# CARBON SEQUESTRATION IN MANGROVE FOREST OF GREAT KWA RIVER, CALABAR AND RAINFOREST OF CROSS RIVER NATIONAL PARK (OBAN DIVISION) AKAMKPA, CROSS RIVER STATE, NIGERIA

BY


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## CERTIFICATION

This is to certify that this thesis titled **"Carbon sequestration in mangrove forest of Great Kwa river, Calabar and rainforest of Cross River National Park (Oban Division) Akamkpa, Cross River State, Nigeria"** and carried out by Ononyume, Martin Ogheneriruona with Reg. Number: BOT/Ph.D/15/008 has been examined and found worthy of the award of the degree of Doctor of Philosophy (Ph.D) in Plant Ecology.

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## DECLARATION

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## ABSTRACT

The high carbon density of tropical forests is increasingly viewed as an avenue for mitigation of climate change. The carbon sequestration potential of the mangrove forest of Great Kwa River, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa was investigated. General allometric equations for moist forests was used to estimate aboveground and belowground biomass. Planar intersect method was used to determine dead and downed wood biomass. Canopy closure was estimated using a spherical densiometer. Soil bulk density was determined by the intact core method and soil total carbon and nitrogen was determined by dry combustion method. Analysis of variance showed that canopy closure, total soil carbon and nitrogen, and carbon/nitrogen ratios within transects sampled in both forests were not statistically different. Total aboveground and belowground biomass and carbon stocks within both forests varied significantly (P = 0.05) between the transects. In the mangrove, total carbon stock density was 423.31 Mg C $ha^{-1}$. Total carbon in soil ranked highest in constituting the total carbon stock density with 89.79 %, followed by aboveground biomass with 8.43 %, belowground biomass 1.68 %, and dead and downed wood biomass with 0.07 %. In the rainforest, total ecosystem carbon stock estimate was 226.65 Mg C $ha^{-1}$. Aboveground biomass ranked highest, constituting 50.35 %, followed by total carbon in soil with 39.38 %, belowground biomass, 10.06 % and dead and downed wood with 0.18 %. Dead and downed wood carbon stock and soil bulk density varied significantly (P = 0.05) within both forests between the different size classes and depths investigated respectively. Two-sample Students t-test results revealed that mean canopy closure was significantly higher (P = 0.001) in the rainforest 88.83±1.06 % than the mangrove 24.11±4.62 %. Mean aboveground biomass and carbon stock, and belowground biomass and carbon stock were significantly higher ($P = 0.001$) in the rainforest 242.82±195.79 t ha$^{-1}$; 114.12±92.02 Mg C ha$^{-1}$ and 48.55±39.16 t ha$^{-1}$; 22.82±18.40 Mg C ha$^{-1}$ respectively, than the mangrove 76.08±22.40 t ha$^{-1}$; 35.71±10.49 Mg C ha$^{-1}$ and 15.21±4.48 t ha$^{-1}$; 7.13±2.09 Mg C ha$^{-1}$ respectively. Conversely, mean total soil carbon, 380.13±41.09 Mg C ha$^{-1}$, and nitrogen, 18.55±1.99 Mg N ha$^{-1}$ stocks and carbon/nitrogen ratio, 20.48±0.27:1 in the mangrove was significantly higher ($P = 0.001$) than that of the rainforest 89.27±10.84 Mg C ha$^{-1}$, 6.91±0.77 Mg N ha$^{-1}$ and 12.08±0.58:1 respectively. At the landscape scale, the mangrove and rainforest show potential of storing up to an estimated 82.54 million Mg and 67.99 million Mg of carbon respectively. This study has presented an assessment of the carbon stocks in the mangrove and rainforest in Cross River State and their potential to mitigate climate change. Also, these potentials could be exploited in the context of accrued benefits from carbon credits within the framework of REDD+ (Reducing emissions from deforestation and forest degradation, role of conservation, sustainable management of forests and enhancement of forest carbon stocks) and other marketing mechanisms.

**(Word count: 483)**

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AGB | - | aboveground biomass |
| BGB | - | belowground biomass |
| $CO_2$ | - | Carbon dioxide |
| COP | - | Conference of the Parties |
| CRNP | - | Cross River National Park |
| DBH | - | Diameter at breast height |
| $eCO_2$ | - | Carbon dioxide equivalent |
| EIA | - | Environmental Impact Assessment |
| ENSO | - | El-Nino Southern Oscillation |
| FAO | - | Food and Agricultural Organization |
| GHG | - | Greenhouse gas |
| Gt | - | gigatonnes |
| ha | - | hectare |
| IPCC | - | Intergovernmental Panel on Climate Change |
| K | - | kilo |
| LUA | - | Land Use Act |
| m | - | metre |
| Mg | - | megagram |
| mm | - | millimetre |
| NGHGI | - | National greenhouse gas inventory |
| NGO | - | Non-governmental Organization |
| NP | - | National Parks |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Statement of the problem

Global climate change is a widespread and growing concern that has led to extensive international discussions and negotiations (IPCC, 2001; Gorte, 2009). Responses to this concern have focused on reducing emissions of greenhouse gases, especially carbon dioxide ($CO_2$), and on valuing carbon absorbed by and stored in forests, soils, and water (FAO, 2011). Multiple studies published in peer-reviewed scientific journals show that 97 per cent or more of actively publishing climate scientists agree that climate-warming trends over the past century are extremely likely to be due to human activities (Ackerman *et al.*, 2013). The 2013 and 2014 reports of the Intergovernmental Panel on Climate Change (IPCC) clearly attribute the majority of recently observed global climate change to human-made greenhouse gas emissions. The IPCC projects a temperature increase by year 2100 of between 1.5 °C and 4.8 °C, relative to pre-industrial levels. The concentration of carbon dioxide ($CO_2$) in the atmosphere has increased from approximately 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), the beginning of the Industrial Era, to 402.8 ppm in 2016 (Dlugokencky and Tans, 2016). The atmospheric $CO_2$ increase above preindustrial levels was, initially, primarily caused by the release of carbon to the atmosphere from deforestation and other land-use change activities (Ciais *et al.*, 2013), while emissions from fossil fuels started before the industrial era, they only became the dominant source of anthropogenic emissions to the atmosphere from around the year 1920 and their relative share has continued to increase until present. Impacts of climate change have already begun to affect climate patterns. These effects range in scope from melting polar ice to rising sea levels, from collapse of marine ecosystems to increasingly severe water stress in large parts of the world, from changing weather patterns accompanied by more frequent and more violent climatic episodes (hurricanes, floods, droughts) to wider spreading of pathogens and diseases. The World Health Organization (WHO, 2016) has estimated that more than 140, 000 people per year are already dying as a direct result of climate change, primarily in Africa and Southeast Asia. The Intergovernmental Panel on Climate Change estimates that, by the year 2050, global $CO_2$ emissions must be reduced by 85 per cent from levels seen in 2000 to prevent a global mean temperature increase of 2 °C (McLeod *et al*., 2011). This calculation assumes that the reduction in emissions is the only mechanism by which we can reduce $CO_2$ concentrations. A more recent approach suggests refocusing efforts from a single emissions reduction strategy to a plan that combines reducing anthropogenic sources of $CO_2$ (mitigation) with supporting $CO_2$ uptake and storage through the conservation of natural ecosystems with high C sequestration rates and capacity (Canadell and Raupach, 2008).

## 1.2 Background to the study

Carbon sequestration is used to describe both natural and deliberate processes by which $CO_2$ is either removed from the atmosphere or diverted from emission sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediments), and geologic formations (Sundquist *et al*., 2008). Carbon sequestration in growing forests is known to be a cost-effective option for mitigation of global warming and global climatic change. Trees play an important role in the reduction of carbon dioxide from the atmosphere by carbon sequestration. Active absorption of $CO_2$ from the atmosphere through the process of photosynthesis and its subsequent storage in different plant parts in the form of biomass in growing trees is the carbon storage (Chavan and Rasal, 2010).

The amount of carbon sequestered continuously by a tree increases substantially over time till it matures. The process of carbon capture in photosynthesis is influenced by different factors including the tree age, leaf area and photosynthetic efficiency (Chavan and Rasal, 2012). The rate of carbon storage increases in young tree species, while it declines after full growth as the stand ages (Jana *et al.*, 2009).

Tropical forests are an important component of global carbon stocks. They contribute an estimated 448 Petagrams of carbon globally, divided between vegetation and soils. However, there is a great deal of uncertainty in these numbers (Watson, 2000; Donato *et al.*, 2011; Hunter *et al.*, 2013). As a consequence of their high carbon density, tropical forests are increasingly viewed as an avenue for mitigation of climate change. In an effort to reduce deforestation and degradation by creating monetary value for the carbon in forests, the United Nations has developed REDD+ (Reducing emissions from deforestation and forest degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks) (Gibbs *et al.*, 2007). It is an international climate policy framework aimed at generating incentives to protect and better manage forest resources, by recognizing and establishing an economic value for the additional carbon stored in trees or not emitted to the atmosphere (Corbera and Schroeder, 2011). REDD+'s procedural rules have evolved over time (Pistorius, 2012) and its implementation means are country-specific. REDD+ thus promotes the commodification of ecosystems' primary production by isolating carbon storage and sequestration functions from other services provided by forests; quantifying such functions with a standard unit of measurement (tonnes of $CO_2$); monitoring and reporting carbon stocks and fluxes over time and landscapes; and economically valuing the cost of avoided or sequestered forest carbon emissions for the purpose of exchange between buyers and sellers (Engel *et al.*, 2010). It upscales the model of project-based



Tropical forests harbor the largest terrestrial reservoir of biodiversity from the gene to the habit level, with more than half of the world's plant and animal species (Dirzo and Raven, 2003). This biome contains up to 55% of global terrestrial C stocks (Pan *et al.*, 2011), exchanges more water and carbon dioxide ($CO_2$) with the atmosphere than any oth

- To determine canopy closure of the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.
- To determine the above ground biomass of the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.
- To determine the below ground biomass of the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.
- To determine the bulk density, total carbon, total nitrogen and carbon/nitrogen ratio in soils of the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.
- To compare the canopy cover, biomass and carbon stock, bulk density, total carbon and nitrogen and carbon/nitrogen ratio of the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.
- To quantify the total carbon stock, estimate the relative carbon capture and storage potential in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, (Oban West Division), Akamkpa.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Carbon sequestration

Carbon sequestration is the term given to capturing atmospheric carbon and converting it into forms unable to contribute to global warming (Zeng, 2008). Several technological options for sequestration of $CO_2$ exist and can be broadly categorized into two; abiotic and biotic sequestration.

### 2.1.1 Abiotic sequestration

This is based on physical and chemical reactions and engineering techniques without intervention of living organisms. It involves the storage of $CO_2$ in oceanic and geological formations. Oceanic injection involves the injection of pure $CO_2$ stream into great depths below 1, 000 m in the ocean and being lighter than water, $CO_2$ rises to approximately 1, 000 m depth forming a droplet plume, it can also be injected as a denser $CO_2$-seawater mixture at 1, 000 m depth and the mixture sinks into the deeper ocean, direct discharge from ships into the ocean from reservoirs or tanks and pumping of $CO_2$ into depressions in the ocean floor to form $CO_2$ lakes (Lal, 2008). Oceanic injection, though promising, packs some adverse effects on deep sea biota (Seibel and Walsh, 2001, Aurebach *et al.*, 1997)

Geological injection involves capture, liquefaction, transport and injection of industrial $CO_2$ into deep geological formations. The $CO_2$ may be injected into coal seams, old oil wells, stable rock strata and saline aquifers (Lal, 2008). Geologic sequestration is currently used to store only small amounts of carbon per year. Much larger rates of sequestration are envisioned to take advantage of the potential permanence and capacity of geologic storage. The permanence of geologic sequestration depends on the effectiveness of the $CO_2$ trapping mechanisms. After $CO_2$ is injected underground, it will rise buoyantly until it is trapped beneath an impermeable barrier, or seal. In principle, this physical trapping mechanism, which is identical to the natural geologic trapping of oil and gas, can retain $CO_2$ for thousands to millions of years (Sundquist *et al*., 2008).

### 2.1.2 Biotic sequestration

Biotic sequestration is based on removing $CO_2$ from the atmosphere into ocean, vegetation and soils by plants and microorganisms. Oceanic sequestration involves several biological processes leading to carbon sequestration in the ocean through photosynthesis by phytoplankton (Rivkin and Legendre, 2001). Some of the particulate organic material formed by phytoplankton is deposited at the ocean floor and is thus sequestered (Raven and Falkowski, 1999). Terrestrial carbon sequestration deals with storage of $CO_2$ in vegetation and in soils, in the above ground and below ground biomass, processes termed as phytosequestration and soil carbon sequestration, respectively (Post *et al*., 2009). This process has been widely accepted because of advantage of long-term storage. In terrestrial ecosystems, carbon storage mainly occurs by photosynthesis as well as in the form of live and dead organic matter, hence acting as major carbon sinks. So far, it is known that the carbon storage capacity of soil is more than the storage capacity of both vegetation and the atmosphere and hence a small increase in soil carbon surely provides significant effects on overall carbon balance of the environment. Soil carbon sequestration occurs when atmospheric $CO_2$ captured by plants is majorly converted into organic material by photosynthesis while a small proportion of it is translocated through plant roots into the soil, where it is stored in organic as well as inorganic forms (Jansson *et al*., 2010). Woody debris and detritus also contribute to the soil carbon sink in forests (Wofsy, 2001). So far, it is known that the carbon storage capacity of soil particularly in wetlands is more than the storage capacity of both vegetation and the atmosphere (Garnett *et al*., 2001), and hence a small increase in soil carbon surely provides significant effects on overall carbon balance of the efficiency of soil carbon sequestration which mainly depends on climate, temperature, rainfall, clay content, mineralogy, moisture content and soil texture (Metting *et al*., 2001).

## 2.2 Climate change and colours of carbon

Climate change refers to some observable variations in the climate system that are attributable to human activities, especially those that alter the atmospheric composition of the earth and ultimately lead to global warming (Idowu *et al*., 2011). Anthropogenic climate change is caused by the rising content of greenhouse gases and particles in the atmosphere. Firstly by the burning of fossil fuels, releasing greenhouse gases such as $CO_2$ and dust particles, secondly by emissions from clearing natural vegetation, forest fires and agricultural emissions, including those from livestock; and thirdly – by the reduced ability of natural ecosystems to bind carbon through photosynthesis and store it (Trumper *et al*., 2009). Climate Change has driven widespread appreciation of atmospheric $CO_2$ as the main greenhouse gas and of the role of anthropogenic $CO_2$ emissions from energy use and industry in affecting temperatures and the climate. These emissions are referred to as "brown carbon" for greenhouse gases and "black carbon" for particles resulting from impure combustion, such as soot and dust. Terrestrial carbon stored in plant biomass and soils in forest land, plantations, agricultural land and pasture land is often called "green carbon". The importance of "green carbon" has been recognized through anticipated agreement at the United

Nations Framework Convention on Climate Change Conference of the Parties (COP) in Copenhagen, December 2009, which includes forest carbon – through various mechanisms, be they REDD and afforestation, REDD+, and/or others such as Forest Carbon for Mitigation. The world's oceans bind an estimated 55 per cent of all carbon in living organisms. Mangroves, marshes and seagrasses capture and store most of the carbon buried in marine sediments and are referred to as blue carbon sinks. Coastal vegetated wetlands such as mangrove forests provide multiple ecosystem services, though are potentially threatened by contemporary accelerated sea level rise, in addition to other immediate threats such as agriculture and coastal development (Sasmito *et al.*, 2016; Edu *et al.*, 2014). These ecosystems, however, are being degraded and disappear at rates 5 – 10 times faster than rainforests. Together, by halting degradation of "green" and "blue" carbon binding ecosystems, they represent an emission reduction equivalent to 1 – 2 times that of the entire global transport sector – or at least 25 per cent of the total global carbon emission reductions needed, with additional benefits for biodiversity, food security and livelihoods. It is becoming increasingly clear that an effective regime to control emissions must control the entire spectrum of carbon, not just one colour (Nellemann *et al.*, 2009).

## 2.3 Global climate change effects on plant species

Climate change represents one of the greatest research challenges currently faced by plant biologists, agronomists and conservation biologists. With global greenhouse gas emissions set to continue to rise for the foreseeable future, the impact of elevated atmospheric $CO_2$ ($eCO_2$), and associated shifts in temperature and precipitation are all expected to impact plant ecophysiology, distribution and interactions with other organisms (IPCC, 2014). With specific reference to plants, Working Group II of the Intergovernmental Panel on Climate Change concluded with high confidence that anthropogenic climate change has had, and will continue to have, a strong effect on plant life cycles and species' interactions (IPCC, 2014). Wolkovich *et al*. (2012) showed that phenological responses to experimental warming treatments failed to match long-term observational responses for many plants, even for the same species growing in the same regions. Cook *et al*. (2012), also found that some three-quarters of 'nonresponding' species to phonological shifts actually were responding quite strongly to warming seasons, simply in more complex ways than previously recognized. The overall message from global meta-analyses of long-term observational datasets indicated that major shifts in species' distributions have already occurred, with some species showing range contractions and others range expansions (Parmesan and Yohe, 2003; Root *et al*., 2003; Parmesan, 2006; Poloczanska *et al*., 2013). Further, as species alter their distributions in attempts to track a shifting climate space, they move into novel geographic areas, opening the possibility for these exotic species to become invasive. Indeed, early concerns about climate change were that existing exotics would benefit over natives and become invasive, and that already invasive species could become even more damaging to native communities and ecosystems (Dukes and Mooney, 1999). The way in which species respond to warming may itself be changing. In a study of 13 temperate trees from 1980–2012, Fu *et al*. (2015) found that the 'heat requirement' for leaf flushing had increased over time in every case, on average by almost 50 %, a striking result for which the mechanism was not understood. In their global meta-analysis of marine systems, Poloczanska *et al*. (2013) found that predators (fish and zooplankton) had advanced significantly more than their potential food resources (phytoplankton). Similarly, in a meta-analysis of northern hemisphere data, herbivorous insects (butterflies) had advanced at rates three times faster than potential



(Schweiger *et al*., 2008).

Bellard *et al*. (2012) stated that because of climate change, species might not acclimate through plasticity to the set of environmental conditions in a given region and could therefore fall outside their respective climatic niche. They further stated that to persist, individuals, popul forest management (Thompson *et al*., 2013). Carbon emissions from tropical deforestation and degradation currently contribute an estimated 8 to 15% of annual global anthropogenic carbon emissions, further exacerbating global warming (Houghton *et al*., 2015). Tropical deforestation is estimated to have released of the order of 1–2 billion tonnes of carbon per year during the 1990s (Malhi and Grace, 2000; Fearnside and Laurance, 2004). In 2015 forest covered 3999 Million ha (M ha) globally. This is equivalent to 31% of global land area, or 0.6 ha for every person on the planet (Keenan *et al*., 2015). A further 1204 M ha are covered by other wooded land. Three quarters of all forest is in high income and upper middle income countries, with just 25% of the total in countries classified as having lower middle or low income (FAO, 2015). Overall, there was a net decrease in global forest area of 3% between 1990 and 2015, from 4128 M ha to 3999 M ha. Half of global forest area as reported by Keenan *et al*. (2015) is in sub-regions where forest cover is expanding: Europe, North America, the Caribbean, East Asia, and West and Central Asia. The remainder is in sub-regions where forest area continues to decline: Central America, South America, South and Southeast Asia and all three sub-regions in Africa. In Africa, the greatest net losses in forest area between 2010 and 2015 were in Nigeria (410 K ha $y^{-1}$), Tanzania (372 K ha $y^{-1}$), Zimbabwe (312 K ha $y^{-1}$) and Democratic Republic of Congo (311 K ha $y^{-1}$). Tropical forest is largely being converted to cropland and pasture for the production of soy, beef, palm oil, and timber (Rudel *et al*., 2009; Hosonuma *et al*., 2012), with the majority of new global agricultural land coming at the expense of tropical forest (Gibbs *et al*., 2010). Understanding the drivers of deforestation and forest degradation is believed to be fundamental for developing policies and measures that can alter current trends of forest loss and degradation (Rudel *et al*., 2009). A recent study found that 30 % of the global land area has been degraded since the 1980s while land improvement has concurrently occurred on approximately 3% of the global land area until 2013 (Le *et al.*, 2014). The proximate causes of land degradation are direct causes consisting of biophysical factors and unsustainable land management practices. On the other hand, the underlying causes are more complex, cutting across institutional, socioeconomic, and policy factors including population density, poverty, land tenure security and property rights, access to markets, agricultural subsidies, and taxes (Nkonya *et al.*, 2013; Mirzabaev *et al.*, 2015). Mangrove ecosystems are also threatened by land use/land cover change as well as global climate change (Alongi, 2002; Giri *et al.*, 2011; Kauffman *et al.*, 2011). The global area of mangroves has decreased from around 16.1 million ha in 1990 to 15.6 million ha in 2010 (FAO, 2010). Urbanization of coastlines has led to the destruction of 3.6 million ha of mangroves worldwide from 1980 to 2005 (FAO, 2007). It is estimated that about 1 to 2% of mangrove forests are being deforested per year globally (Duke *et al.*, 2007; FAO, 2007), accounting for 10% of the carbon released from deforestation annually; and yet mangroves cover just 0.7% of the tropical forest areas (Donato *et al.*, 2011; Giri *et al.*, 2011). Annual land use change related emissions from mangrove forest loss is equivalent to 10 per cent of the total emissions from land use change, even though a smaller areal extent is lost. Overall, land use change emissions from mangrove forest loss is estimated to be on the order of 0.073 to 0.44 Gt $CO_2$ $yr^{-1}$ (Donato *et al.*, 2011).

