	3770	1885	12.48	0.000
Error	69	10426	151		
Total	71	14196			

5B: Tukey's HSD Post hoc test for mean carbon density at Amanzule mangrove forest

Plot	Carbon Density
A	21.25^{c}
C	27.99^{b}
B	38.81^{a}

Appendix 6: One-way ANOVA for mean pH with respect to depth at Kakum forest

Source	DF	SS	MS	F	P
Treatment	3	32.47	10.82	7.74	0.000
Error	68	95.14	1.40		
Total	71	127.60			

6B: Tukey's HSD Post hoc test for mean pH at Kakum forest

Depth	pH
0-15	4.54[a]
15-30	4.11[a]
30-50	3.64[a]
50-100	2.73[b]

Similar exponent indicate no significance

Appendix 7: One-way ANOVA for mean pH with respect to sampling plots for Kakum forest

Source	DF	SS	MS	F	P
Treatment	2	33.60	16.80	12.33	0.000
Error	69	94.00	1.36		
Total	71	127.60			

7B: Tukey's HSD Post hoc test for mean pH with respect to sampling plots at Kakum forest

Plot	pH
A	4.70[a]
B	3.12[b]
C	3.45[b]

Similar exponent indicate no significance

Appendix 8: One-way ANOVA for mean salinity with respect to depth for Kakum forest

Source	DF	SS	MS	F	P
Treatment	3	141.8	47.3	0.77	0.512
Error	68	4148.4	61.0		
Total	71	4290			

Appendix 9: One-way ANOVA for mean salinity with respect to sampling plots for Kakum forest

Source	DF	SS	MS	F	P
Treatment	2	195.3	97.6	1.65	0.200
Error	69	4094.9	59.3		
Total	71	4290.2			

Appendix 10: One-way ANOVA for mean pH with respect to depth at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	3	0.276	0.092	0.22	0.881
Error	68	28.255	0.416		
Total	71	28.532			

Appendix 11: One-way ANOVA for mean pH with respect to sampling plots at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	2	7.276	3.638	11.81	0.000
Error	69	21.256	0.308		
Total	71	28.532			

11B: Tukey's HSD Post hoc test for mean pH with respect to sampling plots at Amanzule forest

Plot	pH
C	3.70[a]
A	3.10[b]
B	3.0[b]

Similar exponent indicate no significance

Appendix 12: One-way ANOVA for mean salinity with respect to depth at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	3	13.9	4.6	0.05	0.986
Error	68	6650.5	97.8		
Total	71	6664.5			

Appendix 13: One-way ANOVA for mean salinity with respect to sampling plots at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	2	1821.3	910.6	12.97	0.000
Error	69	4843.2	70.2		
Total	71	6664.5			

13B: Tukey's HSD Post hoc test for mean salinity with respect to sampling plots at Amanzule forest

Plot	Salinity
B	21.16[a]
A	19.44[a]
C	9.73[b]

Similar exponent indicate no significance

Appendix 14: One-way ANOVA for bulk density with respect to depth at Kakum forest

Source	DF	SS	MS	F	P
Treatment	3	0.269	0.090	0.54	0.654
Error	68	11.188	0.165		
Total	71	11.456			

Appendix 15: One-way ANOVA for bulk density with respect to sampling plots at Kakum forest

Source	DF	SS	MS	F	P
Treatment	2	4.7929	2.3964	24.82	0.000
Error	69	6.6633	0.0966		
Total	71	11.4562			

15B: Tukey's HSD Post hoc test for bulk density with respect to sampling plots at Kakum forest

Plot	Bulk density
A	0.62^{c}
C	1.06^{b}
B	1.24^{a}

Appendix 16: One-way ANOVA for bulk density with respect to depth at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	3	0.3543	0.1181	1.68	0.180
Error	68	4.7885	0.0704		
Total	71	5.1428			

Appendix 17: One-way ANOVA for bulk density with respect to sampling plots at Amanzule forest

Source	DF	SS	MS	F	P
Treatment	2	1.0946	0.5473	9.33	0.000
Error	69	4.0481	0.0587		
Total	71	5.1428			

17B: Tukey's HSD Post hoc test for bulk density with respect to sampling plots at Amanzule forest

