KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF SCIENCE

DEPARTMENT OF THEORETICAL AND APPLIED BIOLOGY

CARBON STOCK IN PLANTATIONS OF INDIGENOUS TREE SPECIES IN THE WET EVERGREEN VEGETATION OF GHANA

BY

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BSc. (HONS) NATURAL RESOURCES MANAGEMENT

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A THESIS SUBMITTED TO DEPARTMENT OF ENVIRONMENTAL SCIENCE IN PARTIAL FULFILMENT FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN ENVIRONMENTAL SCIENCE

BY

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DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Carbon sequestration is one of many valuable environmental facilities that forests provide. Traditionally, society has enjoyed the benefits of environmental conditions such as clean air, nutrient cycling, and watershed protection without any payment. The role of terrestrial ecosystem in mitigating the effects of climate change entails the assessment of carbon stocks in various pools. This thesis seeks to provide information about growth and carbon stock of thirteen indigenous and one exotic tree species (*Terminalia ivorensis, Terminalia superb*a, *Milicia excels*a, *Ceiba pentandra, Entandrophragma angolense, Aningeria robusta, Heritiaris utilis, Khaya ivorensis, Antiaris toxicaria, Mammea africana, Triplochiton scleroxylon, Pycnanthus angolensis and Cedrela odorata*) in agroforestry, mixed and pure plantations in the wet evergreen vegetation of Ghana. A three (3) hectare plot was evaluated at the Oda Kotoamso Agroforestry Project site in the Western Region of Ghana. Results revealed that carbon accumulation and growth performance per tree species increased from trees in pure to mixed and to agroforestry plantations. Results from this study also indicated fast growing species (*Ceiba pentandra, Milicia excelsa, Terminalia superba and Terminalia ivorensis*) had the highest carbon accumulation per tree. Also shade, age and initial planting distance were observed as key factors that influenced growth parameters among tree species in plantations. Among the tree species studied, *Ceiba pentandra* recorded the highest amount of carbon per tree in pure plantation (52.2 kg C), 95.6 kg C in mixtures and 184.9 kg C in agroforestry plantation. The volume growth performance of *Ceiba pentandra* was the best among the remaining tree species with the highest volume of 0.4 m^3 in the agroforestry plantation. Four different allometric equations were used in calculating amount of carbon in tree species. Results indicated variations in all four allometric models used for estimating carbon. Lastly, an assumed carbon concentration (50%) and specific carbon concentrations were used to convert tree biomass to carbon stored. It was observed that the assumed carbon concentration overestimated the carbon stock by 1.8% to 3.6% per tree species and 3.0% on substantial scale (per hectare) compared to specific carbon concentration of the same tree species. This research therefore supports the concept that tropical plantations can serve diverse economic, social, and ecological functions while also ultimately helping reduce atmospheric CO_2 accumulation.

TABLE OF CONTENTS

CHAPTER ONE………………………………………………………………… 1

1.0 INTRODUCTION……………………………………………………… 1

1.1 Background…………………………………………………………… 1

1.2 Main Objective……………………………………………………….. 3

1.3 Specific Objectives…………………………………………………… 3

CHAPTER TWO………………………………………………………………… 5

2.0 LITERATURE REVIEW………………………………………………. 5

2.1 Forest………………………………………………………………….. 5

2.1.1 Tropical forest………………………………………………………. 5

2.1.2 Deforestation………………………………………………………... 6

2.2 Carbon sequestration………..…………………………………………… 6

2.2.1 Carbon allocation in trees…………………………………………..... 7

2.2.2 Carbon cycling in forest…………………………………………….. 8

2.2.3 The role of forest in carbon sequestration……………………………… 9

2.2.4 Carbon in Agroforestry……………………………………………. 9

2.2.4.1 Carbon Sequestration by tree-based systems……………………………. 10

2.2.4.2 Alleycropping………………………………………………………… 11

2.3 Indigenous tree species…………………………………………………… 11

2.3.1 *Terminalia ivorensis*……………………………………………………. 12

2.3.2 *Triplochiton scleroxylon*…………………………………………......... 12

2.3.3 *Terminalia superba*……………………………………………….......... 13

2.3.4 *Ceiba pentandra*……………………………………………………………………… 13

2.4 Growth of trees and its importance……………………………………………… 14

2.4.1 Growth requirements of indigenous tree species……………………………. 14

2.4.1.1 Light…………………………………………………………………….. 14

2.4.1.2 Spacing………………………………………………………………….. 15

2.4.1.3 Texture and drainage……………………………………………………. 15

2.4.1.4 Pathological and entomological problems………………………………. 15

2.4.1.5 Shade……………………………………………………………………. 16

2.4.1.6 Water………………………………………………………………….... 16

2.4.2 Important growth parameters………………………………………………….. 17

2.4.2.1 Diameter growth………………………………………………………… 17

2.4.2.2 Height growth……………………………………………………………… 17

2.5 Allometric equation……………………………………………………………… 18

2.5.1 Wood density………………………………………………………………….... 19

2.6 Carbon concentration…………………………………………………………….. 20

CHAPTER THREE…………………………………………………………………... 22

3.0 MATERIALS AND METHODS………………………………………………. 22

3.1 Study area…………………………………………………………………… .. 22

3.2 Species under study………………………………………………………………… 23

3.3 Experimental design……………………………………………………………... 24

3.4 Collection of field measurement……………………………………………...…. 24

3.5 Carbon contents of tree species ……………………………………………..… 24

3.6 Allometric equations……………………………………………………..…. 25

3.7 Data analysis……………………………………………………………….... 27

CHAPTER FOUR…………………………………………………………..… 28

4.0 RESULTS……………………………………………………………….… 28

4.1 Carbon sequestration of indigenous tree species plantations…………………… 28

4.1.1 Relation between biomass and Carbon stored in tree species…………………. 28

4.1.2 Carbon stock among tree species occurring in mixed, agroforestry and pure plantations………………………………………………………………………. 30

4.1.3 Carbon stock for trees species in mixed plantation in wet.vegetation of Ghana…………………………………………………………..…………. 31

4.1.4 Carbon stock for trees species in agroforestry plantation in wet vegetation of Ghana…………………………………………………….…………………….. 32