## 2.5 Overview of Nigeria in context of population and biodiversity.

Nigeria is Africa's most populous nation with an estimated population of about 200 million and located between latitudes 40° and 140° north of the equator and longitudes 30° and 140° east of the Greenwich Meridian (Adewale, 2011). The country lies entirely within the tropical zone. It occupies about 3 % of Africa's landscape (FAO, 2015). According to the United Nations, by 2050 the population of Nigeria is projected to surpass 300 million (UN-DESA, 2017).

Nigeria contains a rich series of climatic and vegetation zones across landscapes resulting in diverse range of habitats, from desert zones in the northeast to tropical rain and swamp forests along the south coast. According to the latest assessment by FAO (2015), Nigeria's forests and woodlands currently cover about 6,993,000 hectares (7.7 per cent of total land area). The country is endowed with rich biodiversity – some 4,600 plants, 839 birds and 274 mammal species. The *Gulf of Guinea's* forests stretch into southern Nigeria: these forests are recognized as a global biodiversity hotspot. There are 22 primate species, including threatened and endangered species such as the Cross River Gorilla, Drill and Preuss's Guenon monkey. The major vegetation types are rain forests, mangrove swamp forests, tropical high forests (montane) and savannah woodlands. A review of the management effectiveness of the different forest management regimes in Nigeria revealed that apart from National Parks, the rest were ineffectively management (UN-REDD, 2015). The forestry sector plays a major role in the rural economy through the provision of Non-Timber Forest Products (NTFPs) and also accounts for a high proportion of domestic energy (over 70 per cent of the energy needs in the rural areas), forest sourced foods and medicines to the rural population. Fuel-wood accounts for over 50 per cent of overall energy consumption in the country and is the dominant source of energy in the domestic sector (UN-REDD, 2015).

### 2.6 Brief history of United Nations-REDD+ in Nigeria

Deforestation and forest degradation account for greenhouse gas (GHG) emissions, more than the entire global transportation sector and second only to the energy sector. In response, Parties to the United Nations Framework Convention on

Climate Change (UNFCCC) have developed a climate change mitigation approach designed to incentivize developing countries to reduce carbon emissions from deforestation and forest degradation. This mitigation approach is known as REDD+ and is defined as "reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks". REDD+ aims to incentivize developing countries to contribute to climate change mitigation actions in the forest sector by: reducing carbon emissions from deforestation; reducing carbon emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks. In 2009, the Nigerian government and the Cross River State government implored the United Nations-REDD programme to create and promote REDD+ activities in the country. The result was a national programme for REDD+ or UN-REDD programme which was preceded by intense policy, planning and technical support. Approval was given by the UN-REDD policy board in 2012. Since 2012, REDD+ has been a mechanism for the introduction of a number of forest policies and programmes by Nigeria to check the trend of deforestation in the country (R-PP, 2013).

## 2.7 Policy, law and regulatory framework supporting REDD+ in Nigeria

Preparatory studies to implement REDD+ provided detailed analysis of existing policies, laws, and regulatory frameworks relevant to REDD+ at both Federal and Cross River State levels during the REDD+ Strategy development process for Cross River State. Policy law and regulatory framework arrangements to support REDD+ implementation at the Federal level include;

### 2.7.1 Draft Bill for a National Forest Act, 2003

The bill sets out to provide for the establishment, conservation, sustainable management of the nation's forest resources and its rich biodiversity in conformity with local, national and international processes and initiatives on global forests and environment. The bill is significantly responsive to the REDD+ five activities. It hinges on the principles of sustainable forest management of forest resources in and outside forest reserves. It recognizes the rights of local communities to fair and equitable sharing of benefits derived from genetic resources and prescribed the requirement of prior informed consent of communities for access to biological resources outside forest reserves. It further provides for the recognition and protection of local communities' traditional knowledge, cultural heritage and intellectual property outside forest reserves. The Bill also provides for private sector participation in forestry development programmes and the establishment of a National Forestry Trust Fund at the Federal Level. The fund is to facilitate the promotion and financing of forestry development projects and programmes as a sustainable source of funding. The Bill further seeks to promote the participation of women and youths in sustainable forest resources management and utilization.

### 2.7.2 National Forest Policy, 2006

The National Forest Policy is the overarching framework on forestry development in Nigeria. The overall objective of the policy is to achieve sustainable forest management that would ensure increases in the economic, social and environmental benefits from forests and trees for the present and future generations including the poor and vulnerable groups. The policy promotes and supports the decentralization of roles and functions amongst stakeholders (public, private, NGOs, including, Community Based Organizations and civil society) towards the attainment of sustainable management of forests. The policy recognizes the environmental functions of forests in carbon capture and carbon sequestration and the need to employ the international financial mechanisms to enhance the carbon stocks. It promotes helping citizens, especially the rural communities and forest dependent persons to better adapt to climatic change, and to benefit from emerging carbon markets. The policy instrument contains strategies for carbon trading, benefit sharing, tree ownership and accessing carbon credit within the framework of the Clean Development Mechanism of the Kyoto Protocol. The policy in general, is supportive of REDD+ implementation.

### 2.7.3 Land Use Act Cap 202 LFN 1990 Cap L5 LFN 2004

The Land Use Act (LUA) is the principal law in Nigeria regulating the use and access to all lands in the country. By virtue of Section one ofthe Act, all lands in Nigeria are under the control of the respective State Governors. The section provides that "subject to the provisions of this Act, all land comprised in the territory of each state in the Federation are hereby vested in the Governor of that State and such land shall be held in trust and administered for the use and common benefit of all Nigerians in accordance with the provisions of the Act". The Federal Government does not play a major role in land administration other than in relation to federal land acquired before the enactment of LUA and such other lands as may be acquired under the Act or any other enabling legislation. National Parks (NPs) are also under the jurisdiction of the Federal Government. Other Acts relating to land acquisition for federal projects within the context of LUA include, the Minerals and Mining Act, 2007, Oil pipelines Act, Cap 07 LFN 2004 and Electric Power Sector Reform Act, No. 6 of 2005. Local Governments are not vested with power of administration of land in the urban areas.

They are responsible for the control and management of land in non-urban areas over which they have the power to grant customary rights of occupancy. The power is exercised subject to the type of use and a limitation on the size of land, above which there is reversion to the Governor of the State. The Governor, however, retains overriding powers over all lands in the state.

### 2.7.4 Minerals and Mining Act, 2007

The Minerals and Mining Act LFN 2007 is the principal law on the mining sector in Nigeria. Mining and minerals are in the Exclusive Legislative List of the 1999 Constitution, hence only the Federal Government has the authority to grant mining permits or licenses. The Act gives superior rights to use land for mining purposes over the statutory right of occupancy or customary ownership of such land. It provides that the use of land for mining operations shall have priority over other uses of land, as it constitutes an overriding public interest within the meaning of the Land Use Act. Mining activities, if conducted in an eco-unfriendly manner, lead to the clearing of vegetation and could significantly compromise the implementation of REDD+ activities in an area where a mining license/permit has been granted. According to the provisions of the Mining Act, a mining cycle, based on the term of license/permit, is a minimum of 25 years in the first instance before renewal, while that of quarrying is five years. Therefore, it is desirable that mining activities should incorporate offset planting of trees as part of the mitigation measures at the commencement of activities, which is not presently the case. That will be in addition to the requirement for reclamation at closure. Some provisions of the Act promote and support REDD+ activities and the Cancun safeguards. Such responsive provisions include, exclusion of lands constituting National Parks from minerals exploration and exploitation, prohibition of mineral exploration in sacred areas or injury or damage to sacred/venerated trees, restoration and reclamation of mined lands, requirement for Environmental Impact Assessment (EIA) before the grant of license or permit and establishment of Environmental Protection and Rehabilitation Fund. However, the Act is silent on the exploration and exploitation of minerals and mining within forest reserves and other ecologically sensitive areas or critical ecosystems which are under the control and management of the State Government. Overall, the Minerals and Mining Act is moderately responsive to REDD+ implementation.

### 2.7.5 Petroleum Act Cap 10, LFN, 2004

There are also several federal statutes regulating oil exploration, prospecting and mining in Nigeria. The Petroleum Act is the principal law on the industry with subsidiary legislation enacted under it. Some of the permits granted under the regulatory framework in the petroleum industry include Oil Pipeline Survey Permit, Oil Pipeline License, Oil Prospecting License and Oil Mining Lease. These permits/licenses have implications for the ecosystem. The Environmental Guidelines and Standards for the Petroleum Industry in Nigeria elaborate on environmental standards and safeguards applicable in the petroleum industry in the country. These are in addition to the provisions in the Environmental Impact Assessment (EIA) Act for projects in the oil and gas industry.

### 2.7.6 Environmental Impact Assessment Act, Cap E12, LFN 2014

The Act sets out the general principles, procedures and methods to enable the prior consideration of environmental impact assessment on certain public or private projects. It further provides that before a decision is taken to undertake or authorize the undertaking of any activity, those matters that may likely or to a significant extent affect the environment or have an environmental effect on those activities shall first be taken into account. The drivers of deforestation and forest degradation for which mandatory study is required include agriculture, infrastructure, logging and conversion of forest to other land use, mining and housing. Environmental sensitivity and the area coverage of a project are some of the criteria for an EIA. The Act supports REDD+ implementation in the country and valuable in promoting the adherence to REDD+ principles and safeguards in projects touching on the forests, including measures to mitigate impacts of drivers of deforestation and forest degradation in land use sectors. The EIA process provides for public display of draft EIA report as well as public review. This process strengthens stakeholder participation and public access to information by concerned people and other stakeholders. It also provides for the establishment of a public registry for all EIAs to enhance transparency and accountability.

### 2.7.7 National Park Service Act, Cap N65 LFN, 2004

The Act established the National Park Service (NPS), with mandate for the preservation, enhancement and protection of wild animals, plants and other types of vegetation in the National Parks and for matters connected therewith. Cross River National Park is one of the seven National Parks managed under the Act. Protected areas for biodiversity management could overlap with potential REDD+ activities insofar as habitat for flora and fauna can be preserved while also reducing the emission of greenhouse gases. The Cancun Safeguards provide that REDD+ activities take into account the multiple functions of forests and other ecosystems and be consistent with the conservation of natural forests and biological diversity. The objectives of the Act support the implementation of REDD+ in Nigeria.

### 2.7.8 National Policy on Environment, 1999

In response to the various environmental issues, Nigeria developed several sectoral policies on environment with strategies and framework of actions. The National Policy on Environment defines the framework for environmental governance in the country. The policy identifies key sectors requiring integration of environmental concerns and sustainability with development. The goal of the policy is to achieve sustainable development and seeks in particular to enhance the quality of the environment, promote the sustainable use of natural resources, restore and maintain the ecosystem and ecological processes and preserve biodiversity, raise public awareness and promote understanding of linkages between environment and development and cooperate with government bodies and other countries and international organizations on environmental matters. The policy elaborates on issues of cross-sectoral coordination and strategies.

### 2.7.9 National Policy on Climate Change, 2012

The strategic goal of the Climate Change policy is to foster low-carbon, high growth economic development and build a climate resilient society through implementation of mitigation measures that will promote low carbon as well as sustainable and high economic growth. Also, enhancement of national capacity to adapt to climate change, raising climate change related science, technology, research, and development to a new level that enables the country to better participate in international scientific and technological cooperation on climate change. Further, significant increase in public awareness and involvement of private sector participation in addressing the challenges of climate change and strengthening of national institutions and mechanisms (policy, legislative and economic) will establish a suitable and functional framework for climate change governance. The policy elaborates on adaptation and mitigation programmes and actions in key sectors including energy, agriculture, water, transport and human settlement. On the forestry and land use sector, the policy direction is the promotion of sustainable forestry and land use that are able to respond to the challenges of climate change. The strategy is to develop and implement a Forestry Development Programme within the context of an Integrated Land Use Planning framework for sustainability including the promotion of ecosystems integrity and environmental goods and services as well as carbon capture. This would help achieve the REDD+ objectives. However, the policy advocates the development and implementation of forestry development in the following activity areas including increase in forest cover through afforestation, reforestation and prevention of deforestation, ensuring the enforcement of forestry laws and regulations, enhancing carbon density of plot and landscape levels through rehabilitation of degraded areas and increased tree planting activities. Also, promotion of agroforestry, encouraging sustainable forest management for integrated vulnerability reduction, adopting fiscal and regulatory measures towards reducing wood utilization particularly in construction and charcoal production. Improvement of governance in forestry resource, that would ensure the sustainable use of forest resources to contribute to the livelihood of rural communities as they adapt to climate change and promote sustainable forestry. These will enable Nigeria benefit maximally from the potential of REDD+ and at the same time adequately protect individuals and communities whose traditional forest based incomes would be impacted.

### 2.7.10 National Biodiversity Strategy and Action Plan, 2016-2020

Nigeria has developed the National Biodiversity Strategy and Action Plan (NBSAP) 2016–2020, to guide the conservation and sustainable utilization of biodiversity, access to genetic resources and the fair and equitable sharing of the benefits arising from their utilization. It provides information on biodiversity and their threats and analyses institutional and legal frameworks that govern biodiversity issues in Nigeria. It makes direct references to deforestation, forest degradation and conservation of biodiversity. As such, it covers the same land use types considered in the REDD+ Strategy – national parks, forest reserves, community forests, open areas, agricultural lands (for agro-biodiversity), wetlands and other aquatic ecosystems. National Biodiversity Strategy and Action Plan provides sectoral actions for mainstreaming biodiversity into national development, poverty reduction and climate change activities. It also elaborates on programme and actions for the conservation of Nigeria's biological diversity and its sustainable use by integrating biodiversity considerations into national planning, policy and decision-making processes. NBSAP provides frameworks for addressing biodiversity conservation, sustainable use of biological resources, equitable sharing of benefits arising from the utilization of biological resources, conservation of agro- biodiversity and biosafety. These are aimed at improving the quality of the biological ecosystems and the positive role in carbon cycle and global climate change phenomena.

### 2.7.11 The Green Alternative Agricultural Promotion Policy (APP), 2016-2020

Agriculture is a significant driver of deforestation and forest degradation in Nigeria, both at the level of small-holder farmers and large scale production. Agricultural initiatives and programmes traditionally result in significant incursion into the forestry frontiers in meeting the demand for land. The Green Alternative Agricultural Promotion Policy (APP) aims at solving the core issues at the heart of limited food production and delivery of quality standards for the country's food production value chain as well as increasing export earnings through the involvement of and partnership building among all key stakeholders. It builds on the successes of the Agriculture Transformation Agenda (2011–2015). The policy thrust of APP includes focusing policy instruments on the sustainability of the use of natural resources (land and soil, water and ecosystems) with the future generation in mind while increasing agricultural production, marketing and other human activities in the agricultural sector. The policy is also based on inclusiveness and participation of all key stakeholders. The policy thrust promotes climate smart agriculture through increasing public awareness on climate smart agriculture, improving management of land, water, soil and other natural resources, strengthening of institutional linkages and partnerships for ensuring climate smart agricultural governance, policies, legislations and financial mechanisms, conducting environmental impact assessment on major agricultural projects, promoting the use of renewable energy with the involvement of private sector, facilitating the production and use of soil map to improve land use and management practices and promoting the increased adoption of global best practices in handling climate change, including the aspects of adaptation, mitigation and carbon credit.

#### 2.7.12 National Renewable Energy and Energy Efficiency Policy (NREEEP)

National Renewable Energy and Energy Efficiency Policy was approved by the Federal Executive Council for the Electricity Sector on 20th April, 2015. The policy is aimed at driving the development of electricity generation from biomass through the implementation of the following national strategies which are REDD+ smart such as effectively harnessing biomass resources and integrating them with other energy resources for electricity generation, promoting the use of efficient biomass conversion technologies, encouraging the use of waste wood as a source of electricity in the nation's energy mix and intensification of efforts to increase the percentage of land mass covered by forests in the country. Government also has a deliberate policy of promoting the use of clean stoves that are fuel-wood efficient. Although the NREEEP encourages the use of biomass as biofuel, the policy implementation strategies if sustainably managed, monitored, reported and verified may also increase the carbon stock and could be eligible as REDD+ project. In addition, there is need for the policy to promote alternative renewable energy sources other than just biomass fuel such as solar, and wind.

## 2.8 Canopy closure

Canopy closure is defined as the proportion of the sky hemisphere obscured by vegetation when viewed from a single point (Jennings *et al.*, 1999) and is of particular interest to forest ecologists studying the variability of understory environments. Canopy structural parameters are often used to give adequate representation of vegetated ecosystems for purposes ranging from primary productivity, climate system, water and carbon gas exchanges, and radiation extinction (Breda, 2003; Middelboe and Binzer 2004; Kulakowski *et al.*, 2011; Yuan *et al.*, 2012). Percent canopy closure can easily be measured directly in the field using a spherical densiometer (Jennings *et al.*, 1999). It consists of a convex or concave mirror with an overlaid grid of squares, the spherical densiometer is handheld horizontally at elbow height whilst the operator takes at least four sampling positions (Cook *et al.*, 1995; Fiala *et al.*, 2006). Some authors classified the spherical densiometer as a quick and reasonably precise method to determine the long-term light environments, even though it is faced with the problem of subjectivity (Englund *et al*., 2000). Canopy closure can also be estimated from prism or fixed radius plot data and knowledge of the relationship between DBH and crown size of tree species (Parker, 2014). Similar to canopy closure is the concept of canopy cover, defined as the proportion of the forest floor covered by the vertical projection of the tree crowns. Conceptual differences exist between the two parameters, however both attributes can be used to describe canopy properties (McLane *et al*., 2009). Several other methods employed in the estimation of canopy closure and cover are mentioned in the paragraphs that follow.

The line-intercept or point quadrat method that measures canopy cover by recording horizontal distances covered by live crown along a line-transect (Canfield, 1941). It includes the entire length within the outline of a crown as cover.

The moosehorn that employs a square grid similar to the spherical densiometer. With the aid of an angled mirror at 45 degrees, vertical canopy cover is reflected through an aperture in the side of the instrument through which the observer records the number of cross-hairs intersected by cover (Robinson, 1947; Bonnor, 1967).

The 'MacArthur and Horn' photographic method that allows the determination of the ratio of sky to plant area in a photograph made in an upward direction from under the canopy. The photograph is covered with a grid of lines, and the per cent cover of the canopy is estimated by the per cent of grid squares with more than 50% covered (MacArthur and Horn, 1969).

Hemispherical photography is commonly implemented with analog or digital cameras equipped with 180 ° field-of-view (FOV) "fisheye" lenses pointing upward. The first processing step is to estimate the amount of sky visible through the canopy, by classifying each pixel of the photograph as belonging either to the sky or to any blocking element from the vegetation (canopy, leaf, branches, or stems) (Gonsamo, *et al.*, 2011). This is usually carried out by thresholding the image, which is done by selecting a brightness value and considering the image pixels above this as belonging to the sky and below to vegetation. Thresholding can be manual, if the operator visually decides the best brightness value to use, or automatic, if software-based techniques are applied to make the process objective and reproducible (Nobis and Hunziker, 2005).