Plot	Bulk density
A	0.59^{a}
C	0.59^{a}
B	0.33^{b}

Similar exponent indicate no significance

Appendix 18: One-way ANOVA for mean height of mangrove species at Kakum forest

Source	DF	SS	MS	F	P
Treatment	2	42.5	21.3	70.7	0.000
Error	2250	676.5	0.3		
Total	2252	719.0			

Appendix 19: One-way ANOVA for mean DBH of mangrove species at Kakum forest

Source	DF	SS	MS	F	P
Treatment	2	9.3	4.7	7.5	0.001
Error	2250	1404.6	0.6		
Total	2252	1413.9			

Appendix 20: Levene's test for Homogeneity of Variances for mean height of mangrove species in Kakum forest

Levene Statistic	df1	df2	Sig.
3.518	2	2250	.030

Multiple Comparisons

(I) Mangrove Species	(J) Mangrove Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval
					Lower Bound
Rhizophora	*Avicennia*	.145*	.053	.023	.02
	Laguncularia	.631*	.070	.000	.46
Avicennia	*Rhizophora*	-.145*	.053	.023	-.27
	Laguncularia	.486*	.048	.000	.37
Laguncularia	*Rhizophora*	-.631*	.070	.000	-.80
	Avicennia	-.486*	.048	.000	-.60

* The mean difference is significant at the 0.05 level.

Appendix 21: Levene's test for Homogeneity of Variances for mean DBH of mangrove species in Kakum forest

Levene Statistic	df1	df2	Sig.
5.544	2	2250	.004

Multiple Comparisons

(I) Mangrove Species	(J) Mangrove Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval
					Lower Bound
Rhizophora	*Avicennia*	-.031	.067	.954	-.19
	Laguncularia	.207*	.081	.032	.01
Avicennia	*Rhizophora*	.031	.067	.954	-.13
	Laguncularia	.238*	.052	.000	.11
Laguncularia	*Rhizophora*	-.207*	.081	.032	-.40
	Avicennia	-.238*	.052	.000	-.36

* The mean difference is significant at the 0.05 level.

Appendix 22: One-way ANOVA for mean height of mangrove species in Amanzule forest

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1184.153	2	592.077	91.921	.000
Within Groups	8946.796	1389	6.441		
Total	10130.949	1391			

Appendix 23: Levene's test for Homogeneity of Variances for mean height of mangrove species in Kakum forest

Levene Statistic	df1	df2	Sig.
10.161	2	1389	.000

Multiple Comparisons

(I) Mangrove Species	(J) Mangrove Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval
					Lower Bound
Rhizophora	*Avicennia*	2.459*	.157	.000	2.08
	Laguncularia	4.578*	.184	.000	4.09
Avicennia	*Rhizophora*	-2.459*	.157	.000	-2.84
	Laguncularia	2.119*	.217	.000	1.57
Laguncularia	*Rhizophora*	-4.578*	.184	.000	-5.06
	Avicennia	-2.119*	.217	.000	-2.66

Appendix 24: One-way ANOVA for mean DBH of mangrove species in Amanzule forest

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2014.707	2	1007.354	11.314	.000
Within Groups	123671.827	1389	89.037		
Total	125686.534	1391			