4.1.5 Carbon stock for trees species in pure plantation in wet vegetation of Ghana…………………………………………….…………………………….. 33

4.2 Growth of indigenous tree species in the wet vegetation of Ghana…………….… 34

4.2.1 Growth parameters of tree species in mixed plantation ……………………..…. 34

4.2.2 Growth parameters of tree species in agroforestry plantation …………………. 35

4.2.3 Growth parameters of tree species in pure plantation………………………… 36

4.3 Effect of different allometric equations on carbon stock……………...………… 38

4.4 Effect of carbon concentration on carbon stock…………………………………. 41

CHAPTER FIVE………………………………………………………………….. 42

5.0 DISCUSSION…………………………………………………………..…….. 42

5.1 Carbon sequestration values……………………………………………………. 42

5.2 Carbon sequestration of indigenous tree species plantations……………………. 43

5.2.1 Carbon sequestration among indigenous tree species…………………………. 44

5.3 Growth of indigenous tree species plantations………………………………… .. 45

5.3.1 Growth among indigenous tree species …………………………………….. 47

5.4 Effect of different allometric equations on carbon stock………………………… 48

5.5 Effect of carbon concentration on carbon stock………………………………….. 50

CHAPTER SIX………………………………………………………………..……. 52

6.0 CONCLUSION AND RECOMMENDATION……………………………….. 52

6.1 Conclusion……………………………………………………………………..…. 52

6.2Recommendation…………………………………………………………… … 53

REFERENCES………………………………………………………………. … 54

APPENDICES………………………………………………………………….. 68

LIST OF TABLES

Table 1: Carbon concentration and specific wood density of tree species………… 25

Table 2: Mean carbon stock for tree species in mixed plantation in wet vegetation of Ghana.. 31

Table 3: Mean carbon stock for tree species in agroforestry plantation in wet vegetation of Ghana.. 33

Table 4: Mean carbon stock for tree species in pure plantation in wet vegetation of Ghana………………………………………………….………… 34

Table 5: Growth parameters of tree species in mixed plantation in the wet vegetation of Ghana……………………………………………….............. 35

Table 6: Growth parameters of tree species in agroforestry plantation in the wet evergreen vegetation of Ghana………………………………………. . 36

Table 7: Growth parameters of tree species in pure plantation in the wet evergreen vegetation of Ghana......…………………………………………... 37

Table 8: Total above ground biomass calculation using different allometric equations... 40

LIST OF FIGURES

Figure 1: Map of Oda-Kotoamso Agroforestry Project site (OCAP)…………….……….... 23

Figure 2: Relationship between tree biomass and carbon stored in tree species in mixed plantation.. 28

Figure 3: Relationship between tree biomass and carbon stored in tree species in agroforestry plantation.. 29

Figure 4: Relationship between tree biomass and carbon stored in tree species in pure plantation.. 29

Figure 5: Carbon stock among tree species occurring in mixed, agroforestry and pure plantations…...…………...……………………………………………….... 30

Figure 6: Difference in volume among three tree species in mixed, agroforestry and pure plantations ………................................………………... 37

Figure 7: Variation in carbon stock using three different allometric equations…………... 38

Figure 8: Difference in carbon stock using two different carbon concentration values…... 41

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The international mechanism for the Clean Development Mechanism (CDM) was introduced during the Kyōto Protocol in 1997. CDM offers new opportunities to make climate change mitigation more cost effective, conserve the environment, and ensure socio-economic development for developing countries. Ghana CDM is abundantly promoted by the government and development agencies as a potential option for rural development. Under CDM, industrialized countries can achieve these targets by investing in emission reduction projects, including carbon sequestration through afforestation and reforestation in developing countries (Fenhann, 2005; UNFCCC, 2003). The Kyoto Protocol allows for reduction in carbon emission through forest based carbon sequestration projects (UNFCCC, 2002).

With high dependence on land and forests for subsistence coupled with the growing threat of widespread natural resource degradation (Rohit *et al.*, 2006), the economic and environmental benefits of carbon sequestration projects are particularly relevant for Africa. Accordingly, efforts to mitigate climate change through carbon sequestration projects can bring in money both to regenerate natural resources and raise local incomes (Kituyi, 2002).

According to the Millennium Development Goals Report 2010, there has been a decline in Ghana’s forest cover from 33% to 22% (1990-2009) under indicator 7.1 (Proportion of land area covered by forest) of Target 7a: (Integrate the principles of sustainable development into country policies and programmes; reverse loss of environmental resources)**.** The depletion of the natural forest of Ghana has led to expanded programmes of forest plantations using indigenous tree species for the future supply of wood products and carbon sequestration. This has focused on the need for sustainable management of these plantations in the broadest sense to combat climate change. Managing forests through agroforestry, forestry and plantation systems is seen as an important opportunity for climate change mitigation and adaptation (IPCC, 2007; Canadell and Raupach, 2008).

In the wake of these, German Development Agency, Deutscher Entwicklungsdienst (DED, German Development Service) is collaborating with Samartex Timber and Plywood Company Limited, a private timber processing company in a Public Private Partnership (PPP) in the Wassa Amenfi district in the Western Region. The goal of this partnership is to ensure long-term continuity of timber supply by reducing slash-burn forest destruction and promoting the planting of new trees.

This community-based project approach is called Oda Kotoamso Community Agroforestry Project (OCAP) and was initiated in 1997. To date, it is being replicated in other areas of the district. Under the project, the communities offer their land while Samartex Timber and Plywood Company Limited provide capital, technology, and market. The Deutscher Entwicklungsdienst (DED, German Development Service) supports through technical know-how.

OCAP has restored about 450 ha degraded off-reserves forest in a way that has enhanced the environment and increased the biodiversity of the area with valuable species. There has also been considerable improvement in the living standard of the community through the sustained incomes from the project and the national economy has been enhanced through the creation of more employment and from the processing of the value-added product.

There have been conscious efforts to reduce the amount of CO_2 in the atmosphere, with those employing the services of trees seen as among the most environmentally friendly. The role of tropical forests in these efforts is described by Affum-Baffoe (2009) as critical because they are carbon-dense and highly productive. However, uncertainty remains regarding their quantitative contribution to the global carbon cycle and to potential carbon sequestration.