All the methods mentioned are rather fast and non-destructive, which is a general advantage shared by these measurements. However, disadvantages are as manifold as the approaches. Both point quadrat or line intercept methods are unfortunately not suitable for large canopies. The assumption of random distribution of the foliage elements is also a drawback (Whitehead *et al.*, 1990; Chason *et al.*, 1991). Hemispherical photography and the MacArthur and Horn method are fast, they produce permanent image records, and they are rather inexpensive and easy to carry. The problems encountered here are more in the detail of the measurements. Camera settings are sensitive to the weather and the image analysis is not free of subjectivity. MacArthur and Horn images are prone to distortions in the images, which is not completely eliminated in the hemispherical lenses as well (Herbert 1987; Schwalbe 2005). The Moosehorn and the spherical densitometer are easy to use and portable. Others advantages are their extremely low prices and the usage independently from any computer accessibility. Anyway, these simple instruments are prone to subjectivity and are of low resolution according to the three dimensional character of the canopy structure data that can be obtained.

## 2.9 Biomass estimation methods

The main methods used for estimating forest biomass are the destructive method and non-destructive method. The destructive method involves the harvesting of all trees in a known area. After harvest, the trees are separated into component parts, and the fresh weight of the individual components, trunk, branches, twigs, leaves and roots are measured (Ravindranath and Ostwald, 2008). The components are then oven dried after which their weight is measured again (Liu and Westman, 2009). The difference obtained from comparing the fresh and dry weights of the component parts is used to estimate the biomass. Although this method is regarded as accurate for a particular area, it is tedious, destructive, expensive and is not applicable for a large scale analysis (Liu and Westman, 2009). In a mature tropical forests, the total weight of individual trees often reaches several tons (Komiyama *et al.*, 2005). Therefore, the harvest method cannot be easily used in mature forests and in itself is not reproducible because all trees must be destructively harvested.

Non-destructive methods mostly employed in recent times include remote sensing technologies and allometry. Remote sensing is the process of acquiring information from a distance without direct contact with the source or area being examined (Vashum and Jayakumar, 2012).

Remote-sensing technology, which has wide coverage and repeated observation capabilities, has promoted research on the spatial distribution and temporal variation of forest biomass. Biomass models based on remote-sensing data have been shown to be more accurate than other models (McRoberts *et al.*, 2013). The characteristics of the forest can be estimated using the airborne or space-borne multi-spectral remote sensing method (Ahamed *et al.*, 2011). Airborne remote-sensing data, such as aerial photographs, are most useful when fine spatial detail is critical, which are often used for modeling forest canopy structures or tree parameters (Lu, 2006; Ahamed *et al.*, 2011). Three types of remote-sensing data are currently available for biomass estimation such as optical sensor data, radar data, and LiDAR (Light detection and ranging) data (Zhang *et al.*, 2014; Lu, 2006; Lu *et al.*, 2005). Each of these has its own advantages and disadvantages for estimating biomass. Optical remote sensing can be used for continuous estimation of forest biomass due to its long observation time, wide spatial coverage, and multiple bands, which can provide abundant information about the canopy spectrum. Optical remote sensing is limited by its relatively poor penetration. Estimating forest AGB using optical sensor data is based on the close relationship between foliage biomass and forest ecosystem biomass. However, foliage biomass accounts for less than 10 per cent of the total biomass of a mature forest ecosystem (Dobson *et al.*, 1992). The signal saturation of optical sensor data in dense vegetation is an important factor restricting biomass inversion. The results obtained by Lu *et al* (2005) confirmed that Thematic Mapper (TM) spectral reflectance changes regularly with increasing AGB in forest sites with low biomass density. As for forest sites with high biomass density, the relationship between AGB and TM spectral reflectance is not obvious. Radar data are also a promising data source for estimating AGB because of their independence of weather and their ability to penetrate the canopy and thereby receive information about trunks and branches (Drake *et al.*, 2003; Yu *et al.*, 2015). Signal saturation is also a problem for radar data (Mougin *et al.*, 1999; Sandberg and Tsoukas, 2011). LiDAR, an active remote-sensing technology, can acquire forest vertical structure information, which is strongly related to forest biomass. LiDAR data are not affected by signal saturation (Hajj *et al.*, 2017; Fayad *et al.*, 2016). Incomplete data coverage, short running time, and the effects of clouds and terrain make spatial LiDAR data less than ideal for biomass mapping Zhang *et al.*, 2014; Yu *et al.*, 2015; Lu *et al.*, 2016).

Biomass estimation equations, also known as allometric equations or regression models, are used to estimate the biomass or volume of aboveground tree components based on diameter at breast height (DBH) and height data. These equations are derived based on measured values of tree weight related to its DBH and height from sample trees. Using biomass equations is a common and cost-effective method to estimate biomass of tree species present in a forest or plantation (Ravindranath and Ostwald 2008). Basuki *et al.*, (2009) reported the use of destructive sampling, allometric equations and remote sensing for the estimation of above-ground biomass in tropical forests. Several other authors including Djomo *et al.*, 2010; Henry *et al.*, 2010; Ebuy *et al.*, 2011; Vieilledent *et al.*, 2012; Fayolle *et al.* 2013 have reported allometric equations developed for African tropical rainforests and Chave *et al.*, 2005; Komiyama *et al.*, 2005 for mangroves. Salunkhe *et al.*, (2018) reviewed biomass estimation methods of above-ground biomass and carbon stocks of Indian forests by several authors. He stated that most of the estimates were based on the non-destructive allometric equation approach. However, the site- and species-specific dependencies of allometric equations pose a problem to researchers because tree weight measurement in tropical forests is labor-intensive. Gibbs *et al.*, (2007) observed in their review of biomass estimation methods that the effort required to develop biomass equations of specific species or sites does not normally enhance the accuracy of biomass estimates. De Lima *et al.*, (2017) stated that the specific equations for some species are not necessarily better than the generic equation, which includes the total height of the tree as a predictive variable.

as 358.1±31.9 Mg ha$^{-1}$ and 179.0±15.9 Mg C ha$^{-1}$, respectively. Lung and Espira (2015) reported aboveground biomass for an African tropical forest as 279±32.78 Mg ha$^{-1}$, Houghton *et al.* (2001) also reported aboveground biomass values in Amazonian forests ranging from 312 – 464 Mg ha$^{-1}$ and Lewis *et al.* (2013) reported aboveground biomass for closed-canopy tropical forests as 395.7 Mg ha$^{-1}$. Using the same diameter range of greater than five centimetres, Fischer *et al.* (2015) estimated the total aboveground biomass as 385 Mg ha$^{-1}$ for an African tropical Montane forest on Mt. Kilimanjaro. Hansen *et al.*, (2015) Clark *et al.*, (2011); Asner *et al.*, (2012a); Mascaro *et al.*, (2011); Vincent *et al.*, (2012) and Asner *et al.*, (2010) reported maximum biomass densities with the use of Airborne Laser Scanner for aboveground biomass estimation in tropical forests in South America of about 500 Mg ha$^{-1}$, Hou *et al.*, (2011) reported similar results in Asia and Asner *et al.*, (2012b) far greater estimates in Africa. Brown (2002) reported that most hardwood forests have aboveground biomass in the range of 75–175 Mg ha$^{-1}$ equivalent to 38 – 90 Mg C ha$^{-1}$. Ross *et al.* (2001) reported aboveground biomass in dwarf mangrove forests to be 22.28 ± 5.18 Mg ha$^{-1}$ and in fringe forests as 56.02 ± 11.96 Mg ha$^{-1}$ in USA. Green *et al.*, (2007) reported the use of root shoot ratios in estimating the belowground biomass stocks. Mokany *et al.* (2006) conducted a global analysis of root:shoot ratio and they proposed a value of 0.26, suggesting that belowground biomass may be directly inferred from aboveground biomass. Luo *et al.* (2012) also reported similar results in Chinese forests. Belowground biomass of roots down to 100 cm has been reported by Nguyen *et al.*, (2009) increasing from 0.7 to 4 t C ha$^{-1}$ in three and 10 years old plantations, respectively in *Kandelia candel* L. in Northern Vietnam. In Gazi bay, Kenya, live belowground carbon ranged from 3.8 ± 0.2 t ha$^{-1}$ and 17.9 ± 0.6 t ha$^{-1}$, 24.2 ± 0.4 t ha$^{-1}$ and 37.7 ± 1.0 t ha$^{-1}$ and 19.5 ± 0.4 t ha$^{-1}$ and 21.9 ± 0.9 t ha$^{-1}$ for *Rhizophora mucronata*, *Sonneratia alba* and *Avicennia marina* stands, respectively, depending on the age of the stand (Tamooh *et al*., 2008). Saner *et al*. (2012) reported above-ground biomass of 457.1 Mg $ha^{-1}$ in a tropical lowland rainforest in Borneo and a below-ground biomass ratio of 18 %. Adame *et al*. (2013) reported on aboveground biomass of coastal wetlands in Mexico with ranges from 3.0±0.4 Mg $ha^{-1}$ to 176.2± 47.4 Mg $ha^{-1}$, they further reported BGB values of 8.7±0.9 Mg $ha^{-1}$ to 156.6±44.2 Mg $ha^{-1}$. Kauffman *et al*., (2011) reported total above-ground biomass estimates in the range of 204 Mg $ha^{-1}$ to 323 Mg $ha^{-1}$ and Below-ground biomass estimates ranging from 171 Mg $ha^{-1}$ to 312 Mg $ha^{-1}$ in Micronesian mangrove forests. They further reported a mean downed wood biomass estimate within range of 29.6 Mg $ha^{-1}$ and 43.1 Mg $ha^{-1}$ in the same mangrove. Saldarriaga *et al*. (1988) reported an almost 20 % contribution to aboveground biomass of coarse woody debris or downed wood biomass stock for a slow growth, high wood density tropical forest in Venezuela. Baker *et al*. (2007) reported coarse woody debris stocks of 24.4±5.3 Mg $ha^{-1}$ using the line-intersect sampling method and 17.7±2.4 Mg $ha^{-1}$ within permanent plots in Southern Peru. Using the line-intersect method, Chao *et al*., (2008) reported coarse woody debris biomass estimates for three different forest types in a tropical lowland forest of Northwestern Amazonian landscape of 31.5 ± 6.6 Mg $ha^{-1}$ in the clay-rich forest, 45.3 ± 13.2 Mg $ha^{-1}$in the white sand forest, and 10.7 ± 6.1 Mg $ha^{-1}$ in the floodplain forest. In Southeast Asia, Pfeifer *et al*. (2015) reported coarse woody debris stocks within the range of 20 and 60 t $ha^{-1}$. Mean biomass estimates for downed wood in a tall and medium mangrove forest in the Mexican Carribean was reported by Adame *et al*. (2013) as 16.7±4.2 Mg $ha^{-1}$ with range from 7.0±1.5 Mg $ha^{-1}$ to 25.7±4.4 Mg $ha^{-1}$ and a mean carbon stock estimate of 8.3±2.1 Mg C $ha^{-1}$. Gairola *et al*. (2011) reported a range of 215.5 to 486.2 Mg $ha^{-1}$ and 107.8 to 234.1 Mg C $ha^{-1}$ for total live tree biomass density and live carbon density respectively, in Uttrakhand, India. Borah *et al*.

(2013) reported aboveground biomass in the range of 32.47 Mg $ha^{-1}$ to 261.64 Mg $ha^{-1}$ and a carbon stock range of 16.24 Mg $ha^{-1}$ to 130.82 Mg $ha^{-1}$ in Northeast India. Pragasan (2015) recorded total carbon stock of 10.9 ± 3.6 t C $ha^{-1}$ and tree carbon stock ranging from 3.53 t C $ha^{-1}$ to 38.92 t C $ha^{-1}$ in tropical forests of Bodamalai hills, Tamil Nadu. Li *et al.* (2015) reported tree carbon estimates and soil carbon stock estimates ranging from 0.02±0.001 Mg C $ha^{-1}$ to 141.43±5.29 Mg C $ha^{-1}$ and 81.08±10.13 Mg C $ha^{-1}$ to 160.39±17.96 Mg C $ha^{-1}$, respectively in a converted secondary forest in South Yunnan Province, Southwest China. Dalal and Allen, (2008) stated that tropical rainforests have an average soil carbon of 243 t C $ha^{-1}$. Cusack *et al.* (2017) reported soil carbon stocks to a depth of one meter ranging between 72 and 203 Kg C $m^{-2}$ in tropical forests of Panama. Chhabra *et al.* (2003) reported estimated mean soil carbon densities in the range of 37.5 t $ha^{-1}$ in tropical dry deciduous forests to 92.1 t $ha^{-1}$ in littoral and swamp forests in India. Pandey and Pandey (2013) report a total soil carbon estimate for dense, moderate and sparse mangrove in India as 87.83 t C $ha^{-1}$, 36.99 t C $ha^{-1}$ and 44.08 t C $ha^{-1}$ respectively. Matsui *et al.* (2013) reported soil carbon estimates of 71.8 – 154.8 t C $ha^{-1}$ in an abandoned mangrove shrimp pond in Khanom, Thailand. Donato *et al.* (2012) reported soil carbon estimates of 631 – 754 Mg C $ha^{-1}$ in tropical mangroves in the Pacific. Total mean ecosystem carbon pools of 937 t C $ha^{-1}$ were reported by Alongi, (2012) for mangroves across six locations in Asia. Ngo *et al.* (2013) reported total carbon stocks of 337 Mg C $ha^{-1}$ and 274 Mg C $ha^{-1}$ in a primary and secondary forest in Singapore.

## 2.11 Soil bulk density

Soil bulk density is an indicator of soil compaction. Expressed as the ratio of mass of dry solids to bulk volume of soil, it is an essential variable for estimating soil mass, nutrient pools, and carbon storage (Han *et al.* 2016). Different methods have been used in the determination of soil bulk density including direct methods which can be obtained from the core (Walter *et al.*, 2016; Cassanova *et al.*, 2016), excavation (Bauer *et al.*, 2014) and the clod (Cassanova *et al.*, 2016) procedures. Bulk density changes over time, depending on cultivation and field management operations (Don *et al.*, 2011). Jeyanny *et al.* (2014) reported soil bulk density values for topsoils of montane forest and lowland forest in Malaysia of 0.3 – 0.5 g $cm^{-3}$ and 1.2 – 1.3 g $cm^{-3}$ respectively. Hafkenscheid (2000) reported soil bulk density values at 0 – 14 cm depth between the range of 0.40 g $cm^{-3}$ and 0.72 g $cm^{-3}$ in a tropical montane forest of Jamaica. Marchio *et al.* (2016) reported mean soil bulk density in the dwarf mangroves of 0.16±0.04 g $cm^{-3}$ in Southwest Florida. Lupembe, (2014) reported soil bulk density in the range of 0.53 – 1.17 g $cm^{-3}$ with mean of 0.89±0.17 g $cm^{-3}$ in mangrove ecosystems in Tanzania. Soil bulk density is however, not an intrinsic soil property but depends on external conditions, with changes associated with a variety of factors and with various natural and anthropogenic processes (Zeng *et al.*, 2013). Given its spatial variability, an accurate and efficient sampling of bulk density has challenged soil scientists, especially in highly variable forest soils. Determining the properties of forest soils requires more intensive sampling, and they often have less predictive value than agricultural soils for site assessment purposes.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Study area

The study area included two study sites; the mangrove forest along the Great Kwa river, Calabar and the Oban division of the Cross River National Park (Figure 1). The Great Kwa River originates from the Oban hills in Cross River State, Nigeria and flows into the Cross River estuary. The Great Kwa River has a continuous band of forested mixed mangrove wetlands extending from the mouth of the river up to the reaches of the tidal flushing near Atimbo. This area estimated to be 195,000 hectares lies within latitudes 04° 45′ and 04° 15′ North of the Equator and longitudes 008° 15′ and 008° 30′ East of Greenwich Meridian. Diurnal tides exist in the area varying from high to low tides. The dominant species in the area are *Nypa fruticans* Wormb (Family: Arecaceae), *Rhizophora racemosa* Meyer (Family: Rhizophoraceae) and *Avicennia africana* Palisot de Beauvois (Family: Avicenniaceae).

The Cross River National Park (CRNP) lies between latitudes 5° 05' and 6° 29' N and longitudes 8° 15' and 9° 30' E in the south eastern corner, Cross River State, Nigeria. It covers an area of about 400, 000 hectares of primary tropical moist rainforest ecosystem in the south and central parts and montane mosaic on the Obudu Plateau. Cross River National Park is an important ecological gene pool containing one of the oldest rainforests in Africa. It lies in the Guineo-Congolian rainforest refugia with close canopy and scattered emergent trees which reach a height of 40 and 50 metres.

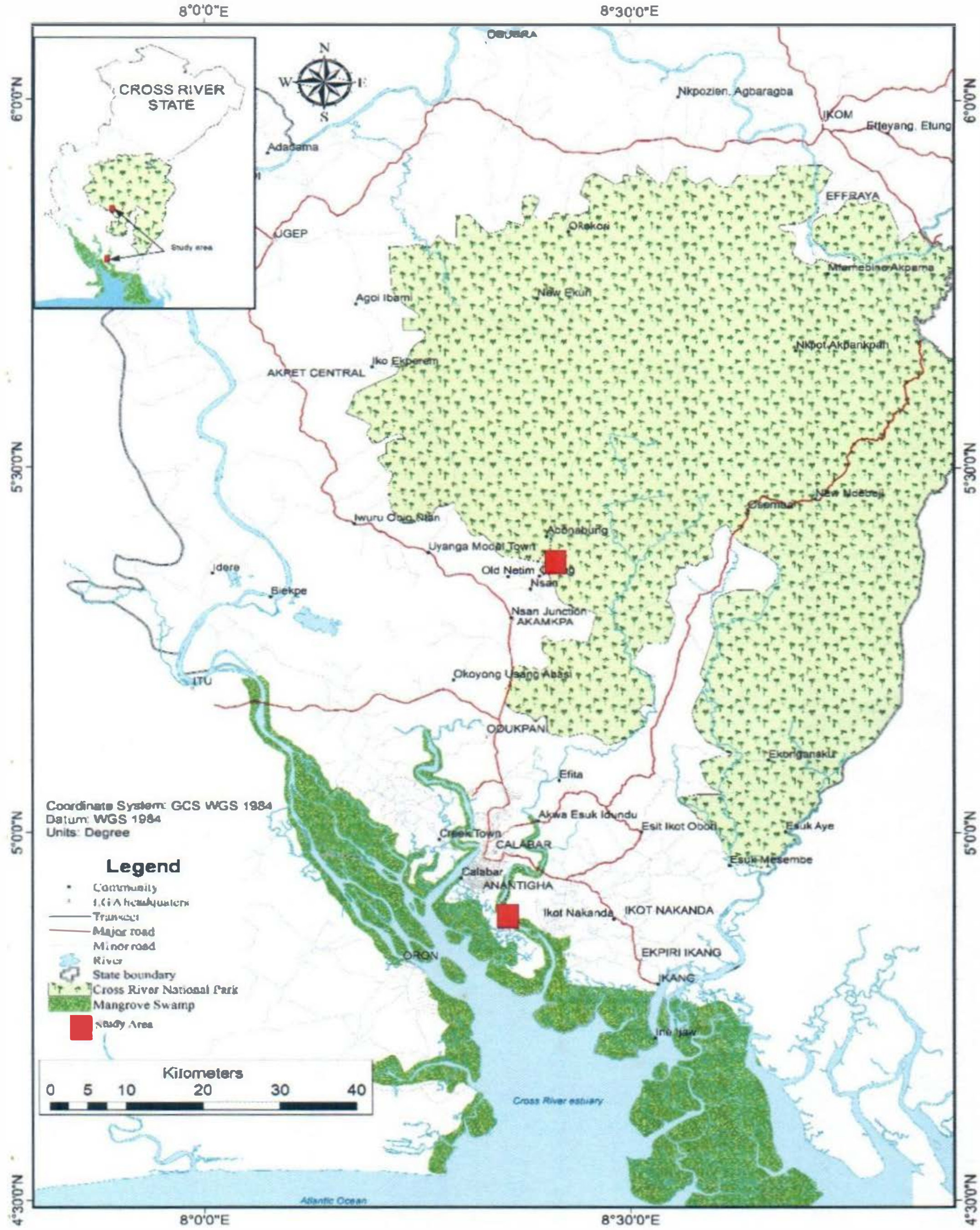


**FIG 1**: General map of study areas highlighting the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa, Cross River State, Nigeria.