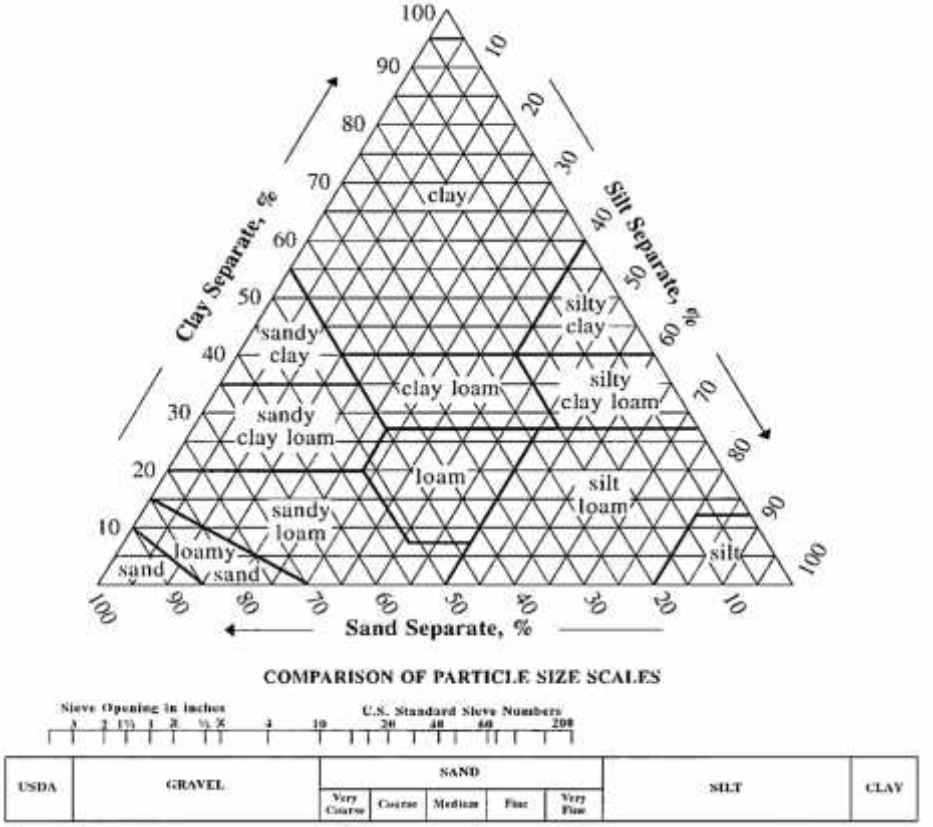
Appendix 25: Levene's test for Homogeneity of Variances for mean DBH of mangrove species in Amanzule forest

Levene Statistic	df1	df2	Sig.
10.860	2	1389	.000

Multiple Comparisons

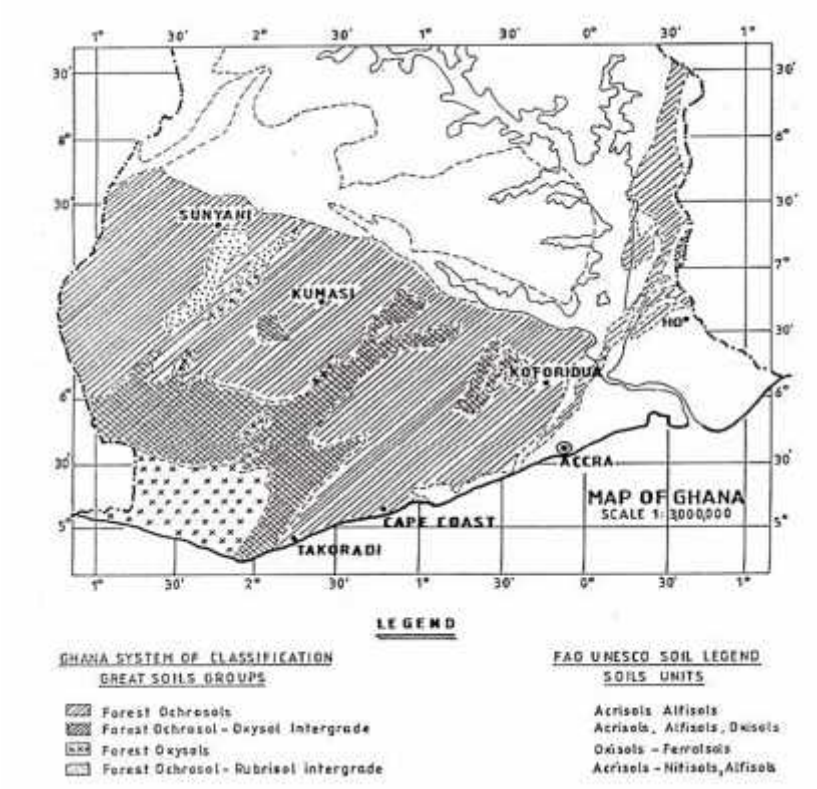
(I) Mangrove Species	(J) Mangrove Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval
					Lower Bound
Rhizophora	*Avicennia*	3.057*	.540	.000	1.76
	Laguncularia	6.907*	.381	.000	5.97
Avicennia	*Rhizophora*	-3.057*	.540	.000	-4.35
	Laguncularia	3.850*	.523	.000	2.59
Laguncularia	*Rhizophora*	-6.907*	.381	.000	-7.84
	Avicennia	-3.850*	.523	.000	-5.11

Appendix 26: USDA soil texture classification scheme



Source: (USDA, 2008)

Appendix 27: Soil classification in southern Ghana, including the study areas



Source: (Anim-Kwapong & Frimpong, 2008)