1.2 Main Objective

To estimate the amount of carbon stored in indigenous tree species under various plantation types in the wet evergreen vegetation of Ghana.

1.3 Specific Objectives

The specific objectives were:

i. To estimate the amount of carbon in 12 (twelve) indigenous tree species in mixed plantation.

ii. To estimate amount of carbon in 12 (twelve) indigenous tree species in agroforestry plantation.

iii. To estimate amount of carbon in *Terminalia superba, Ceiba pentandra*, *Khaya ivorensis* and *Cedrela odorata* in pure plantation.

iv. To assess the growth performance of fourteen (14) tropical tree species

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Forest

The Food and Agriculture Organization (FAO) has defined forest as land with tree crown cover (or equivalent stocking level) of more than 10% and area of more than 0.5 hectare. The trees should be able to reach a minimum height of 5 m at maturity in situ. It is among the most heavily disturbed resources by human activity. According to Davids (1966), forest ecosystems produce valuable materials such as lumber, paper pulp and domestic livestock that are important in human culture. They also play vital roles in the regulating climate, controlling water runoff, providing wildlife habitat, purifying the air and a host of other ecological services.

Furthermore, these terrestrial biomes have scenic, cultural and historic values that are protected. Much attention of environmental groups over the past century has been devoted to protecting forests, prairies, and other landscapes (Davids, 1966).

2.1.1 Tropical forest

Carbon sequestration and release vary substantially by forest. Nonetheless, some generalizations are possible, because of the relative similarity of forests in specific "biomes"— tropical, temperate, and boreal forests (Henry, 1993).

Some of the richest and most diverse terrestrial ecosystems on the earth are Tropical Forests. Although they occupy less than 10 per cent of the earth land surface, these forests are thought to contain more than two thirds of higher plant biomass and at least half of all the plant, animal and microbial species in the world as reported by Taylor (1960).

Some years ago, an estimated 12.5million km^2 of tropical lands were covered with closed-canopy forest. About 0.8 per cent of the remaining tropical forest is cleared each year (Miller, 1972).

2.1.2 Deforestation

According to Vanclay (1994) deforestation is the indiscriminate cutting or over-harvesting of trees for lumber or pulp, or to clear the land for agriculture, ranching, construction, or other human activities. During logging for valuable tropical hardwood such as mahogany, loggers may take only one or two of the largest trees per hectare but because the canopy of tropical forests is often strongly linked by vines and interlocking branches, felling one of the trees can bring down dozens of others. In many places, land is also cleared for cattle ranching, banana or pineapple plantations or for other export crop production (Miller, 1972).

2.2 Carbon sequestration

The rate of increase in atmospheric CO_2 concentration can be reduced through the process of C sequestration. The term carbon sequestration is defined as the uptake of C containing substances, in particular CO_2, into a long-lived reservoir (IPCC, 2007). It is a natural process. More specifically, carbon sequestration can be defined as the transfer and secure storage of atmospheric CO_2 into the other long-lived pools that would otherwise be emitted or remain in the atmosphere (Lal, 2008). Most important for the short-term C cycle in forest ecosystems is the exchange with the atmospheric CO_2 pool. Thus C sequestration in forest ecosystems occurs primarily by uptake of atmospheric CO_2 during tree photosynthesis and the subsequent transfer of some fixed into vegetation, detritus and soil pools for secure C storage. The efficiency in C sequestration differs among the 100,000 tree species as they vary widely in properties that drive C sequestration such as growth, mortality, decomposition and their dependency on climate (Purves *et al*., 2008). In total, estimates of the C uptake vary from between 0.49 and 0.72 Pg C /yr for the boreal, to 0.37Pg/yr for the temperate, and between 0.72 and 1.3Pg C/yr for the tropical forest biome (Lorenz and Lal, 2010). However, biome data are lacking specifically with regards to forest stands of all species at all stages in the life cycle from regeneration to harvest, and the impacts of disturbances and effects of climate change. Thus, estimates of C sequestration in global forest biomes and their net C budget are uncertain (Jarvis *et al*., 2005) and potential gain and accounting procedures for carbon credit are complicated (Forestry Commission in Great Britain, 2012).

Atmospheric C can be securely stored through binding in inorganic and organic compounds. The C sequestered in forests is primarily bound as organic compounds in vegetation, detritus and soil. However, C may also be sequestered in soil as carbonates.

2.2.1 Carbon allocation in trees

Plants use the carbon absorbed by leaves during photosynthesis to maintain cellular structures and grow new tissues. Maintenance of existing tissues requires an expenditure of carbon during respiration, which reduces the carbon available for new growth. The net carbon available to a plant, along with the nutrients require for new growth, is then allocated to the growth of leaves, roots stems, flowers, and seeds and the production of chemicals for the protection from insects and herbivores. Collectively, the partitioned of resources to plants parts and functions is known as allocation (Cannell and Dewar, 1994; Bazzaz, 1996).

Allocation of available resources is a critical determinant of plant growth and success. For example high allocation to foliage ensures more leaves to capture light and absorb CO_2 for new growth. However, allocation to foliage is inefficient if there is not enough water or nutrients to support the foliage.

Moreover, there usually is a limited amount of resources to spend on growth, maintenance, and reproduction, and allocation to one function is typically at the expense of another function. Hence, plants must allocate resources in a way that balances conflicting needs. Variations among plants in growth rates are determined as much by differences in allocation and how plants balance resource limitations as by different photosynthetic rates (Bonan, 2002).

2.2.2 Carbon cycling in forest

Photosynthesis is the chemical process by which plants use sunlight to convert nutrients into sugars and carbohydrates. Carbon dioxide (CO_2) is one of the compounds essential to building the organic chemicals that comprise leaves, roots, and stems. All parts of a plant — the stem, limbs and leaves, and roots — contain carbon, but the proportion in each part varies enormously, depending on the plant species and the individual specimen's age and growth pattern. According to Gorte (2007), as more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering (storing) it in plant tissue (vegetation) above and below ground. Plants also respire, using oxygen to maintain life and emitting CO_2 in the process. At times (e.g., at night and during winter seasons in non-tropical climates), living, growing forests are net emitters of CO_2, although they are generally net carbon sinks over the life of the forest.