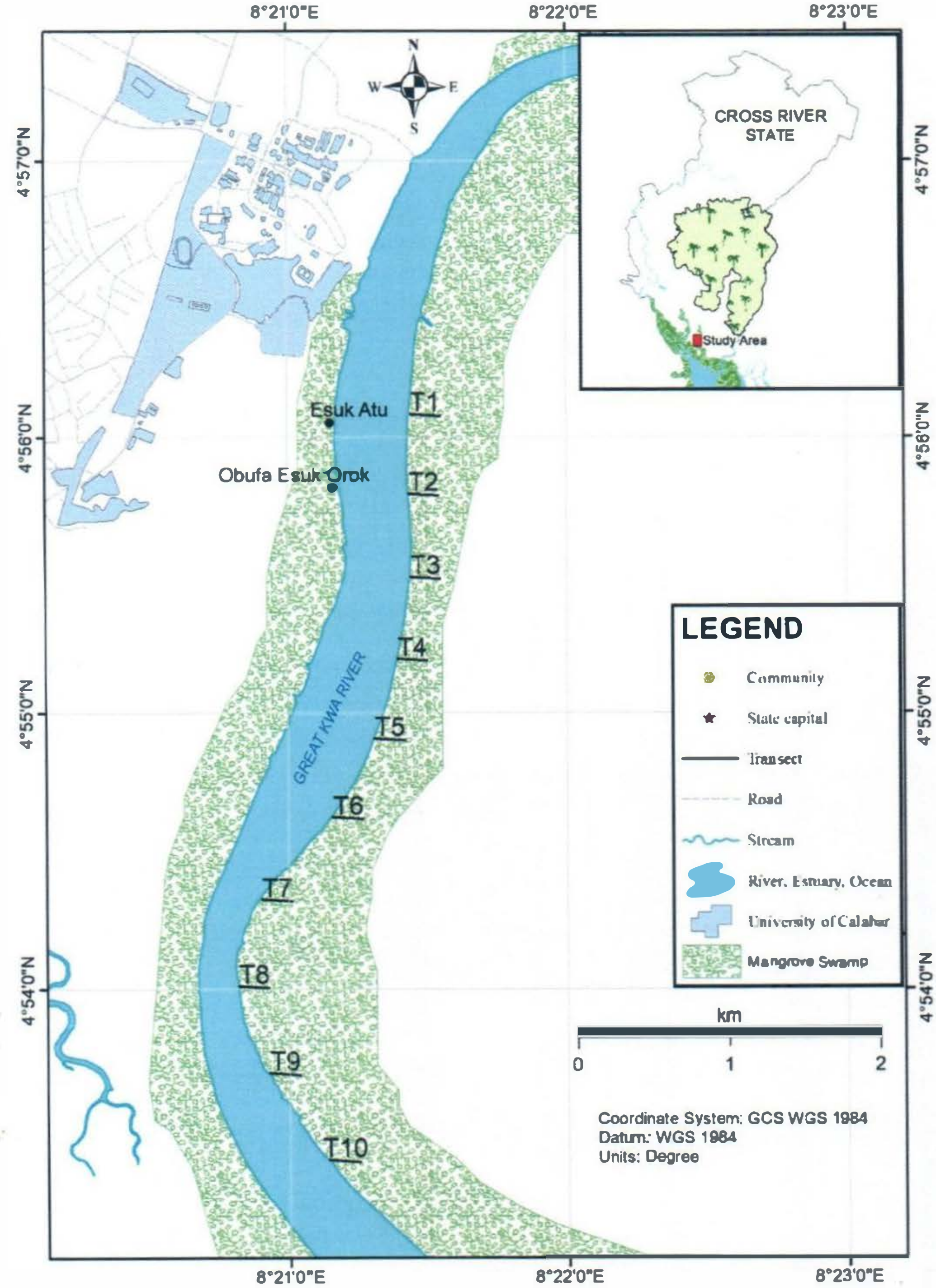


**FIG 2**: Map of study area with transect locations in the mangrove forest of Great Kwa River, Calabar, Cross River State, Nigeria.

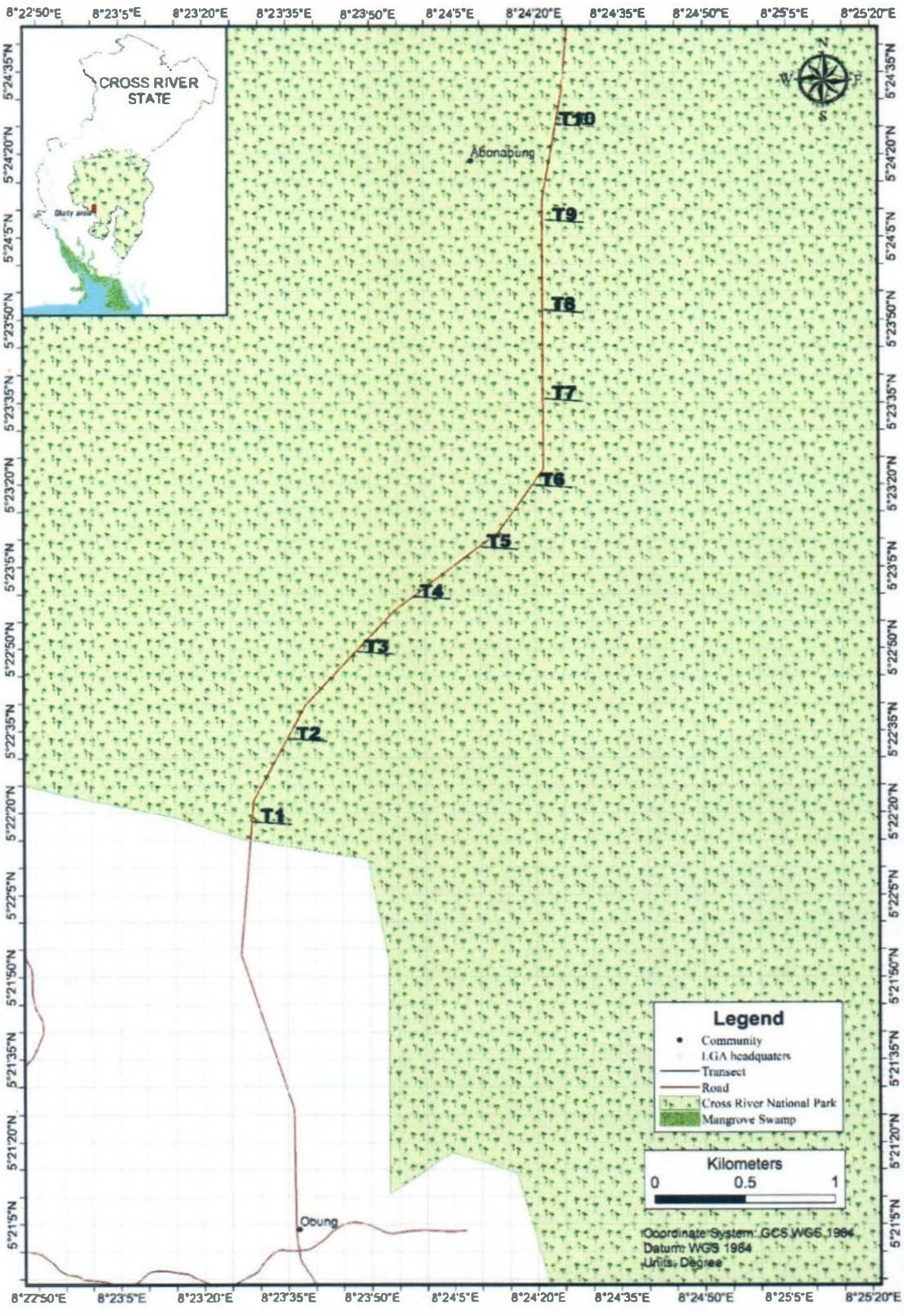


**FIG 3:** Map of study area with transect locations in rainforest of the Cross River National Park, Oban West Division, Akamkpa, Cross River State, Nigeria.

On account of its critical conservation status, it has been designated as one of the 25 United Nations biodiversity hotspots in the world. The park has two distinct non-contiguous divisions; Oban division, about 300, 000 hectares and the Okwangwo division, 100, 000 hectares. The annual precipitation ranges between 2000 mm to 3000 mm; relative humidity in and around the park is well over 30 per cent. The temperature rarely falls below 19 °C with an annual mean of 27 °C.

### 3.2 Field investigations

#### 3.2.1 Study design and plot establishment

Ten line transects of 150 m each were established systematically in both study sites along which three rectangular plots of 250 $m^2$ (10 m × 25 m) were established. In the mangrove, the first plot was established 30 m from the river ecotone at Esuk Atu (Figure 2), while in the rainforest, the first plot was established 30 m from the entry point of the forest at Erokut Camp, Akamkpa (Figure 3). A total of 30 plots each were sampled in both sites covering a total of 1.5 hectares.

#### 3.2.2 Tree sampling

Tree species in the sample plots were measured at 1.37 m above ground level to obtain diameter at breast height (DBH) using a diameter tape (Germany). All tree measurements were done non-destructively. Tree height was measured using a Nikon Forestry Pro rangefinder (Japan). Dead downed wood on the forest floor were measured using a Haglof Mantax caliper (Sweden). Dead and downed wood was non-destructively sampled using a modified planar intersect technique by Kauffman *et al*., (1998). A sub-transect of 12 m length was laid 45 ° off the main transect line. At each transect, diameter of any downed wood intersected by the transect was measured.

Downed wood was categorized into size classes and particle diameter as those determined for woody debris in upland tropical forests by Kauffman and Cole, (2010); 0 – 0.64 cm diameter, 0.64 – 2.54 cm, 2.55 – 7.5 cm and ≥ 7.6 cm diameter. Dead wood ≤ 0.64 cm diameter was measured along 2 m of the transect, 0.65 cm to 2.54 cm along 5 m, 2.55 cm to 7.5 cm along 10 m and ≥ 7.6 cm along 12 m. Canopy cover of dominant tree species in sample plots were measured using a spherical densiometer (USA). Only trees ≥ 10 cm dbh were measured. This is because smaller trees often constitute a relatively insignificant proportion of the total ecosystem carbon stock (Cummings *et al*., 2002; Kauffman and Donato, 2012).

### 3.2.3 Soil sampling

Soil samples were collected from the centre of established plots in both forest types. Four depths were sampled for bulk density, total carbon and nitrogen analysis; 0 cm – 15 cm, 15 cm – 30 cm, 30 cm – 60 cm and 60 cm – 100 cm, using a modified Russian open face peat auger, allowing for the collection of undisturbed soil cores. The collected soil samples for total carbon and nitrogen analysis and bulk density determination were carefully placed in properly labelled polythene bags respectively for transport to the laboratory for drying in the Post graduate laboratory of the Department of Plant and Ecological Studies, University of Calabar. Soil samples were dried at 60 °C for 48 hours in a hot air oven (China).

## 3.3 Laboratory analysis

### 3.3.1 Bulk density determination

Soil cores for bulk density determination were collected by the intact core method using a fabricated hollow cylindrical steel ring of diameter and height 7 cm and

10 cm respectively (McKenzie *et al.*, 2004). The point of collection was prepared by removing debris on the soil surface. The steel ring was gently hammered into the soil till it was filled with soil. Deeper layers > 10cm were sampled with the auger. Excess soil around the ring was excavated using a cutlass without disturbing the soil contained in the ring. The ring was carefully removed with the intact soil and placed in properly labelled polythene bags for transport to the laboratory and thereafter oven dried at 60 °C for 48 hours. Soil bulk density was calculated by dividing the dry soil mass by the soil volume.

### 3.3.2 Total carbon and nitrogen determination in soil

Soil total carbon and nitrogen were determined by dry combustion method (Sollins *et al.*, 1999) using a Thermal Scientific Flash EA 2000 CN analyzer at the ICRAF Soil-Plant Spectral Diagnostics Laboratory, Nairobi, Kenya. The analysis is based on the flash dynamic combustion method, which produces complete combustion of the soil sample within a high temperature reactor, followed by an accurate determination of the elemental gases produced using a thermal conductivity detector. The soil sample was weighed in tin/silver capsules, placed inside the auto-sampler at a preset time, and then dropped into an oxidation/reduction reactor kept at a temperature of 900 – 1000 °C. The exact amount of oxygen required for optimum combustion of the sample was delivered into the combustion reactor at a precise time. The reaction of oxygen with the tin capsule at elevated temperature generated an exothermic reaction which raised the temperature to 1800 °C for a few seconds. At this high temperature both organic and inorganic substances were converted into elemental gases which, after further reduction, were separated in a chromatographic column and finally detected by a highly sensitive thermal conductivity detector and the values were recorded.

### 3.4 Data analysis

Data obtained from canopy closure, biomass, carbon and nitrogen pool differences in both sites were analyzed statistically using One-way ANOVA with Statistical Package for the Social Sciences (SPSS) Version 23 for Windows and means were separated using the Duncan Multiple Range Test at P = 0.05. A two-sample Students *t*-test assuming unequal variances was performed to test that the resulting means of the estimates for the two forest types are equal.

#### 3.4.1 Canopy closure

Canopy closure was calculated by counting the number of squares of the 24 squares on the densiometer covered or not covered by vegetation. Four readings were taken and averaged to give the closure estimate per tree. The number obtained was multiplied by 1.04 to obtain percentage canopy closure. (Englund, 2000).

#### 3.4.2 Above ground biomass (AGB) and Below ground biomass (BGB)

Allometric equation for moist rainforest and mangrove by Chave *et al*., (2005) was used for the estimation of above ground biomass. The equation is as follows;

$AGB_{est} = 0.0509 \times \rho D^2 H$

Where,

$AGB_{est}$ = Above ground biomass estimate (kg)

D = Diameter at breast height (cm)

H = Tree height (m)

ρ = Wood density ($g/cm^3$);

Wood density of species were accessed from Carsan *et al*. (2012). Where wood density was unknown, the standard average of 0.6 $g/cm^3$ was used. Nypa biomass was estimated using the equation by Wilson, (2010);

$AGB_N = 0.029 \times (T)^{2.013}$

Where,

$AGB_N$ = Nypa Above ground biomass

T = Total frond length per plot

A general equation for lianas in tropical upland forest of China by Lu *et al.* (2009) was used to calculate liana biomass. The equation is as follows;

$B = 0.1498 + 1.7895 \times \ln(D) \times \ln(D)$

Where,

B = Biomass (kg)

ln = natural logarithm

D = Diameter (cm)

Below ground biomass was computed as 20 % of above ground biomass (Ponce-Hernandez, 2004).

### 3.4.3 Biomass and carbon stock density

Biomass stock density was calculated by taking the sum of all the individual weights (in kg) of a sampling plot and dividing it by the plot area. This value was converted to tonnes per hectare by multiplying by 10. Biomass stock density was converted to carbon stock density by multiplying with the IPCC, (2006) default carbon fraction of 0.47.

### 3.4.4 Dead and downed wood biomass

Biomass of downed wood was calculated using formulas by Kauffman and Cole, (2010). The formulas are listed below;

$\leq 0.64$ cm diameter; $\rho \times 100\,((\pi^2 NQMD^2)/(8L))$; where $\rho = 0.48$ and QMD = 0.43

### 3.4.7 C:N ratio

Carbon/nitrogen ratio was calculated by dividing the mass of carbon by the mass of nitrogen per depth.

### 3.4.8 Total carbon stock density

Total carbon stock density was calculated by summing the mean carbon stock density (Mg C $ha^{-1}$) of the individual carbon pools using the formula below (IPCC, 2006).

$$TeC = Cagb + Cbgb + Cddw + TCsoil$$

Where,

TeC = Total ecosystem carbon pool

Cagb = Aboveground biomass carbon stock density

Cbgb = Belowground biomass carbon stock density

Cddw = Dead and downed wood carbon stock density

TCsoil = Total soil carbon

While the total carbon stock for the project area was calculated using the formula by (Kauffman and Donato, 2012)

Total carbon stock of project area (Mg C $ha^{-1}$) = Total carbon (Mg $ha^{-1}$) × Area (ha)

### 3.4.9 Carbon dioxide equivalent ($CO_2e$)

Carbon dioxide equivalent ($CO_2e$) was calculated by multiplying the total carbon stock density by 3.67 (Pearson *et al*., 2007; IPCC, 2006)

# CHAPTER FOUR

# RESULTS

## 4.1 Canopy closure

Canopy closure in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa are presented in Figure 4, and Appendix I, II. Analysis of variance revealed no significant difference in mean canopy closure between transects sampled within both forest types (Appendix II). Mean canopy closure in the mangrove was highest in transect two (29.45±3.00 %) and least in transect four (18.61±9.23 %). In the rainforest, highest mean canopy closure was recorded in transects five and nine (89.60±0.45 % and 89.60±0.68 %), respectively, while transects four and six had the least mean canopy closure (88.30±1.30 % and 88.30±2.26 %), respectively. Independent sample t-test showed that mean canopy closure in the rainforest (88.83±1.06 %) were significantly higher ($P = 0.001$) than mean canopy closure in the mangrove (24.11±4.62 %), $t(58) = -74.63$ (Appendix III, IV).

## 4.2 Total aboveground and belowground biomass and carbon stock

Above ground biomass and carbon stock and below ground biomass and carbon stock estimates in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa are presented in Figures 5, 6, 7, 8 and Appendix I, II. Analysis of variance showed significant difference ($P = 0.05$) in above ground biomass and carbon stock and below ground biomass and carbon stock between transects sampled within both forest types (Appendix II).

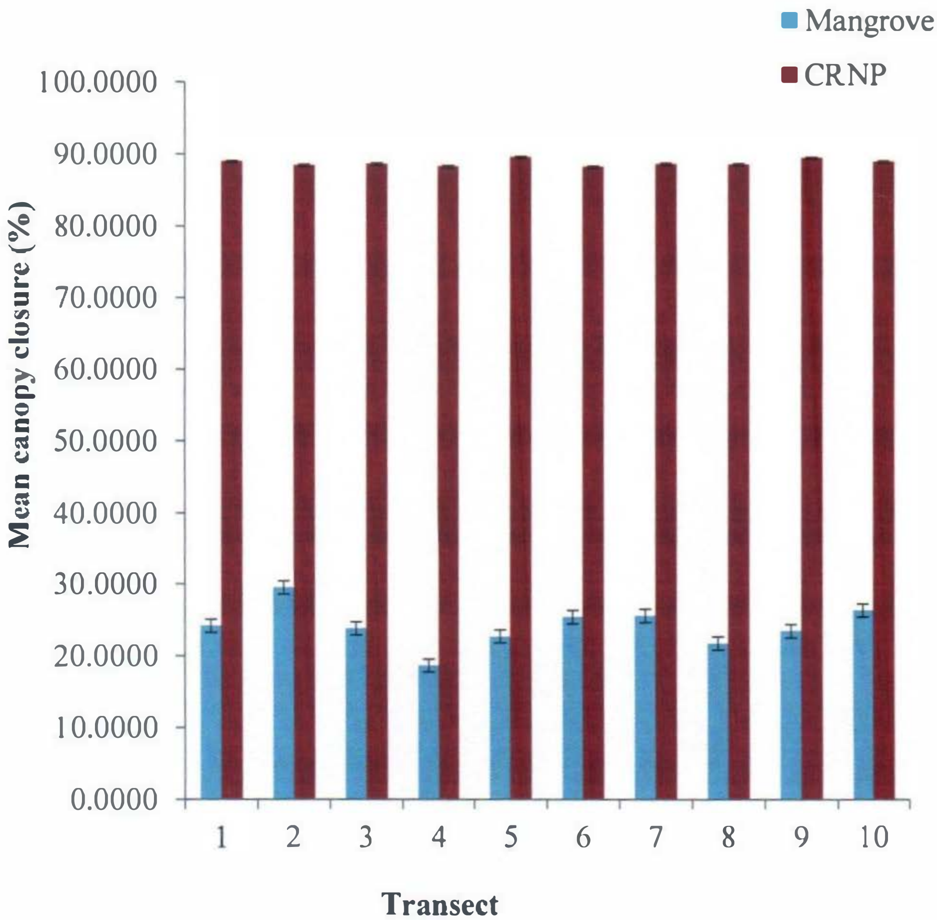


**FIG 4:** Mean canopy closure in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

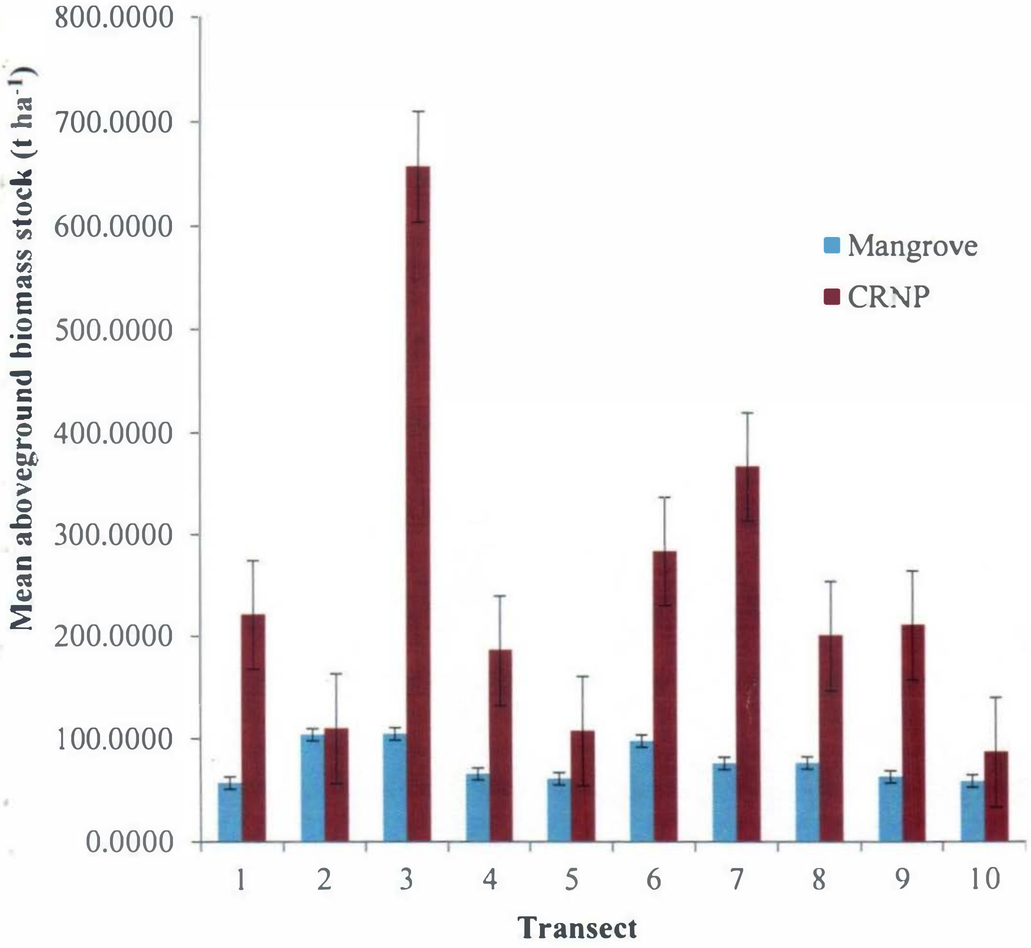


**FIG 5:** Mean aboveground biomass (AGB) stock in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

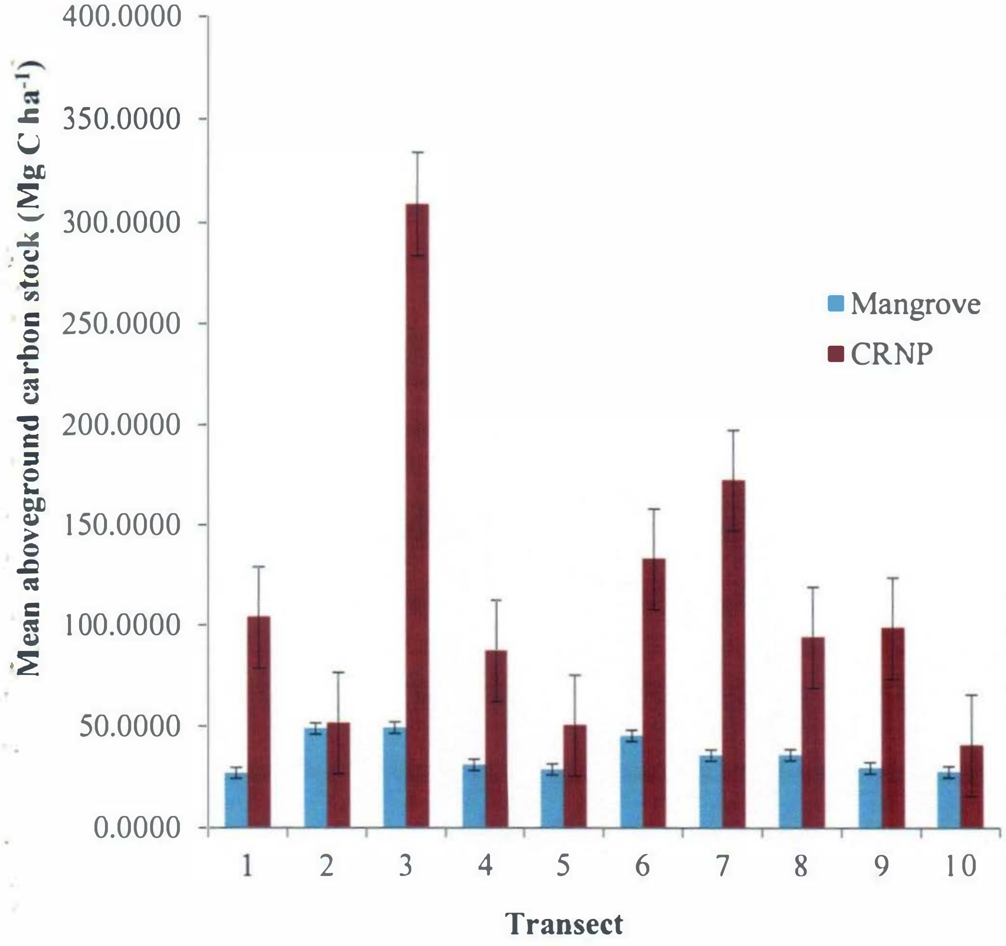


**FIG 6:** Mean aboveground carbon stock in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

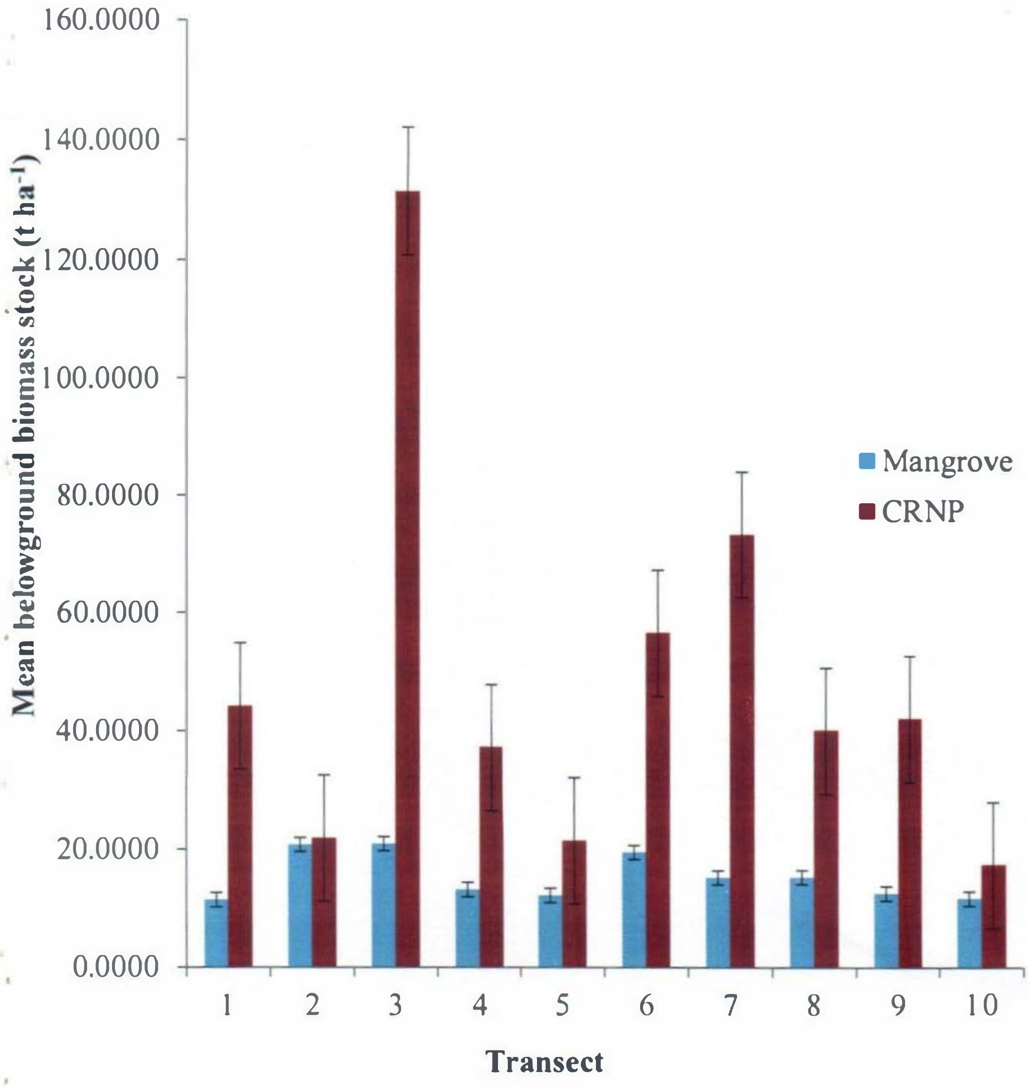


**FIG 7:** Mean belowground biomass stock in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

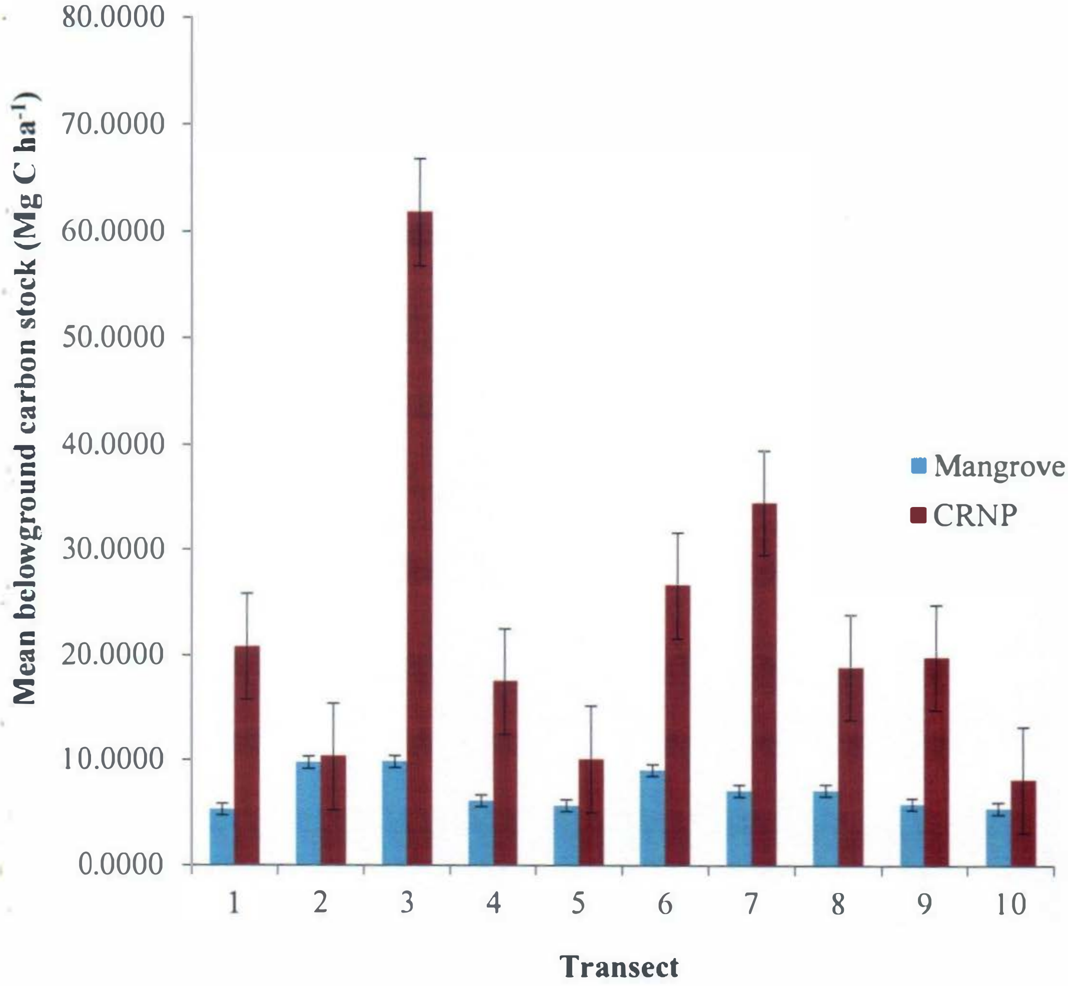


**FIG 8:** Mean belowground carbon stock in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria

In the mangrove and rainforest the highest mean aboveground biomass and carbon stock and below ground biomass and carbon stock were recorded in transect three (104.67±6.57 t $ha^{-1}$; 49.19±3.08 Mg C $ha^{-1}$, 20.93±1.31 t $ha^{-1}$; 9.83±0.61 Mg C $ha^{-1}$) and (657.49±81.90 t $ha^{-1}$; 309.02±38.49 Mg C $ha^{-1}$, 131.49±16.38 t ha-1; 61.80±7.70 Mg C $ha^{-1}$), respectively (Appendix I). The least mean aboveground biomass and carbon stock and belowground biomass and carbon stock were recorded in transects one in the mangrove (56.94±5.04 t $ha^{-1}$; 26.76±2.37 Mg C $ha^{-1}$, 11.38±1.00 t $ha^{-1}$; 5.34±0.47 Mg C $ha^{-1}$) and transect ten in the rainforest (86.49±23.43 t ha-1; 40.65±11.01 Mg C $ha^{-1}$, 17.29±4.68 t $ha^{-1}$; 8.12±2.19 Mg C $ha^{-1}$), respectively (Appendix I). Independent sample t-test showed that mean aboveground biomass and carbon stock, and belowground biomass and carbon stock in the rainforest (242.82±195.79 t $ha^{-1}$, 114.12±92.02 Mg C $ha^{-1}$ and 48.55±39.16 t $ha^{-1}$, 22.82±18.40 Mg C $ha^{-1}$) respectively (Appendix III), were significantly higher ($P = 0.001$) than mean aboveground biomass and carbon stock, and belowground biomass and carbon stock in the mangrove (76.08±22.40 t $ha^{-1}$, 35.71±10.49 Mg C $ha^{-1}$ and 15.21±4.48 t $ha^{-1}$ 7.13±2.09 Mg C $ha^{-1}$) respectively, $t(58) = -4.63$ (Appendix IV).

## 4.3 Dead and downed wood carbon stock

Dead and downed wood biomass and carbon stock estimates for the different size classes sampled in the mangrove forest of the Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban Division, Akamkpa are presented in Figure 9, Table 1 and Appendix V. Analysis of variance showed significant difference

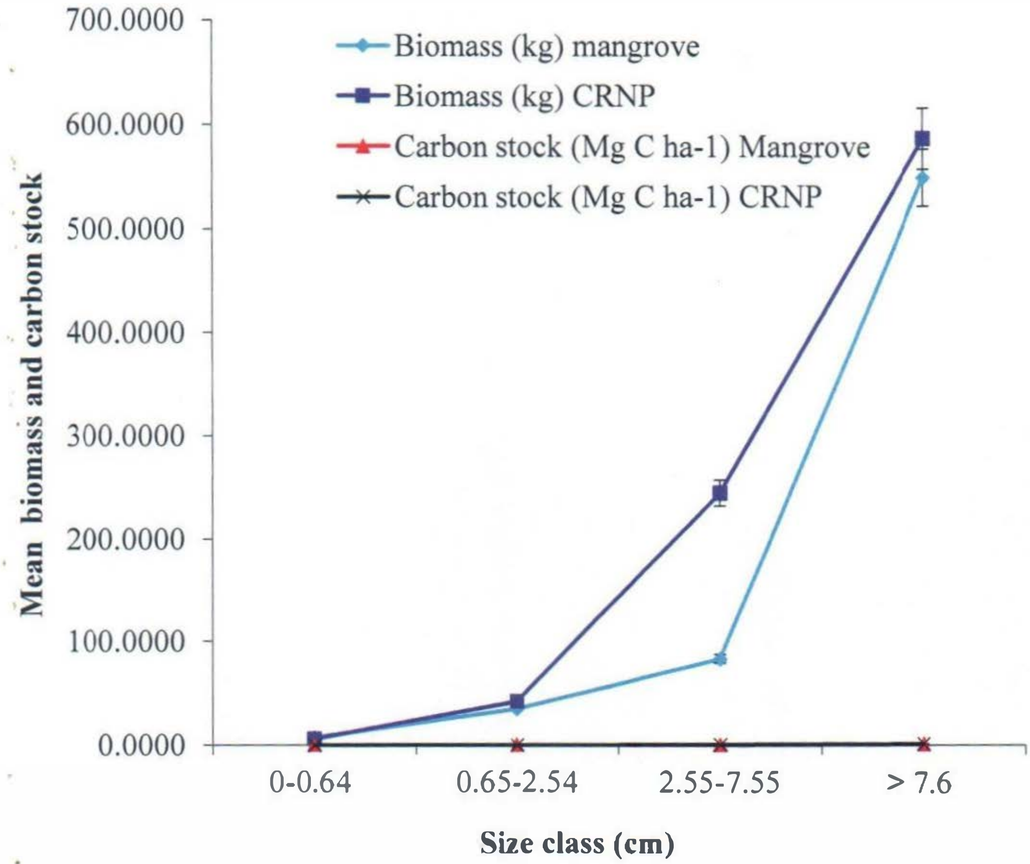


**FIG 9:** Mean dead wood biomass and carbon stock in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

TABLE 1

Mean dead and downed wood biomass and carbon stock by size class in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

| Size class (cm) | Mangrove biomass (kg) | Rainforest Biomass (kg) | Mangrove carbon stock Mg C ha$^{-1}$ | Rainforest carbon stock Mg C ha$^{-1}$ |
|---|---|---|---|---|
| 0 – 0.64 | 7.45±5.82 | 5.83±6.41 | 0.01±0.01 | 0.01±0.01 |
| 0.65 – 2.54 | 35.26±31.66 | 42.08±45.41 | 0.05±0.05 | 0.04±0.06 |
| 0.65 – 2.54 | 85.31±121.94 | 244.57±263.69 | 0.16±0.24 | 0.48±0.52 |
| > 7.6 | 549±1087.44 | 586.78±1190 | 1.09±2.17 | 1.17±2.37 |

(P = 0.05) in the mean downed wood biomass and carbon stock between the different size classes (Appendix V). Mean dead and downed wood biomass and carbon stock in both forests increased with increasing size class. The highest and least mean biomass and carbon stock of dead and downed wood in the mangrove were 549±1087.44; 7.45±5.82, and 1.09±2.17 Mg C ha$^{-1}$; 0.01±0.01 Mg C ha$^{-1}$, respectively. In the rainforest, the highest and least mean dead and downed wood biomass and carbon stock were 586.78±1190; 5.83±6.41 and 1.17±2.37 Mg C ha$^{-1}$; 0.01±0.01 Mg C ha$^{-1}$, respectively (Table 1).