For herbaceous plants, the above-ground biomass dies annually and subsequently begins to decompose. However, for woody plants, some of the above-ground biomass continues to store carbon until the plant dies and decomposes. This is the essence of the carbon cycle in forests — net carbon accumulation (sequestration) with vegetative growth, and release of carbon when the vegetation dies. Thus, the amount of carbon sequestered in a forest is constantly changing with growth, death, and decomposition of vegetation. In addition to being sequestered in vegetation, carbon is also sequestered in forest soils.

2.2.3 The role of forest in carbon sequestration

At present forests cover just over 4 billion hectares or roughly 31% of the earth's surface and sequester (absorb or remove from the atmosphere) and store large quantities of carbon. Forest ecosystems are estimated to store about 650 billion tonnes of carbon (FAO, 2010) and absorb 8.5 billion tonnes of CO_2 per year from the atmosphere. However, deforestation and forest degradation in the tropics through logging, fire and other anthropogenic disturbance results in substantial CO_2 emissions (Nabuurs, 1998).

2.2.4 Carbon in Agroforestry

In tropical regions, agroforestry systems provide various environmental services including carbon sequestration (Pandey, 2002; Jose, 2009; Nair *et al*., 2009). Development of agroforestry plantations in the tropics, especially on private lands, gives opportunity to both local farmers and investing developed countries to reap the benefits of CDM, i.e. income and credit respectively for the sequestered carbon in the systems (Adi *et al*., 2004; Verchot, 2007). In agroforestry systems, trees accumulate large amounts of C in woody biomass. Large amounts of C are lost from the system through harvesting of crops and timber products, while relatively slow release occurs through decomposition of leaf litter and fine roots (Nair, 1993; Wild, 1993; Farrel and Altieri, 1997; Huxley, 1998). Recent studies have shown that agroforestry systems have potential to sequester greater amounts of C than traditional farming systems (Gupta *et al*., 2009; Kaonga and Bayliss-Smit, 2009; Takimoto *et al*., 2009). However, in tropical agroforestry systems, productivity may decline as a result of continuous removal of plant biomass (Sanchez and Palm, 1996; McDowell, 2001; Budiadi *et al*., 2005). Harvesting of plant biomass from the system removes nutrients and may lead to slow degradation of soil fertility (McDonald and Healey, 2000; Shanmughavel *et al*., 2001). In tropical agroforestry systems, appropriate management of the nutrient cycle is important for maintaining productivity and preventing nutrient loss from the system (Montagnini, 2000; Shanmughavel *et al.*, 2001; Nolte *et al*., 2003).

2.2.4.1 Carbon Sequestration by tree-based systems

The basic premise of carbon sequestration potential of land-use systems, including agroforestry systems, is relatively simple: it revolves around the fundamental biological/ecological processes of photosynthesis, respiration, and decomposition (Nair and Nair, 2003). Essentially, carbon sequestered is the difference between carbon 'gained' by photosynthesis and carbon 'lost' or 'released' by respiration of all components of the ecosystem, and this overall gain or loss of carbon is usually represented by net ecosystem productivity. Most carbon enters the ecosystem via photosynthesis in the leaves, and carbon accumulation is most obvious when it occurs in aboveground biomass. More than half of the assimilated carbon is eventually transported below ground via root growth and turnover, root exudates (of organic substances), and litter deposition, and therefore soils contain the major stock of C in the ecosystem. Inevitably, practices that increase net primary productivity (NPP) and/or return a greater portion of plant materials to the soil have the potential to increase soil carbon stock.

2.2.4.2 Alleycropping

Tropical alleycropping systems, the cultivation of arable crops between tree hedgerows, represent a low end with respect to potential for C storage. As trees are periodically pruned to deposit their mulch in the alleys, C is only stored in the stem left after pruning. Therefore, pruning frequency, which can be as high as once every other month during the growing season, greatly affects the C storage capacity of the system. Data from a study of two alleycropping systems from Turrialba, Costa Rica, (Koskela *et al.*, 2000) estimated the annual 'labile' C stocks (C stored in tree leaves, branches, and crops), and compared them with the 'permanent' C stocks in tree stems. In the two systems, the perennial carbon stocks were higher than the labile stocks. However, significant decreases in soil C were detected in both systems after three to five years, thus greatly decreasing the overall value of the alleycropping system as a C sink. Some results from alleycropping experiments report on increases in soil organic carbon when prunings are returned to the soil; these increases are thought to be due to higher density of roots in alleycropping systems in comparison with adjacent plots with conventional agriculture (Schroeder, 1994).

2.3 Indigenous tree species

Taylor (1962) defined indigenous trees as variety of woody plants that are found growing naturally in a specific habitat in an ecological zone of a country. They germinate, regenerate, grow and flourish naturally under prevailing climate conditions. Indigenous plantation is partly due to the concern that, the promotion of monoculture in place of naturally diverse forest would accelerate the loss biodiversity.

Currently, reforestation projects seeks to promote the cultivation of indigenous species as a desirable alternative to exotic stands in as attempt to enhance and sustain biodiversity of the forest ecosystem (Prebble, 1997). Examples of indigenous tree species are:

2.3.1 *Terminalia ivorensis*

Terminalia ivorensis also called Emeri is a species of tree in the Family Combretaceae. It is found in Cameroon, Ivory Coast, Ghana, Guinea, Liberia, Nigeria, and Sierra Leone. It is threatened by habitat loss. The wood which is used as lumber, has a density of about 560 kg per cubic meter. The wood is pale yellow-brown in colour, seasons well with little movement in service, but is generally of low strength. The heartwood is durable. It is used in joinery and high class furniture.

2.3.2 *Triplochiton scleroxylon*

With a common height of 45 meters and a diameter of 1.5 meter, *Triplochiton scleroxylon* is a large tree that can be seen in semi-deciduous forests of Western and Central Africa. It is a fast-growing, light-demanding pioneer species, characteristic for the (disturbed) secondary forest

Wawa (as commonly known) has been the major timber tree for these regions since the late 1950's and is nowadays still the most important economic timber species of Ghana and Cameroon. In 2005, it comprised no less than 70% of the total volume of timber products exported from Ghana and 35% from Cameroon. The timber is commonly used for products like blockboard, furniture, pencils and sculptures. The wood is especially suited for the construction of saunas, more specifically for the interior parts that touch the skin, because of its low heat retention and lack of splinters (Hawthorne and Gyakari, 2006).