## 4.4 Soil bulk density

Soil bulk density at different depths sampled in the mangrove forest of the Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa are presented in Figure 10, Table 2 and Appendix VI. Analysis of variance showed no significant difference in bulk densities at the different depths sampled within both forests (Appendix VI). The highest and lowest mean soil bulk density in the mangrove was recorded in depths 15 – 30 cm with 0.40±0.07 g cm$^{-3}$ and 30 – 60 cm with 0.39±0.07 g cm$^{-3}$, respectively. In the rainforest, the highest and least mean soil bulk density was recorded in depths 0 – 15 cm with 0.80±0.13 g cm$^{-3}$ and 15 – 30 cm with 0.76±0.14 g cm$^{-3}$, respectively (Table 2).

## 4.5 Total soil carbon and nitrogen stocks

Total soil carbon and nitrogen estimates in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa are presented in Figures 11, 12 and Appendix I. Analysis of variance showed

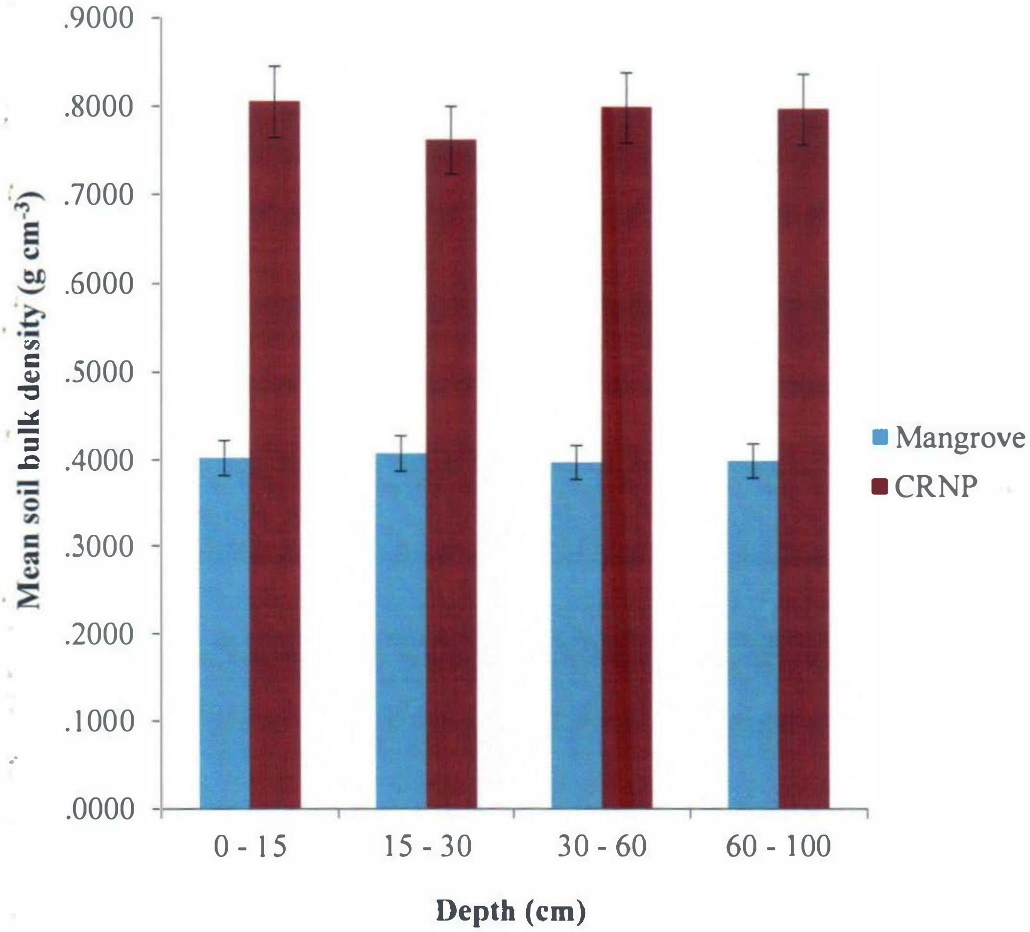


**FIG 10:** Mean bulk density of soil at sampled depths in the mangrove forest of Great Kwa river Calabar and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

## TABLE 2

Mean soil bulk density at different depths in the mangrove forest of Great Kwa river, Calabar and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

| Depth (cm) | Mangrove soil bulk density (g $cm^{-3}$) | Rainforest soil bulk density ( g $cm^{-3}$) |
|---|---|---|
| **0 – 15** | 0.40±0.08 | 0.80±0.13 |
| **15 – 30** | 0.40±0.07 | 0.76±0.14 |
| **30 – 60** | 0.39±0.07 | 0.79±0.16 |
| **60 – 100** | 0.39±0.07 | 0.79±0.16 |

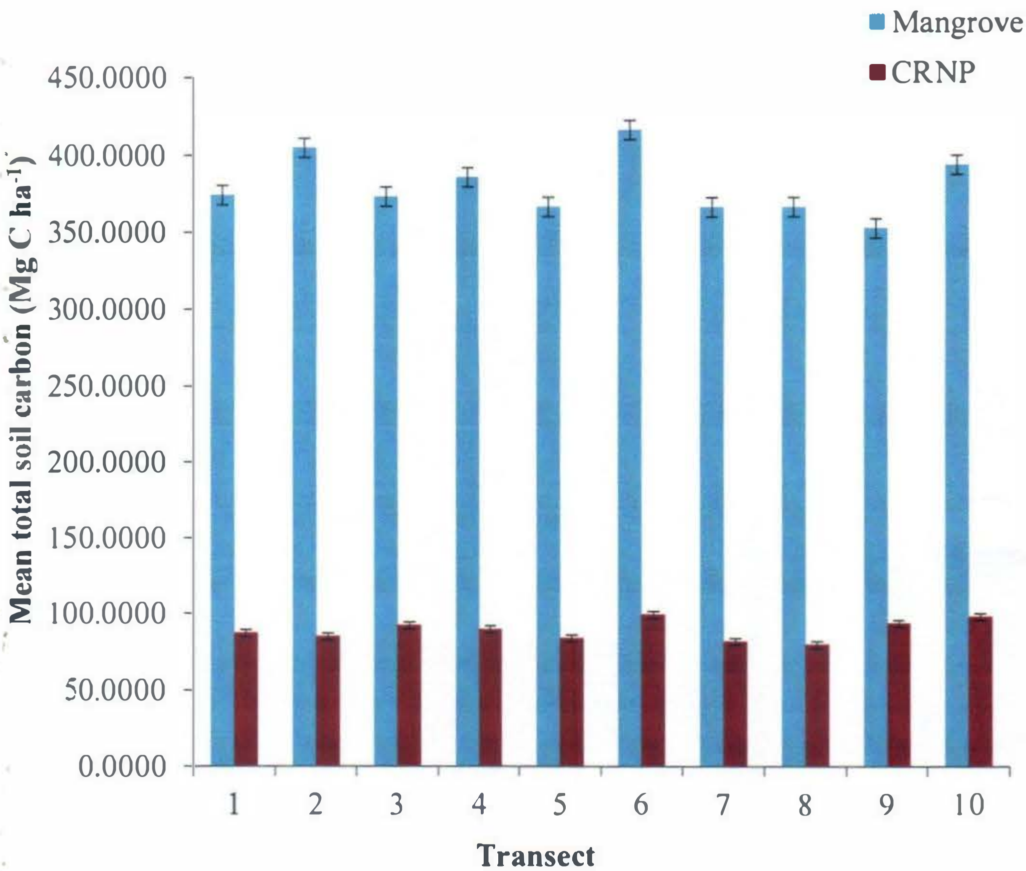


**FIG 11:** Mean total soil carbon in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

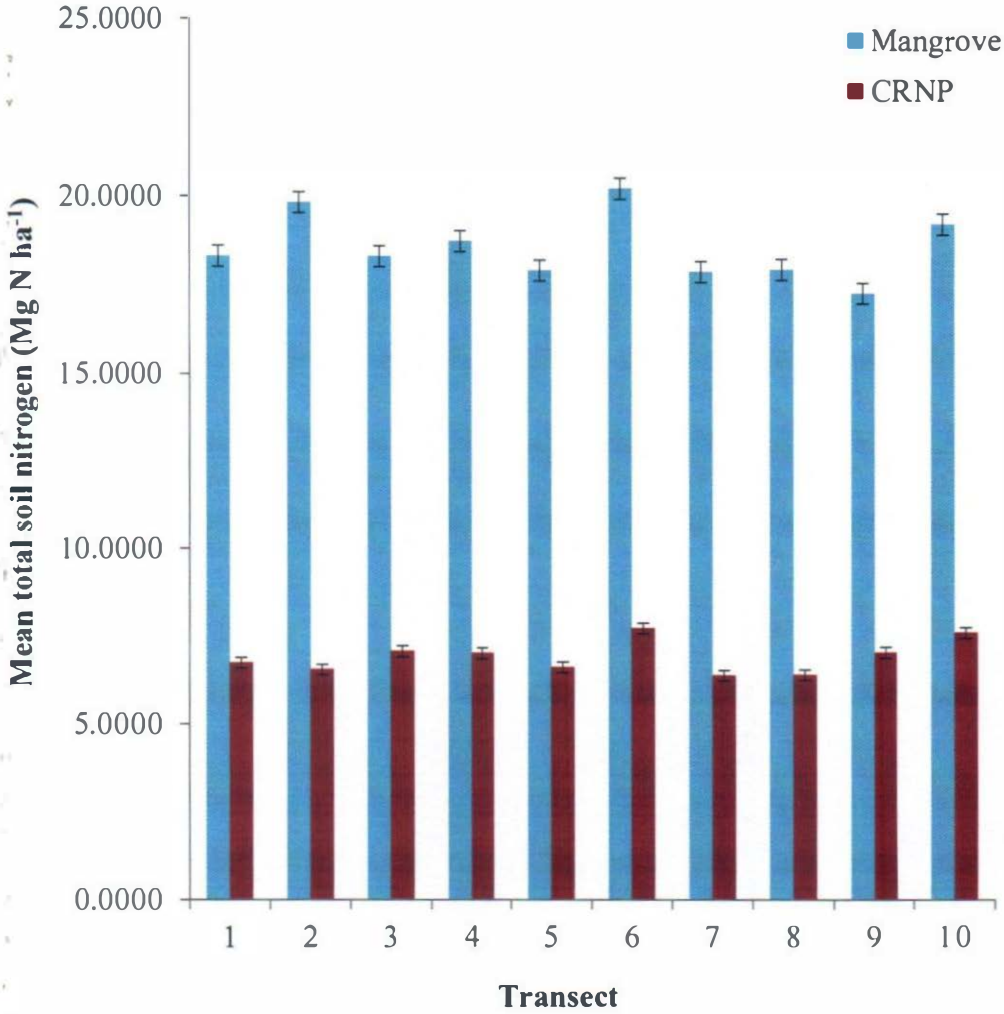


**FIG 12:** Mean total soil nitrogen in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

no significant difference in soil carbon estimates between transects sampled in both forests (Appendix II). In the mangrove forest, the highest and least mean total soil carbon was recorded in transect six (416.55±23.66 Mg C $ha^{-1}$ and transect nine (353.31±46.32 Mg C $ha^{-1}$), respectively (Appendix I). In the rainforest, highest and least mean total soil carbon was recorded in transect six (99.32±7.77 Mg C $ha^{-1}$) and transect eight (80.12±9.33 Mg C $ha^{-1}$), respectively. Independent sample t-test showed that mean total soil carbon in the mangrove (380.13±41.09 Mg C $ha^{-1}$) were significantly higher ($P = 0.001$) than mean total soil carbon in the rainforest (89.27±10.84 Mg C $ha^{-1}$), $t(58) = 37.48$ (Appendix III, IV).

Analysis of variance showed no significant difference in mean total soil nitrogen estimates between transects sampled within both forests (Appendix II). Mean total soil nitrogen in the mangrove was highest in transect six (20.21±1.20 Mg N $ha^{-1}$) and least in transect nine (17.26±2.36 Mg C $ha^{-1}$). In the rainforest, the highest and least mean total soil nitrogen was recorded in transect six (7.71±0.38 Mg N $ha^{-1}$) and transect 7 (6.39±1.43 Mg N $ha^{-1}$), respectively (Appendix I). Independent sample t-test showed that mean total soil nitrogen in the mangrove (18.55±1.99 Mg N $ha^{-1}$) was significantly higher ($P = 0.001$) than mean total soil nitrogen in the rainforest (6.91±0.77 Mg N $ha^{-1}$), $t(58) = 29.75$ (Appendix III, IV).

Analysis of variance showed no significant difference in mean carbon/nitrogen (Figure 13, Appendix II) ratios between transects sampled within both forests. Mean carbon/nitrogen ratio in the mangrove was highest in transect four (20.62±0.33:1) and least in transect three (20.37±0.09:1). In the rainforest, the highest and least mean carbon/nitrogen ratio was recorded in transects nine (13.36±0.57:1) and transect eight (12.48±0.39:1), respectively (Appendix I). Independent sample t-test showed mean

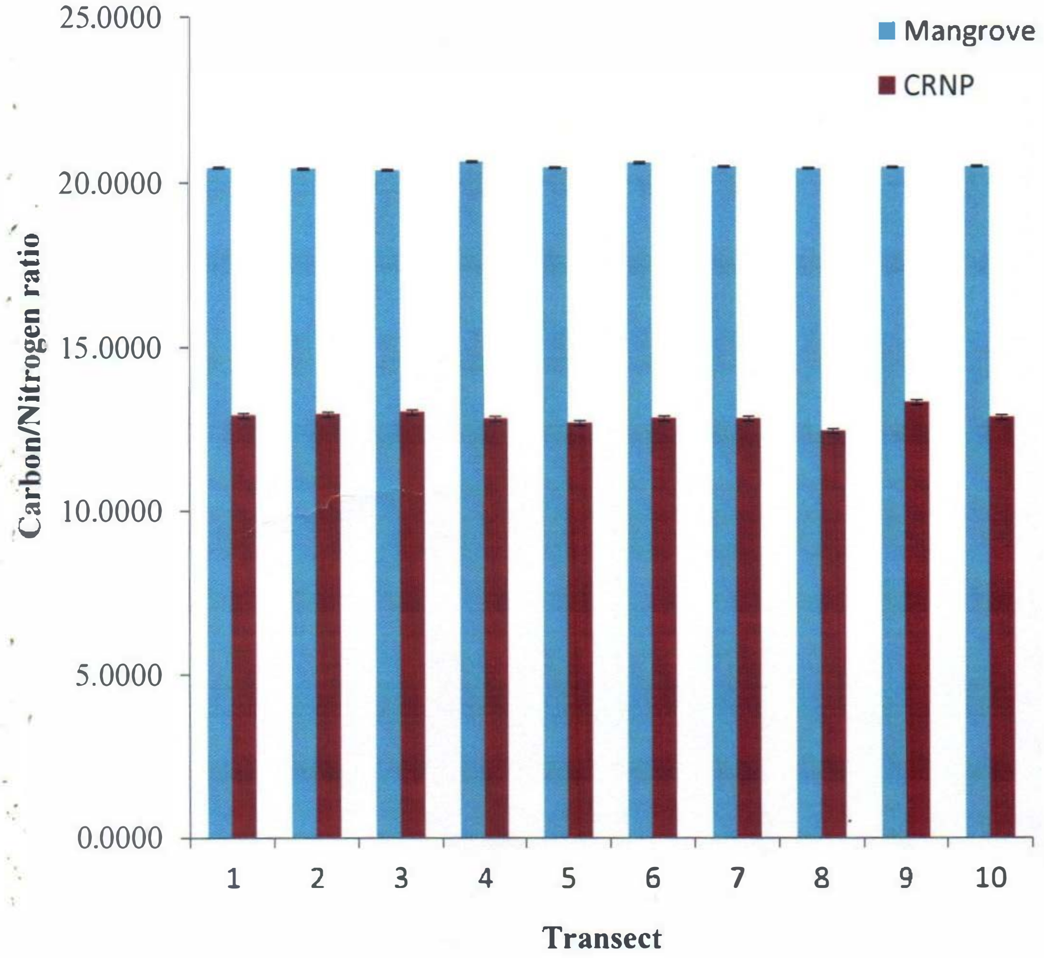


**FIG 13:** Mean carbon/nitrogen ratio in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria.

carbon/nitrogen ratio in the mangrove (20.48±0.27:1) was significantly higher (P = 0.001) than mean carbon/nitrogen ratio in the rainforest (12.08±0.58:1). t (58) = 64.74 (Appendix III, IV).

### 4.6 Total carbon stock, project area total and carbon dioxide equivalent

Total carbon stock density estimates for the mangrove forest of the Great Kwa river, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa are presented in Figure 14. In the mangrove, total carbon stock density was 423.31 Mg C $ha^{-1}$. Total carbon in soil ranked highest in constituting the total carbon stock density with 89.79 %, followed by aboveground biomass with 8.43 %, belowground biomass 1.68 %, and dead and downed wood biomass with 0.07 %. Carbon dioxide equivalent ($CO_2e$) of the mangrove was 1, 553.54 Mg. In the rainforest, total ecosystem carbon stock estimate was 226.65 Mg C $ha^{-1}$. Aboveground biomass ranked highest, constituting 50.35 %, followed by total carbon in soil with 39.38 %, belowground biomass, 10.06 % and dead and downed wood with 0.18 %. Carbon dioxide equivalent ($CO_2e$) of the rainforest was 831.80 Mg.

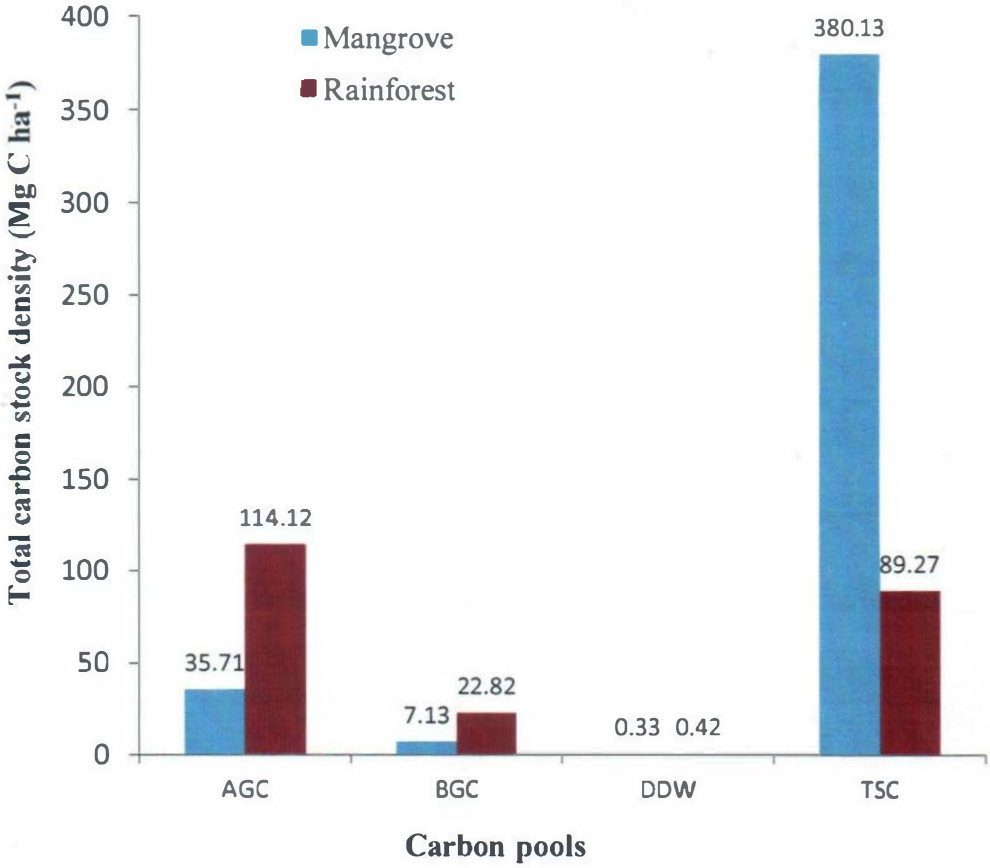


**FIG 14:** Total carbon stock density of pools in the mangrove forest of Great Kwa river Calabar, and rainforest of the Cross River National Park, Oban West Division, Akamkpa, Cross River State, Nigeria. AGC: Aboveground carbon, BGC: Belowground carbon, DDW: Dead and downed wood, TSC: Total soil carbon.

# CHAPTER FIVE

# DISCUSSION, SUMMARY AND CONCLUSION

## 5.1 Discussion

### 5.1.1 Canopy closure

Canopy closure in forests have been directly related to the light regime and microclimate, therefore affecting plant growth and survival at the point of measurement (Gonsamo *et al*., 2013). Parker (2014) noted that percent canopy closure measured with a densiometer helped to predict gap light index of forests. The higher canopy closure estimates of this study in the rainforest (88.83 %) in contrast to the mangrove forest (24.11 %) (Figure 4, Appendix I) depicts a contrast in ecosystem forest textural characteristics and forest structure (Bongers, 2001). The rainforest canopy closure estimates in this study were comparable with estimates reported for red and white pines in eight different locations in Ontario of 47.8 %, 65.7 %, 42 %, 61.0 %, 66.6 %, 87.8 %, 65.8 % and 82.0 % using a spherical densiometer (Parker, 2014), and in Italy of 86.2 % (Paletto and Tosi, 2009). Mangrove canopy closure estimates in this study were slightly higher than that reported by Loria-Naranjo *et al.* (2014) of 17.2 % in Santa Rosa National Park, Costa Rica. The canopy closure estimates in the mangrove were generally low compared to the rainforest and may be due to large canopy gaps which are a common feature in mangroves facing disturbance regimes such as selective harvesting and natural mortality of trees (Miles *et al*., 2006). However, gaps created that reduce canopy closure provide opportunity for tree recruitment within the mangroves as there is increased light penetration to the forest floor (Sherman *et al*., 2000). As canopy closure increases, the forest microclimate is increasingly protected from direct solar radiation and provides lower maximum temperatures and increased humidity, a phenomenon termed 'mesophication' (Nowacki and Abrams, 2008). The overall effect of this phenomenon is uncertain, but most likely canopy closure may counteract the effects of macroclimate warming on the forest understory (De Frenne *et al*., 2013; Nowacki & Abrams, 2015). Also, with photosynthetic rates being proportional to growth, more biomass and slower decomposition rate occurs where there is high closure and less biomass and higher decomposition rates where closure is low (Maginniss *et al*., 2002). Canopy closure directly or indirectly governs development and distribution of understorey vegetation by regulating understorey light and soil conditions (Chen *et al*., 1999; Bartels and Chen, 2010; Verheyen *et al*., 2012).

### 5.1.2 Total above-ground and below-ground biomass and carbon stock

The above ground biomass and carbon stock estimates of the mangrove forest of the Great Kwa river in this study was 76.08±22.40 t $ha^{-1}$ and 35.71±10.49 Mg C $ha^{-1}$ respectively (Figures 5, 6 and Appendix I). These estimates were lower than estimates reported by Sitoe *et al*. (2014) of 134.6 t $ha^{-1}$ and 58.6 Mg C $ha^{-1}$ in Sofala bay, Central Mozambique, Abino *et al*. (2014), 561.2 t $ha^{-1}$ and 263.8 Mg C $ha^{-1}$ in a natural mangrove forest in Palawan, Trettin *et al*. (2015), 113 t $ha^{-1}$ in mangroves of the Zambezi river delta, Chandra *et al*. (2011), and 116.8 t $ha^{-1}$ in Sarawak mangrove forest in Malaysia. Kauffman *et al*. (2011) reported mean above ground biomass stock estimates in the range of 254 t $ha^{-1}$ to 406 t $ha^{-1}$ in Micronesian mangroves, which were greater than the results of this study. Higher mangrove above ground biomass carbon stocks were reported by Kridiborwon *et al*. (2012) of 140.5 Mg C $ha^{-1}$ in Thailand, and lower than the results of this study were reports by Chen *et al*. (2012) of 55.0 Mg C $ha^{-1}$ in China. These differences may be as a result of variations in allometric equations as some equations are species-specific, as this study made use of general equations generated elsewhere for the tropics (Chave *et al*., 2005). However, the estimates of this study were comparable and slightly higher than the reports by Khan and Subasinghe, (2018) of 63.04 t $ha^{-1}$ and 22.05 Mg C $ha^{-1}$ in the mangroves of Muthurajawela wetland, Sri Lanka and Fatoyinbo *et al*., (2008) of 67 t $ha^{-1}$ in Inhambane, along the Mozambique coasts, Murdiyarso *et al*. (2009) of 61.4 t $ha^{-1}$ in north Sulawesi. The above ground biomass and carbon stocks estimates of this study are also within the ranges reported by Borah *et al*. (2013) of 32.47 t $ha^{-1}$ - 261.64 t $ha^{-1}$ and 16.24 Mg C $ha^{-1}$ - 130.82 Mg C $ha^{-1}$ in Northeast India, although the upper limits are far greater. Hastuti *et al*. (2017) and Bindu *et al*., (2018) reported mangrove above ground biomass estimates of 38.60 t $ha^{-1}$ in Bali and 19.33 t $ha^{-1}$ in Kerala, Indonesia, respectively using remote sensing. These estimates were lower than the estimates in this study and may be due to the method employed in biomass estimation. Lu, (2006), stated that field measurements are the most accurate in biomass data collection though expensive, time consuming and labour intensive.

Below ground biomass and carbon stock estimates in the mangrove forest in this study were 15.21±4.48 t $ha^{-1}$ and 7.13±2.09 Mg C $ha^{-1}$, respectively (Figures 7, 8 and Appendix I). Below ground biomass was estimated using 20 percent of above ground biomass (Ponce-Hernandez, 2004). Below ground biomass stock estimates for dwarf mangroves in Mexico have been reported by Adame *et al*. (2013) as 8.7 t $ha^{-1}$ and Trettin *et al*., (2015) reported a combined below ground biomass stock of 11.40 t $ha^{-1}$. These estimates are comparatively lower than the estimates in this study and may be due in part to the height differences of tree species within sampled forests. High below ground biomass stock and carbon stock estimates compared to the results of this study, were reported by Abino *et al*. (2014) of 196.50 t $ha^{-1}$ and 92.30 Mg C $ha^{-1}$, Kauffman *et al*. (2011) of 171.0 t $ha^{-1}$ in Palau 80.0 Mg C $ha^{-1}$ and 312.0 t $ha^{-1}$ and 144.0 Mg C $ha^{-1}$ in Yap. These high estimates may be attributed to marked differences in tree trunk diameters of species in their sample sites as tree trunk plays a major role in the estimates of biomass using allometric equations (Komiyama *et al*., (2005). Santos *et al*. (2017) stated that several factors can regulate the belowground biomass in mangrove forests, and consequently, the carbon stock associated with it, including the position of the area that is being sampled and its relation to the water body, or flood tide frequency, and its position in relation to the continent. Aboveground and belowground biomass and carbon stock estimates in rainforest of the Cross River National Park was 242.82±195.79 t $ha^{-1}$ and 114.12±92.02 Mg C $ha^{-1}$ and 48.55±39.16 t $ha^{-1}$, 22.82±18.40 Mg C $ha^{-1}$, respectively (Figures 5, 6,7 8 and Appendix I). These results are comparable to results reported for rainforests in other locations. For instance, Gairola, (2011) reported total live tree biomass density of 215.5 t $ha^{-1}$ and carbon density of 107.8 Mg C $ha^{-1}$, Borah *et al*. (2013), mean aboveground biomass stock ranged from 32.47 t $ha^{-1}$ - 261.64 t $ha^{-1}$ and carbon stock ranges from 16.24 Mg C $ha^{-1}$ to 130.82 Mg C $ha^{-1}$, respectively. Rana *et al*. (2015) reported total biomass of trees ranging between 178 t $ha^{-1}$ and 431 t $ha^{-1}$, and carbon stock between 89.07 Mg C $ha^{-1}$ and 206 Mg C $ha^{-1}$. Thokchom and Yadava, (2017) estimated aboveground biomass and carbon stock ranges between 124.56 t $ha^{-1}$ and 254.99 t $ha^{-1}$ and 60.09 Mg C $ha^{-1}$ to 121.43 Mg C $ha^{-1}$, respectively. Salunkhe *et al*. (2014) reported estimates of aboveground biomass and carbon stock in tropical deciduous forests in India ranging from 3.99 t $ha^{-1}$ - 53.90 t $ha^{-1}$ and 1.89 Mg C $ha^{-1}$ - 25.6 Mg C $ha^{-1}$, respectively, across different study sites. Mtui, (2017) reported aboveground biomass and carbon stock of 168.51 t $ha^{-1}$ and 79.20 Mg C $ha^{-1}$ in a tropical rainforest in Malaysia. Ekoungoulou *et al*. (2014) reported mean above ground carbon stocks estimates in a tropical rainforest in Congo of 168.601 Mg C $ha^{-1}$ and 39.551 Mg C $ha^{-1}$ for belowground suggesting higher biomass stocks than the results of this study. The variation in estimates compared to the estimates of this study may be due to variations in carbon dynamics within tree species and soil in these locations as well as differing vegetation types. Comparing the biomass and carbon stocks of the two forest types sampled in this study, results revealed significantly higher biomass and carbon stocks of the rainforest with reference to the mangrove forest. The differences in biomass may be attributed to varied ecosystem processes and dynamics within both forests which are driven ultimately by the long-term balance between the rate at which wood has been produced and the rate at which it has been lost. Likewise, biomass change, a key variable for understanding forest carbon budgets, results from imbalances between these growth and loss terms (Pan *et al.*, 2013). Increased temperature in terrestrial environments as pointed out by Rusu (2013), determines an increase in the amount of natural atmospheric $CO_2$, which significantly boosts photosynthesis, and enhance metabolism as well as increase the amount of vegetation biomass. Quesada *et al.* (2012) stated that forest attributes including biomass production are also strongly influenced by disturbances, edaphic conditions, topography, and successional sequences. Also, human-induced global environmental changes exert complex effects on forest productivity and carbon storage (Friedlingstein *et al.*, 2006; Magnani *et al.*, 2007).

### 5.1.3 Dead and downed wood carbon stock

The dead and downed wood carbon stock in this study was found to increase with increasing size class in both forests. Carbon stock in the mangrove ranged from 0.01±0.01 Mg C ha$^{-1}$ to 1.09±2.17 Mg C ha$^{-1}$, respectively. While, the rainforest, ranged from 0.01±0.01 Mg C ha$^{-1}$ respectively to 1.17 Mg C ha$^{-1}$, respectively (Table 1). Reports by Woodall *et al.* (2013) on downed wood carbon stock averaged 0.9 Mg ha$^{-1}$ in the United States and is comparable with the results of this study. Oswalt *et al.* (2008)

reported a range of 4.6 – 28.3 Mg ha$^{-1}$, Adame *et al.* (2013), reported a range of 7.0 – 25.7 Mg ha$^{-1}$. Kauffman, *et al.* (2011) reported estimates in the range of 29.6 Mg ha$^{-1}$ and 43.1 Mg ha$^{-1}$ in mangroves in the Federated States of Micronesia and Ngo *et al.* (2013) reported estimates ranging from 8.3 Mg ha$^{-1}$ to 31.3 Mg ha$^{-1}$ in tropical forests in Singapore. These estimates are greater than the estimates of this study, and may be due to inclusion of litter biomass estimates in those studies (Oswalt *et al.*, 2008). Also variations in nomenclature of what constitutes dead and downed wood biomass has led to over or under estimation, depending on whether standing and downed stems and branches, stumps, and dead coarse roots belowground are collectively sampled or some components are excluded (Harmon *et al.*, 2013). Differences in methods of estimation either directly or indirectly with the use of volume estimators and associated biomass conversion constants, which could be general or species specific can give inconsistent estimates (Woodall and Monleon, 2008; Fraver *et al.*, 2007). The accuracy of woody detritus biomass estimates can be improved by incorporating wood density by decay class, species, position with respect to the soil surface, and tissue type (Harmon *et al.*, 2013). Domke *et al.* (2013) stated that the inventory and monitoring of dead and downed wood carbon stocks are essential components of any comprehensive National Greenhouse Gas Inventory (NGHGI). Dead and downed wood dynamics play a key role in many forest ecosystems therefore, understanding the mechanisms involved in the accumulation and depletion of deadwood can enhance our understanding of fundamental processes such as carbon sequestration and disturbance regimes, allowing better predictions of future changes related to alternative management and climate scenarios (Garbarino *et al.*, 2015).

in mangrove forests of Zambezi Delta, Mozambique, Kauffman *et al.* (2011), found 236 Mg $ha^{-1}$ of soil carbon at Yap mangrove forest. Sahu *et al.* (2016) found 54.3 Mg $ha^{-1}$ and 57.6 Mg $ha^{-1}$ in soil to a depth of 30 centimetres in natural and plantation mangroves respectively, in Mahanadi forest in India. These results were lower than the results in this study and may be attributed to the increment in depths sampled in this study. Kauffman *et al.* (2014) reported soil carbon stocks in three mangrove forests in the Dominican republic of 546 Mg $ha^{-1}$, 1084 Mg $ha^{-1}$, and 713 Mg $ha^{-1}$ respectively. Murdiyarso *et al.* (2009) reported 822.1 Mg $ha^{-1}$ in Indonesia. These results were higher than the results of this study and may be due to higher bulk density values of soils in those regions. Depth differences in carbon stock and variations in soil type and landscape could also be a contributing factor to the higher stocks recorded in those studies (Kairo *et al.*, 2008; Quesada *et al.*, 2010). Soil carbon stock in the rainforest were comparable with the results of Walker and Desanker, (2004) with reports of an average of 85 Mg $ha^{-1}$ to a depth of 150 centimetres in Miombo woodlands of Malawi. Also, Dos Santos *et al.* (2015) reported soil carbon stocks to a depth of 30 centimetres of 61.4 Mg $ha^{-1}$ and 47.7 Mg $ha^{-1}$ in disturbed and undisturbed plots, respectively, in a central Amazon forest. The soil carbon stocks of the mangrove in this study was four times that of the rainforest and are lower than the estimates reported for mangroves by other authors. Mangrove forests are reported (Sanderman *et al.*, 2018) as having more soil carbon than other forest types globally on an equal area basis. Donato *et al.* (2011) stated that tropical wetlands are among the highest reported ecosystem carbon pools on earth, with 49 – 98 % of ecosystem carbon stored in their organic soils. This is due to high rates of primary productivity as well as anaerobic soil conditions that limit decomposition, making their carbon stocks among the highest of any forest type (Murdiyarso *et al.*, 2012). Also, structural complexity of vegetated coastal ecosystems, root systems and vegetation, sets up mangroves to be highly efficient in trapping sediment and associated organic carbon originating from autochtonous and allochtonous riverine and oceanic sources (McLeod *et al*., 2011). Yigini and Panagos, (2016) stated that in the soil ecosystem, soil carbon influences soil physical and chemical processes, and serves as a source of plant nutrients and that the storage of carbon in the soil depends on the balance between gains and losses of carbon. Soil carbon stocks are determined mainly by the balance between net primary production from vegetation and the rate of decomposition of organic materials. While climate change is expected to have an impact on soil carbon in the long term, changes in the short term will more likely be driven by land management practices and land-use change which can mask the evidence of climate change impact on soil carbon stocks (EEA, 2012)

The availability of nitrogen has been found to control carbon accumulation, increase primary productivity, increase carbon inputs to the soil and decrease soil respiration thereby decreasing carbon outputs from the soil in forests (Piniero *et al*., 2010; Cheng *et al*., 2011). The results of this study showed that there was no within forest variation in nitrogen stocks for both forests studied, however, independent sample t-test revealed a significantly higher ($P = 0.001$) total soil nitrogen in the mangrove of 18.55±1.99 Mg N $ha^{-1}$ with reference to the rainforest; 6.91±0.77 Mg N $ha^{-1}$. Adame *et al*. (2013) and Kassa *et al*. (2017) also reported values greater than those presented here of 46 Mg N $ha^{-1}$ and 46 Mg N $ha^{-1}$ in Mexico and Ethiopia respectively. Similar to the results reported for the mangrove stocks is the report by Urakawa *et al*. (2016) of 16.3 Mg N $ha^{-1}$ in a Sub-tropical forest of the Japanese Archipelago. Variations in spatial distribution, forest type, climatic condition, land use and soil parent material may be an explanation for the contrasts in soil nitrogen stocks (Urakawa *et al*., 2016; Li *et al.*, 2012). Nitrogen has been found to be a limiting nutrient in forest ecosystems (Davidson *et al.*, 2004) hence, the change in soil nitrogen stocks are a balance of nitrogen inputs and outputs. Changes and differences have also been related to stage of forest development and age (Kimmins, 2004). Hungate *et al.* (2003) stated that carbon sequestration in forests is sustained by the availability of nitrogen. Quantifying forest soil C and N stocks is critical to understanding the ecological responses of forests to changes in climate, land use, and management and to improve global change models (Smith *et al.*, 2012; Dib *et al.*, 2014). In addition to this inherent variability, there is large uncertainty in forest soil C and N estimates associated with the soil sampling methods used (Gifford and Roderick, 2003; Jandl *et al.*, 2014).

Mean carbon/nitrogen ratios in the mangrove 20.48±0.27 was significantly higher ($P = 0.001$) than mean carbon/nitrogen ratio in the rainforest 12.08±0.58 (Appendix IV), buttressing a higher mass of carbon in the soils of the mangrove forest compared to the rainforest. These ratios in the mangrove can be compared with the results of Weiss *et al.*, (2016) which is within the range of 9 – 28, and Kusumaningtyas *et al.* (2019) ranging from 9 – 26.6 in mangroves in Indonesia. Similarly, Yimer *et al.* (2006) reported results similar to that reported in this study in the rainforest in a montane forest in Ethiopia 11.06 – 13.89. Similar results were also reported by Nottingham *et al.* (2015) in a tropical forest of 6.7 – 17. Carbon and nitrogen in soils are the main components of organic matter which depicts soil fertility. Both carbon and nitrogen status associated with C/N ratio may play a key role in regulating soil organic matter mineralization. The ratio of C/N indicates the rate of decomposition of organic matter and this results in the release or immobilization of soil nitrogen (Swangjang, 2015).

### 5.1.6 Total carbon stock density, project area total and carbon dioxide equivalent

The total carbon stock density in the mangrove and rainforest was 423.31 Mg C $ha^{-1}$ and 226.65 Mg C $ha^{-1}$, respectively. In the mangrove the soil carbon constituted the highest percentage in total carbon stock density of 89.79 % and this is coherent with the reports of Donato *et al.* (2011) and Adame *et al.* (2013) who reported a percentage in a range of 49 – 98 % and 78 – 99 %, respectively, further supporting evidence that most of the carbon stored in mangroves is in the soil and sediments. Within the range of the results in the mangroves of this study are reports by Alavaisha and Mangora, (2016) of a range of 414.6 – 684.9 Mg C $ha^{-1}$ in Tanzania, Abino *et al.* (2014) of 529.9 Mg C $ha^{-1}$in a mangrove forest in the Philippines and Adame *et al.* (2013) of a range of 177 – 987 Mg C $ha^{-1}$ in Mexico. Higher and lower estimates were reported by Donato *et al.* (2011) of 1023 Mg C $ha^{-1}$ and Sahu *et al.* (2016) of 147 Mg C $ha^{-1}$, respectively. Similar ranges with the results recorded in the rainforest were reports by Ngo *et al.* (2013) within a range of 274 – 337 Mg C $ha^{-1}$ in Singapore and Lal *et al.* (2016) of 56.06 – 208 Mg C $ha^{-1}$ in India. Lower estimates were reported by Villamor *et al.* (2010) of 151.13 Mg C $ha^{-1}$ in the Philippines, Saner *et al.* (2012) of 167.9 Mg C $ha^{-1}$ and Zaki *et al.* (2018) of 134 – 176.51 Mg C $ha^{-1}$ both in Malaysia, Higher estimates were reported for rainforest in India by Nautiyal and Singh, (2013) of 986.93 – 2420 Mg C $ha^{-1}$. The rainforest had the highest percentage of its total carbon stock allocated aboveground, and may be the result of huge allocation of biomass in large and tall trees with buttresses typical of rainforests in the tropics (Lewis *et al.*, 2013). Overall, observed differences in total carbon stock densities with respect to other regions may be attributed to variances in forest densities, forest age, conservation and management status, and soil depths investigated. The total carbon stock for the project area and carbon dioxide equivalent of the mangrove was 634.96 Mg and $CO_2e$ of 2330.32, respectively. The total carbon stock for the project area and carbon dioxide equivalent of the rainforest was 339.97 Mg and $CO_2e$ of 1247.70, respectively. At the landscape scale, the mangrove forest covering about 195,000 hectares may store up to 82.54 million Mg of carbon while, Cross River National Park covering a total of 300, 000 hectares may store up to 67.99 million Mg of carbon.