2.3.3 *Terminalia superba*

Terminalia superba is a large tree in the family *Combretaceae* and native to tropical West Africa. It grows up to 60 m tall, with a domed or flat crown, and a trunk typically clear of branches for much of its height, buttressed at the base. The leaves are 10 cm long and 5 cm broad, and are deciduous in the dry season (November to February). The flowers are produced at the end of the dry season just before the new leaves; they are small and whitish, growing in loose spikes 10–12 cm long. The fruit is a samara with two wings. The most famous example of its use in guitars is when it was used by Gibson in producing their now highly sought-after Flying V and Explorer guitars in 1958. ((Hawthorne and Gyakari, 2006))

2.3.4 *Ceiba pentandra*

It is a tropical tree of the family *Malvaceae* and native to Mexico, Central America and West Africa. The tree grows to 60-70cm tall and has a very substantial trunk up to 3m in diameter with buttress. The trunk and many of the larger branches are densely crowded with large, robust simple thorns. The seeds produce oil used locally in soap making and can also be used as fertilizer. Bark decoction has been used as diuretic, aphrodisiac and also to treat headache as well as type II of diabetes (Vanclay, 1994).

2.4 Growth of trees and its importance

Growth rate is the increase in the lateral and epical size and length of a species which takes place simultaneously and independently in different parts of a tree (Nkyi, 2007). Longman and Jenik (1987) also define tree growth as the changes that occur in the life of an individual or single tree with time. These principles of forest management are not greatly different from those affecting other agricultural crops. According to Evans (1992) trees, like other crops require light, water, nutrients, space, and protection from insects and diseases. The fundamental growth processes are quite similar. Stevenson and Schores (1961) stated that the major difference is the length of time required by each tree species to reach maturity.

Ofosu (1997) suggested that the growth potential of a tree is determined genetically, but actual growth is determined largely by the environment.

2.4.1 Growth requirements of indigenous tree species

Growth is important for trees because it results appreciate in the value of the crop over time (Pokua-Bonsu, 1998). Growth is periodic over the short term and follows a definite pattern in the long term (Evans, 1992). Factors that account for growth are discussed below:

2.4.1.1 Light

Almost all the energy in the tropical forest originates from solar radiation. Trees differ in their tolerance to shade and light to such a degree that subjective classification was been made by Miller (1972). The classification identifies pioneer species which are light demanders and fail to establish in deep forest shade. Examples include *Ceiba pentandra and Millicia excelsa*. Such species are suitable for plantation conditions. They show favourable growth in gaps and are classified as such. Generally, pioneer species show the fastest growth rate and continue to respond to light than non pioneer species (Longman and Jenik, 1987).

2.4.1.2 Spacing

Nketia (2002) suggested that spacing of individual trees and their resultant crown development affect the rate of diameter growth and the quality of the lumber or their products which may exceed that of open grown trees. Trees like *Ceiba pentandra* require enough space for growth because they have large crowns and large stems.

2.4.1.3 Texture and drainage

Changes in soil texture create barriers to root growth (Foli *et al*., 1996). In addition, textural differences can create drainage problems either the soil is too dry or too wet. Soils with good porosity are capable of handling large quantities of water with no harmful effects to plant roots. Most landscape soils do not have ideal drainage conditions and thus rainy weather may be a challenge. Water-logged soils may lead to root decay and fungal root diseases. Consistently wet soils will have a foul odour caused by the anaerobic bacteria growing in it and roots may appear brown or black (Johnson, 1983). This accounts for the wide ranges in height and diameter measurements of the same tree species planted at the same site.

2.4.1.4 Pathological and entomological problems

Sometimes a tree species may show a good form and have valuable timber but not suitable for plantation establishment owing to its susceptibility to damage by insects and disease (Evans, 1992). Insect defoliations have long been recognized as an important problem in forestry.

Atuahene *et al.,* (1992) observed that the main species of insect defoliators belong to the 3 orders; butterflies and moths (Lepidoptera), grasshopper (Orthoptera) and leaf beetle (Coleoptera). Repeated defoliation can however cause significant growth loss and even result in death of the trees.

2.4.1.5 Shade

The outstanding factor which influences height growth is shading or suppression is shade. According to Atuahene *et al.*, (1992), unless the upper portion of the crown of a tree has full sunlight, its height growth falls off and becomes less in proportion as the shading is more complete or dense. The capacity of a crop to adapt to shade is a major physiological limitation to productivity.

Chapman and Demerritt (1986) suggested three major strategies in response to shade; shade avoiders or oblique sun plants, shade tolerants (facultative sun/shade plants) and shade required plants.

2.4.1.6 Water

Shortage of water restricts productivity. In some areas if the evapotranspiration demand greatly exceeds rainfall during the growing season, trees retard in growth. Demand for water and nutrients may vary according to the type and stage of the development of tree and the environmental conditions (Taylor, 1962). If water deficits occur at crucial stages of development, the consequences for yield may be catastrophic. Some trees are able to tolerate dry conditions by virtue of such mechanisms as shedding of leaves.

Drought which is defined as the occurrence of substantial water deficit in the soil, plant or atmosphere, significantly influence plant performance and survival, disease resistance and susceptibility to herbivore grazing (Johnson, 1983).

2.4.2 Important growth parameters

2.4.2.1 Diameter growth

Diameter growth of most trees has the typical sigmoid curve form, although the growth stages are not markedly separate as in height growth (Nkyi, 2007). The first stage is usually short except in the species with well marked juvenile growth. The growth in diameter particularly the bole of trees is of critical importance in forestry as it determines the rate of production of logs sawn out of trees especially in the tropics where many timber species may be considered unmerchantable until they have attained a certain minimum diameter size (Chapman and Demerritt, 1986).

The rate of diameter at breast height varies greatly with species, age of trees and prevailing environmental conditions. Diameter growth of an individual tree primarily depends upon site factors and stand density. Since stand density can readily be controlled, diameter growth is also subject to effective management control (Nwoboshi, 1984).

2.4.2.2 Height growth

It shows a general brief juvenile period followed by a period of very rapid growth and ending with a relatively long period of slow almost negligible height growth in the old trees (Nkyi, 2007). Most trees growing under favorable conditions conform to this pattern. The rates of height development by trees vary considerably depending on both inherent and external factors which control the rapid and duration of growth.

2.5 Allometric equation

Several allometric equations for estimating biomass or volume of tropical fast-growing trees have been developed. The forms of the equations vary widely, including various polynomials and models incorporating DBH^2H, but the most common equation is the power function B = $aDBH^b$, where B is biomass and DBH is diameter at breast height (Parde, 1980; Crow and Schlaegel, 1988). The allometric method uses allometric equations to estimate the whole or partial (by compartments) mass of a tree from measurable tree dimensions, including trunk diameter and height (Kangas and Maltamo, 2006). Thus, the dendrometric parameters of all of the trees are measured and the allometric equation is then used to estimate the stand biomass by summing the biomass of individual trees. When building allometric equations for an individual tree, sprout or stand, different methods (destructive or not) may be considered. Destructive methods directly measure the biomass by harvesting the tree and measuring the actual mass of each of its compartments, (e.g., roots, stem, branches and foliage) (Kangas and Maltamo, 2006). Indirect methods are attempts to estimate tree biomass by measuring variables that are more accessible and less time-consuming to assess (e.g., wood volume and gravity) (Peltier *et al.*, 2007). Weighing trees in the field is undoubtedly the most accurate method of estimating aboveground tree biomass, but it is time-consuming and is generally based on small sample sizes.

Species-specific allometric equations are preferred because tree species may differ greatly in tree architecture and wood gravity (Ketterings *et al*., 2001). However, in a tropical forest stand, more than 300 tree species may be found (Gibbs *et al.*, 2007) and allometric equations should represent the variability of biomass for those species. According to McWilliam *et al.* (1993), destructive harvesting to build allometric models is seldom conducted in the tropics and sample plot sizes have been small compared to the scale of species diversity patterns; therefore, results may not be representative. Grouping all species together and using generalised allometric relationships that are stratified by broad forest types or ecological zones has been highly effective in the tropics (Brown, 2002). However, there are very few allometric equations for sub-Saharan Africa.

Carbon stock is typically derived from above-ground biomass by assuming that 50% of the biomass is made up by carbon. The most accurate method for the estimation of biomass is through cutting of trees and weighing of their parts. This destructive method is often used to validate others, less invasive and costly methods, such as the estimation of carbon stock using non-destructive in-situ measurements and remote sensing (Clark *et al.*, 2001; Wang *et al.*, 2003). Allometric equations developed on the basis of sparse measurements from destructive sampling are related to more easily collected biophysical properties of trees such as diameter at breast height (DBH) and commercial bole height (CBH). The estimation of carbon over large areas using remote sensing is supported by correlating the reflection of the canopy recorded at the sensor to the carbon measured directly or estimated indirectly on the ground (Chiesi *et al.*, 2005; Gibbs *et al.*, 2007; Myeong *et al.*, 2006; Tan *et al.*, 2007).

2.5.1 Wood density

Wood density or the dry weight per unit volume of wood is an important parameter that can be used in allometric equations that estimates tree biomass and carbon stocks from stem diameter values (Ketterings *et al*., 2001). Wood density varies with tree species, growth conditions and part of the tree measured. The main stem generally has a higher wood density than the branches, while fast growth is generally related to relatively low wood density.

When estimating the above-ground biomass of a forest, Ketterings *et al.* (2001) highlighted that the use of species-specific equations are preferred because trees of different species may differ greatly in tree architecture and wood density. However, due to the great number of different tree species in humid, tropical rain forests and the enormous efforts needed to develop these equations, species specific equations for the humid and tropics are virtually unavailable while relatively few mixed-species equations have been developed.

2.6 Carbon concentration

The general procedure for estimating biomass is to cut down a tree, weigh it, take samples of different tree components, and dry these components. The biomass (dry weight) of the tree is then calculated by applying the moisture loss of the samples to the entire tree. Depending on the researcher, however, the number of samples taken from a tree will vary. Nelson *et al.* (1999) dried a single sample of the bole at breast height, while Kraenzel *et al*. (2003) dried a separate sample for each meter of the bole's length. Moreover, the drying time and temperature varies between researchers. Nelson *et al.* (1999) dried samples at 105.8^{o}C until constant weight was reached while Kraenzel *et al.* (2003) dried the wood for 1 week at 70.8^{o}C. Other researchers (Likens and Bormann, 1970) have dried samples at 80.8^{o}C. Most researchers estimate carbon by assuming the carbon content of dry biomass to be a constant 50% by weight (Brown, 1986; Montagnini and Porras, 1998). However, other authors have used a carbon concentration of 45%

by weight (Whittaker and Likens, 1973). Occasionally, carbon is measured directly by burning the samples in a carbon analyzer (Kraenzel *et al*., 2003).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study area

The study was carried out at Oda-Kotoamso Community Agroforestry Project Site (Fig. 1) in Oda Kotoamso Townships in the Western Region of Ghana. The area falls within the hot humid tropical rainforest of the wet evergreen forest zone of Ghana (Hall and Swaine, 1981). Oda Kotoamso is near Asankeragua within the south-western equatorial climatic zone of Ghana.

Geographically, the area lies between latitude 5^0 18'N and 5^0 45'N and longitude 2^0 10'W and 2^0 10'W. The highest mean temperature is 34°C which is recorded between March and April, while the lowest mean temperature of 20°C is experienced in August (AccuWeather Inc., 2011).

Relative humidity is very high averaging between 75% to 85% in the rainy season and 70% to 80% in the dry season. The area is located within the wettest region in Ghana. It experiences a double maxima rainfall: a major rainy season from April to July, and a minor season from August to September. Average annual rainfall ranges from 1750 to 2000 mm (Hall and Swaine, 1981).

The Oda-kotoamso Community Agroforestry Project site (Fig. 1) has a total size of 290 ha. The area is stocked with about 26 tropical and exotic tree species which are either planted as mixed or single species stands. The agroforestry plantation was developed and is owned by over eighty outgrower farmers with technical and financial support from Samartex Timber and Plywood Company (Samreboi, Ghana). The soil is acidic with pH of about 3 to 4 (Hall and Swaine, 1981).