## 5.2 Summary

The carbon sequestration potential of the mangrove Forest of Great Kwa River, Calabar and Cross River National Park, Oban Division, Akamkpa was investigated. General allometric equations by Chave *et al.* (2005) for moist forests were used to estimate aboveground and belowground biomass. Planar intersect method was used to determine dead and downed wood biomass and canopy cover was estimated using a spherical densiometer. Soil total carbon and nitrogen was determined by dry combustion method using a Thermal Scientific Flash 2000 CN analyzer and bulk density was determined by the intact core method. Analysis of variance was used to test for differences in parameters investigated. Also, two-sample Students *t*-test assuming unequal variances was performed to test that the resulting means of the estimates for the two forest types are equal. Analysis of variance revealed that canopy closure within transects sampled in both forests were not statistically different. Total aboveground and belowground biomass and carbon stocks within both forests varied significantly ($P = 0.05$). Dead and downed wood carbon stock varied significantly ($P = 0.05$) within both forests among the different size classes investigated and was observed to increase with increasing size class. Total soil carbon and nitrogen stocks showed no statistical variation within transects sampled in both forests. Also carbon/ nitrogen ratios were not statistically different within both forests.

Two-sample Students t-test results revealed that mean canopy closure in the rainforest was significantly higher (P = 0.001) than that of the mangrove. Mean aboveground and belowground biomass and carbon stocks in the rainforest were significantly higher (P = 0.001) than means for the mangrove. Conversely, mean total soil carbon and nitrogen stocks as well as carbon/nitrogen ratio in the mangrove was significantly higher (P = 0.001) than that of the rainforest.

Total carbon stock density in the mangrove was higher than that of the rainforest. The mangrove had almost 90 percent of its carbon stocks located in soil, while the rainforest had about 51 percent of its carbon stocks in the aboveground tree biomass. At the landscape scale, the mangrove forest covering about 195,000 hectares may store up to 82.54 million Mg of carbon while, Cross River National Park covering a total of 300, 000 hectares may store up to 67.99 million Mg of carbon.

## 5.3 Conclusion

This study has presented an assessment of the carbon stocks in the mangrove forest of the Great Kwa River, Calabar and rainforest of the Cross River National Park, Oban West Division, Akamkpa, Cross River State, Nigeria. These findings create a general framework to be used for further studies within the mangrove and rainforest in Cross River State and as baseline for other forests in Nigeria.

This study has shown that tropical forests in Nigeria show promise in their ability of mitigating climate change and global warming by sequestering carbon from the atmosphere and storing them in their aboveground, belowground and soil pools. Understanding the global carbon cycle is a difficult and complex task due to changing land use, deforestation degradation of existing forests, and other anthropogenic influences. Further, accurate data on carbon sequestration and stocks are highly deficient especially from tropical forests of Nigeria where diverse forest communities exist due to highly variable climatic and geographical conditions. African tropical rainforests strongly modulate regional climate, especially precipitation patterns, dominating global tropical rainfall during the transition seasons, and are tightly connected to global climate therefore, there is a need for basic ecological understanding of the African rainforest biome including wet, dry and montane biomes. This includes understanding productivity, species distributions, drought, temperature sensitivity and interactions with climate and soils. This may require investment in selected intensive study sites combined with more extensive distributed networks of study sites, both integrated and standardized with parallel efforts in other rainforest continents. Blue carbon trading may also be a significant mitigation opportunity in an attempt to balance the conservation of mangrove ecosystems and sustainable livelihood for coastal inhabitants. Mangroves especially as blue carbon sinks have the ability to transfer and store carbon particularly in their sediments at rates far greater than those of rainforests. Mangroves are under constant flux due to both natural and anthropogenic forces. They are also under immense pressure from clear-cutting, land-use change, hydrological alterations, chemical spill and climate change effects. Long-term monitoring and research into the dynamics controlling mangrove growth and survival under environmental and anthropogenic pressures is critical to increase our understanding of mangrove survival in the face of sea level rise and changing climatic conditions. Variations in stocks among tropical forests are existent due to confounding factors which include species that constitute the vegetation, soil type, elevation effects, watershed, climate and previous land-use. Ongoing exploitation of forests for timber and conversion to agricultural land has highlighted the need to conserve tropical forests and to accurately quantify carbon stocks. Carbon budget variations have also created uncertainties in carbon stock reporting especially for the United Nations Framework Convention on Climate Change. Thus, determination of carbon stocks in various components of forest and within sites is important to monitor carbon stocks and cycling, to calibrate global carbon cycle models, and to support frameworks such as the United Nations REDD+ programme.

## 5.4 Recommendations

The results of this study can be improved upon by incorporating additional datasets and sampling a larger extent in order to reach the highest possible accuracy in the carbon stock and sequestration potential of the forests in Cross River State and Nigeria.

This study can be used to buttress findings on carbon capture and storage potentials of forests in Africa. More frequent assessments of the state of forests in Nigeria especially relating to carbon stocks should be done, as any significant change in the function of carbon stocks would be of great importance to policy makers.

Increased efforts toward energy efficiency through transitioning to renewable energy sources from fossil fuels should be made, in order to reduce pressures on the forests to sequester carbon.

Funding in support of detailed inventory of major carbon stocks and repeated measurements of key stocks through time or modelling should be encouraged in Nigeria.

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**ass stock, aboveground carbon s
isects sampled in the mangrove for
n West Division, Akamkpa, Cross F**

| ock | Total soil carbon (Mg C) | Total soil nitrogen (Mg N) | C:N |
|---|---|---|---|
| | 373.91±57.63 | 18.31±3.00 | 20.4 |
| | 404.66±28.23 | 19.82±1.30 | 20.4 |
| | 373.06±51.45 | 18.30±2.45 | 20.3 |
| | 385.58±56.40 | 18.72±3.04 | 20.62 |
| | 366.51±26.53 | 17.90±1.00 | 20.45 |
| | 416.55±23.66 | 20.21±1.20 | 20.60 |
| | 366.66±45.98 | 17.87±2.01 | 20.49 |
| | 366.84±26.32 | 17.93±1.12 | 20.44 |
| | 353.31±46.32 | 17.26±2.36 | 20.48 |
| | 394.23±55.28 | 19.21±2.56 | 20.50 |
| | 380.13±41.09 | 18.55±1.99 | 20.48 |

**on nitrogen ratio**

## APPENDIX I CONTINUED

| Ecosystem | Transect | Canopy closure (%) | Aboveground biomass stock (t ha$^{-1}$) | Belowground biomass stock (t ha$^{-1}$) | Aboveground carbon stock (Mg C) | Belowground carbon sock (Mg C) | Total soil carbon (Mg C) | Total soil nitrogen (Mg N) | C:N ratio |
|---|---|---|---|---|---|---|---|---|---|
| CRNP | 1 | 89.98±1.41 | 221.10±143.01 | 44.21±28.60 | 103.91±67.21 | 20.77±13.44 | 87.27±10.33 | 6.74±0.74 | 12.94±0.66 |
| | 2 | 88.46±0.75 | 109.82±44.65 | 21.85±9.00 | 51.61±20.98 | 10.32±4.19 | 85.27±11.07 | 6.55±0.61 | 12.97±0.67 |
| | 3 | 88.64±1.17 | 657.49±81.90 | 131.49±16.38 | 309.02±38.49 | 61.80±7.70 | 92.22±11.32 | 7.06±0.77 | 13.04±0.65 |
| | 4 | 88.30±1.30 | 185.90±171.59 | 37.18±34.31 | 87.37±80.65 | 17.47±16.12 | 89.88±11.22 | 7.01±0.98 | 12.85±0.66 |
| | 5 | 89.60±0.45 | 107.18±23.30 | 21.43±4.65 | 50.37±10.95 | 10.07±2.18 | 84.22±6.41 | 6.62±0.39 | 12.72±0.73 |
| | 6 | 88.30±2.26 | 283.03±241.41 | 56.60±48.27 | 133.02±113.46 | 26.60±22.68 | 99.32±7.77 | 7.71±0.38 | 12.87±0.53 |
| | 7 | 88.73±0.75 | 366.66±155.82 | 73.32±31.16 | 172.33±73.23 | 34.46±14.65 | 82.11±17.81 | 6.39±1.43 | 12.86±0.71 |
| | 8 | 88.64±0.54 | 200.28±99.17 | 40.05±19.83 | 94.13±46.61 | 18.82±9.32 | 80.12±9.33 | 6.41±0.68 | 12.48±0.39 |
| | 9 | 89.60±0.68 | 210.30±140.53 | 42.05±28.10 | 98.84±66.05 | 19.76±13.20 | 94.01±4.39 | 7.04±0.56 | 13.36±0.57 |
| | 10 | 89.03±1.10 | 86.49±23.43 | 17.29±4.68 | 40.65±11.01 | 8.12±2.1 | 98.23±10.35 | 7.59±0.38 | 12.91±0.79 |
| | Grand mean | 88.83±1.06 | 242.82±195.79 | 48.55±39.16 | 114.12±92.02 | 22.82±18.40 | 89.27±10.84 | 6.91±0.77 | 12.90±0.58 |

**%: per cent; t ha$^{-1}$: tonnes per hectare; Mg: megagram; C: carbon; N: nitrogen; C:N: carbon nitrogen ratio**

## APPENDIX II

**One Way Analysis of Variance (ANOVA) between transects sampled for canopy closure, aboveground biomass stock, aboveground carbon stock, total soil carbon, total soil nitrogen, C:N ratio, belowground carbon stock and belowground biomass stock in the mangrove forest of Great Kwa river, Calabar and rainforest of Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria from April to May, 2018.**

| Source | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| | Between Groups | 226.520 | 9 | 25.169 | 1.276 | 0.308 |
| Canopy closure (%) for Mangrove | Within Groups | 394.377 | 20 | 19.719 | | |
| | Total | 620.897 | 29 | | | |
| | Between Groups | 6.068 | 9 | 0.674 | 0.498 | 0.859 |
| Canopy closure (%) for CRNP | Within Groups | 27.092 | 20 | 1.355 | | |
| | Total | 33.160 | 29 | | | |
| | Between Groups | 9822.762 | 9 | 1091.418 | 4.607 | 0.002 |
| AGB stock (t ha-$^{1}$) for Mangrove | Within Groups | 4737.907 | 20 | 236.895 | | |
| | Total | 14560.669 | 29 | | | |
| | Between Groups | 768022.695 | 9 | 85335.855 | 4.966 | 0.001 |
| AGB stock (t ha$^{-1}$) for CRNP | Within Groups | 343685.171 | 20 | 17184.259 | | |
| | Total | 1111707.865 | 29 | | | |
| | Between Groups | 2142.283 | 9 | 238.031 | 4.538 | 0.002 |
| AGC stock (Mg C ha$^{-1}$) for Mangrove | Within Groups | 1049.028 | 20 | 52.451 | | |
| | Total | 3191.311 | 29 | | | |
| | Between Groups | 169656.752 | 9 | 18850.750 | 4.966 | 0.001 |
| AGC stock (Mg C ha$^{-1}$) for CRNP | Within Groups | 75920.080 | 20 | 3796.004 | | |
| | Total | 245576.833 | 29 | | | |

**AGB: aboveground biomass; AGC: aboveground carbon; t ha$^{-1}$: tonnes per hectare; Mg C ha$^{-1}$: Megagram of carbon per hectare**

## APPENDIX II CONTINUED

| Source | | Sum of Squares | df | Mean Square | F | Sig |
|---|---|---|---|---|---|---|
| Total soil carbon for Mangrove | Between Groups | 10524.233 | 9 | 1169.359 | 0.608 | 0.776 |
| | Within Groups | 38442.891 | 20 | 1922.145 | | |
| | Total | 48967.124 | 29 | | | |
| Total soil carbon for CRNP | Between Groups | 1179.580 | 9 | 131.064 | 1.174 | 0.362 |
| | Within Groups | 2232.281 | 20 | 111.614 | | |
| | Total | 3411.861 | 29 | | | |
| Total soil nitrogen for Mangrove | Between Groups | 23.672 | 9 | 2.630 | 0.571 | 0.805 |
| | Within Groups | 92.104 | 20 | 4.605 | | |
| | Total | 115.776 | 29 | | | |
| Total soil nitrogen for CRNP | Between Groups | 5.751 | 9 | 0.639 | 1.097 | 0.408 |
| | Within Groups | 11.653 | 20 | 0.583 | | |
| | Total | 17.404 | 29 | | | |
| C:N ratio for Mangrove | Between Groups | .168 | 9 | 0.019 | 0.189 | 0.993 |
| | Within Groups | 1.983 | 20 | 0.099 | | |
| | Total | 2.151 | 29 | | | |
| C:N ratio for CRNP | Between Groups | 1.363 | 9 | 0.151 | 0.360 | 0.941 |
| | Within Groups | 8.415 | 20 | 0.421 | | |
| | Total | 9.778 | 29 | | | |

**C:N: carbon nitrogen ratio**

## APPENDIX II CONTINUED

| Source | | Sum of Squares | df | Mean Square | F | Sig |
|---|---|---|---|---|---|---|
| | Between Groups | 85.622 | 9 | 9.514 | 4.538 | 0.002 |
| BGC stock (Mg C $ha^{-1}$) for Mangrove | Within Groups | 41.930 | 20 | 2.096 | | |
| | Total | 127.552 | 29 | | | |
| | Between Groups | 6786.724 | 9 | 754.080 | 4.967 | 0.001 |
| BGC stock (Mg C $ha^{-1}$) for CRNP | Within Groups | 3036.526 | 20 | 151.826 | | |
| | Total | 9823.251 | 29 | | | |
| | Between Groups | 393.090 | 9 | 43.677 | 4.606 | 0.002 |
| BGB stock (t $ha^{-1}$) for Mangrove | Within Groups | 189.649 | 20 | 9.482 | | |
| | Total | 582.739 | 29 | | | |
| | Between Groups | 30738.324 | 9 | 3415.369 | 4.968 | 0.001 |
| BGB stock (t $ha^{-1}$) for CRNP | Within Groups | 13748.521 | 20 | 687.426 | | |
| | Total | 44486.845 | 29 | | | |

**BGC: belowground carbon; BGB: belowground biomass; t $ha^{-1}$: tonnes per hectare; Mg C $ha^{-1}$: Megagram of carbon per hectare**

## APPENDIX III

**Group statistics on Independent Samples Test for canopy closure, aboveground biomass stock, belowground biomass stock, aboveground carbon stock, belowground carbon stock, total soil carbon, total soil nitrogen and C:N ratio of transects sampled in the mangrove forest of Great Kwa river, Calabar, and rainforest of Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria from April to May, 2018.**

| | Forest_type | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| Canopy closure | Mangrove | 30 | 24.1193 | 4.62712 | 0.84479 |
| | CRNP | 30 | 88.8307 | 1.06931 | 0.19523 |
| AGB stock | Mangrove | 30 | 76.0810 | 22.40741 | 4.09101 |
| | CRNP | 30 | 242.8290 | 195.79263 | 35.74668 |
| BGB stock | Mangrove | 30 | 15.2123 | 4.48268 | 0.81842 |
| | CRNP | 30 | 48.5517 | 39.16668 | 7.15083 |
| AGC stock | Mangrove | 30 | 35.7105 | 10.49024 | 1.91525 |
| | CRNP | 30 | 114.1291 | 92.02264 | 16.80096 |
| BGC stock | Mangrove | 30 | 7.1363 | 2.09722 | 0.38290 |
| | CRNP | 30 | 22.8207 | 18.40469 | 3.36022 |
| Total soil carbon | Mangrove | 30 | 380.1371 | 41.09162 | 7.50227 |
| | CRNP | 30 | 89.2710 | 10.84668 | 1.98032 |
| Total soil nitrogen | Mangrove | 30 | 18.5568 | 1.99806 | 0.36480 |
| | CRNP | 30 | 6.9167 | 0.77469 | 0.14144 |
| CN ratio | Mangrove | 30 | 20.4857 | 0.27236 | 0.04973 |
| | CRNP | 30 | 12.9047 | 0.58067 | 0.10601 |

**AGB: aboveground biomass; BGB: belowground biomass; AGC: aboveground carbon; BGC: belowground carbon; C:N: carbon nitrogen ratio**

## APPENDIX IV

**Independent Samples Test on canopy closure, aboveground biomass stock, belowground biomass stock, aboveground carbon stock, belowground carbon stock, total soil carbon, total soil nitrogen and C:N ratio of transects sampled in the mangrove forest of Great Kwa river, Calabar, and rainforest of Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria from April to May, 2018.**

| Source | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | 95% Confidence Interval of the Difference | |
| | | | | | | | | | Lower | Upper |
| Canopy closure | Equal variances assumed | 16.402 | 0.000 | -74.633 | 58 | 0.000 | -64.71133 | 0.86706 | -66.44694 | -62.97573 |
| | Equal variances not assumed | | | -74.633 | 32.089 | 0.000 | -64.71133 | 0.86706 | -66.47728 | -62.94539 |
| AGB Stock | Equal variances assumed | 50.123 | 0.000 | -4.634 | 58 | 0.000 | -166.74800 | 35.98002 | -238.76983 | -94.72617 |
| | Equal variances not assumed | | | -4.634 | 29.760 | 0.000 | -166.74800 | 35.98002 | -240.25390 | -93.24210 |
| BGB stock | Equal variances assumed | 50.124 | 0.000 | -4.632 | 58 | 0.000 | -33.33933 | 7.19751 | -47.74671 | -18.93196 |
| | Equal variances not assumed | | | -4.632 | 29.760 | 0.000 | -33.33933 | 7.19751 | -48.04359 | -18.63508 |
| Carbon stock AGB | Equal variances assumed | 50.194 | 0.000 | -4.637 | 58 | 0.000 | -78.41853 | 16.90977 | -112.26712 | -44.56995 |
| | Equal variances not assumed | | | -4.637 | 29.754 | 0.000 | -78.41853 | 16.90977 | -112.96489 | -43.87217 |
| Carbon stock BGB | Equal variances assumed | 50.196 | 0.000 | -4.638 | 58 | 0.000 | -15.68433 | 3.38197 | -22.45408 | -8.91459 |
| | Equal variances not assumed | | | -4.638 | 29.753 | 0.000 | -15.68433 | 3.38197 | -22.59364 | -8.77503 |
| Total soil carbon | Equal variances assumed | 34.225 | 0.000 | 37.486 | 58 | 0.000 | 290.86612 | 7.75924 | 275.33432 | 306.39791 |
| | Equal variances not assumed | | | 37.486 | 33.022 | 0.000 | 290.86612 | 7.75924 | 275.08023 | 306.65201 |
| Total soil nitrogen | Equal variances assumed | 17.810 | 0.000 | 29.751 | 58 | 0.000 | 11.64010 | 0.39125 | 10.85692 | 12.42328 |
| | Equal variances not assumed | | | 29.751 | 37.526 | 0.000 | 11.64010 | 0.39125 | 10.84772 | 12.43248 |
| CN ratio | Equal variances assumed | 21.682 | 0.000 | 64.742 | 58 | 0.000 | 7.58108 | 0.11710 | 7.34669 | 7.81548 |
| | Equal variances not assumed | | | 64.742 | 41.171 | 0.000 | 7.58108 | 0.11710 | 7.34463 | 7.81754 |

**AGB: aboveground biomass; BGB: belowground biomass; C:N: carbon nitrogen ratio**

## APPENDIX VI

**One Way Analysis of Variance (ANOVA) on soil bulk density by depth in the mangrove forest of Great Kwa river, Calabar and rainforest of Cross River National Park (CRNP), Oban West Division, Akamkpa, Cross River State, Nigeria from April to May, 2018.**

| Source | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Mangrove soil BD | Between Groups | 0.002 | 3 | 0.001 | 0.100 | 0.960 |
| | Within Groups | 0.706 | 116 | 0.006 | | |
| | Total | 0.707 | 119 | | | |
| CRNP soil BD | Between Groups | 0.035 | 3 | 0.012 | 0.496 | 0.686 |
| | Within Groups | 2.689 | 116 | 0.023 | | |
| | Total | 2.724 | 119 | | | |

**BD: bulk density**