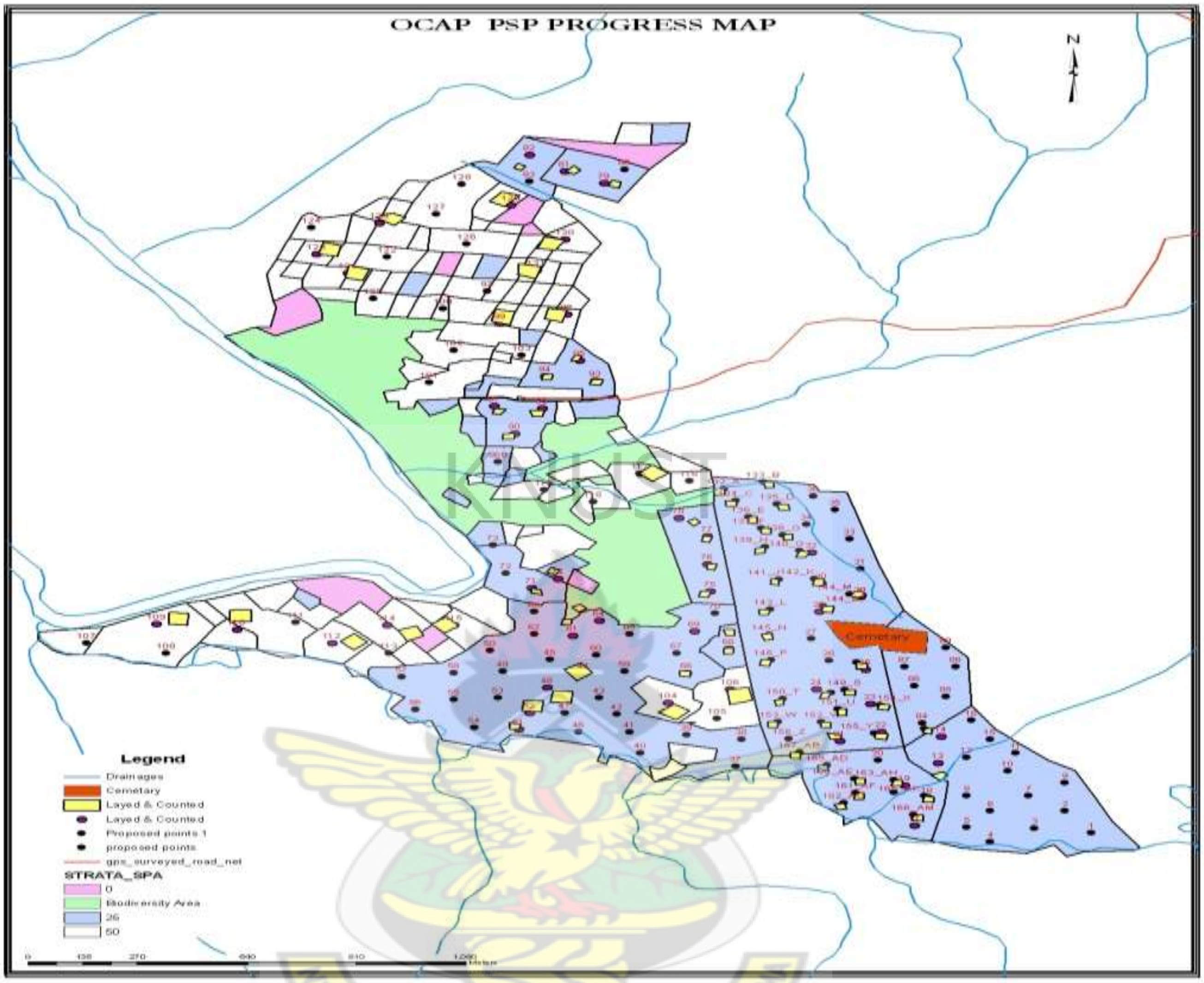

Fig. 1: Map of Oda-Kotoamso Agroforestry Project site (OCAP).

3.2 Species under study

Thirteen (13) different indigenous tree species and one (1) exotic species were studied to determine their growth performance and carbon accumulation capability. They are *Terminalia ivorensis, Terminalia superb*a, *Milicia excels*a, *Ceiba pentandra, Entandrophragma angolense*, *Aningeria robusta, Heritiaris utilis, Khaya ivorensis, Antiaris toxicaria, Tieghmella hecklii, Mammea africana, Triplochitin scleroxylon, Cedrela odorata* (exotic) *and Pycnanthus* *angolensis.* These species were selected based on their economic value and preference by farmers.

3.3 Experimental design

The entire study area had a total size of three (3) hectares (30,000 m^2) and was divided into three (3) plantations; mixed, agroforestry and pure. Each stand had a size of one (1) hectare (10,000 m^2) and was divided into four (4) plots (0.25 ha). Each plot was further divided into four subplots (625 m^2). Four (4) trees were selected for each tree species from each plot such that each subplot had one tree species. A total of 448 trees were measured on the entire study area. The planting distance determined the number of trees in each plantation. Planting distances were 2.5 x 2.5 m for pure stands, 5 x 5 m for mixed stands and 5 x 10 m for agroforestry stands. The tree species in the mixed and agroforestry plantations were not in an orderly sequence but were randomly planted along the lines according to their respective planting distances.

3.4 Collection of field measurement

The diameter (cm) of each tree sampled was measured with a diameter tape at breast height (1.3 m above ground level) and the total height (m) of each tree (above ground level) was measured using graduated poles.

3.5 Carbon contents of tree species.

A mass-based carbon concentration of 50% in dry wood is widely accepted as a constant factor for conversion of biomass to carbon stock (Lewis *et. al.*, 2009). According to Yeboah (2011) carbon concentration varies with tree species. Since carbon concentration and specific wood density of tree species were known (Yeboah, 2011) (Table 1), the specific values were used to convert total biomass to estimated carbon stock.

Table 1: Carbon concentration and specific wood density of tree species.

Tree species	Mean C concentration (%)	Wood density (g cm^{-3})
Aningeria robusta	48.0	0.497
Antiaris toxicaria	47.4	0.356
Cedrela odorata	48.3	0.381
Ceiba pentandra	46.8	0.273
Entandrophragma angolense	46.3	0.439
Heritiera utilis	48.5	0.464
Khaya ivorensis	47.2	0.523
Mammea africana	48.6	0.622
Milicia excelsa	46.6	0.458
Pycnanthus angolensis	46.2	0.354
Terminalia ivorensis	48.0	0.381
Terminalia superba	46.7	0.419
Tieghemelia heckelii	47.7	0.581
Triplochiton scleroxylom	47.2	0.429

Source: Yeboah (2011)

3.6 Allometric equations

Total above ground biomass (TAGB) for tree species was calculated using three (3) different allometric equations. The first equation (Model 1) was developed by Chave *et al.* (2005). It is a pan-tropic model developed from data compiled from various tropical forests trees since 1950s from 27 study sites. The samples were collected from 2,410 trees with DBH that ranged from 5 to 156 cm. Basuki *et al.* (2009) described this equation as the best pan-tropic model for tropical forest trees based on DBH measurements and wood density. The equation is:

TAGB = $\rho \exp(-1.499+2.148\ \text{In(DBH)}+0.207(\text{In(DBH)})^2-0.0281(\text{In(DBH)})^3)$, where ρ is the species-specific wood density (g/cm^3) and exp is exponential.

The second equation (Model 2) used, was the model of Brown (1997). The equation was derived from the data collected by several authors from different tropical countries and at different types. The diameters used to establish the equations ranged from 5 to 148 cm, and number of sampled trees was 170. The equation is TAGB = $\exp(-2.134+2.53\ln(\text{DBH}))$.

The third equation (Model 3) was an update from Brown, (1997), through Schroeder *et al*. (1997) and revised by Brown and Schroeder, 1999. The IPCC used this equation as a tool to estimate above ground biomass of tropical tree species. The model was designed for tropical trees with diameter ranging from 4 to 114 cm. The equation is $Y=21.297-6.953(\text{DBH}) + 0.74(\text{DBH})^2$.

Since species-specific wood density of tree species were known, the allometric equation developed by Chave *et al.* (2005) was used as standard with which the other two equations were compared.

Also, biomass values calculated for tree species using the three allometric equations were further compared to allometric equation designed by Yeboah (2011) for the same ecological zone.

$M = a(dbh)^b$

Where a and b are scaling coefficients, and M = biomass.

3.7 Data analysis

The average DBH, total height, basal area, volume, above ground biomass and carbon sequestration of each tree species was calculated. Since form factors were not known for the tree species, the volume of the trees were calculated using Newbould (1967) formula. Volume = basal area x height x 0.5.

To obtain the basal area, volume and carbon per hectare, two steps were followed. First, for each plot, the stand density per ha was calculated by multiplying the number of individuals in the plot by 10,000 m^2 divided by the plot area. Secondly, the stand density was multiplied by the values per species for each variable.

Analyses were performed using Special Package for Social Scientist (SPSS). One way analysis of variance with Tukey B was used to determine statistical significance in growth performance and carbon sequestration among species. Statistical significance was set at $P < 0.05$.

CHAPTER FOUR

4.0 RESULTS

4.1 Carbon sequestration of indigenous tree species plantations

Thirteen different indigenous and one exotic tree species on a three (3) hectare land were studied for growth performance and carbon stock. Data were collected on trees in agroforestry, mixed and pure plantations. The data for carbon stocks and growth parameters were presented in values for individual trees and per hectare. Tree biomass values were calculated using three different allometric equations (Model 1, Model 2 and Model 3).

4.1.1 Relation between biomass and Carbon stored in tree species

Regression analysis using values from Model 1 (Chave *et al*., 2005) showed a positive relation between biomass and carbon stored in tree species in all three plantations (R^2 = 0.973, 0.976, and 0.959) (Fig. 2, 3 and 4).

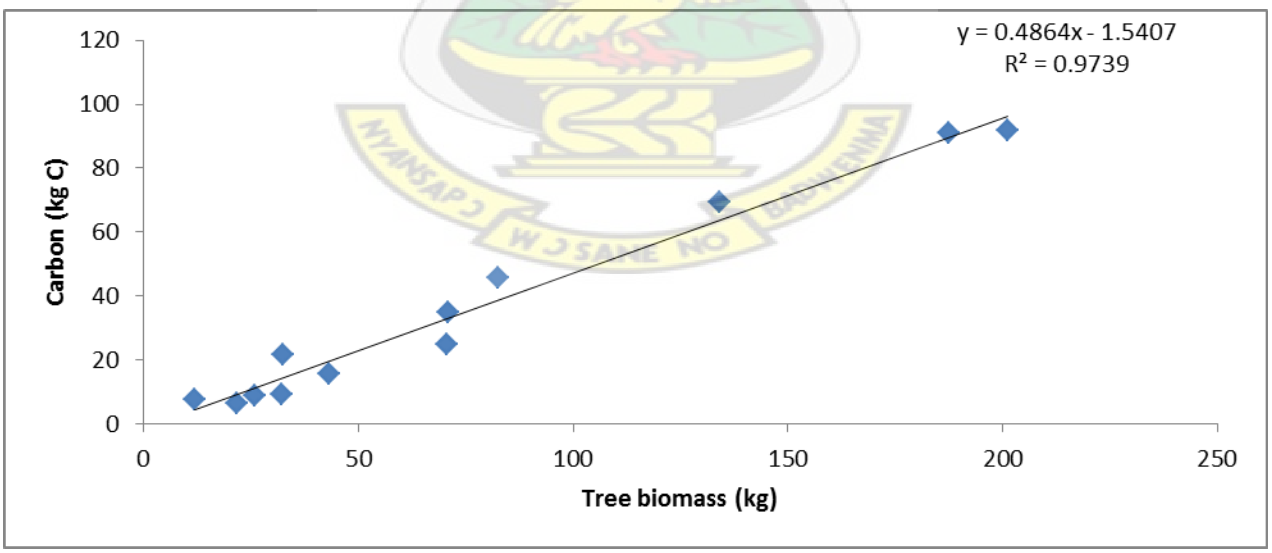

Fig. 2: Relationship between tree biomass and carbon stored in tree species in mixed plantation.

The relation between biomass and carbon stored in tree species in agroforestry plantation was the strongest among the three plantations (R^2 = 0.976).

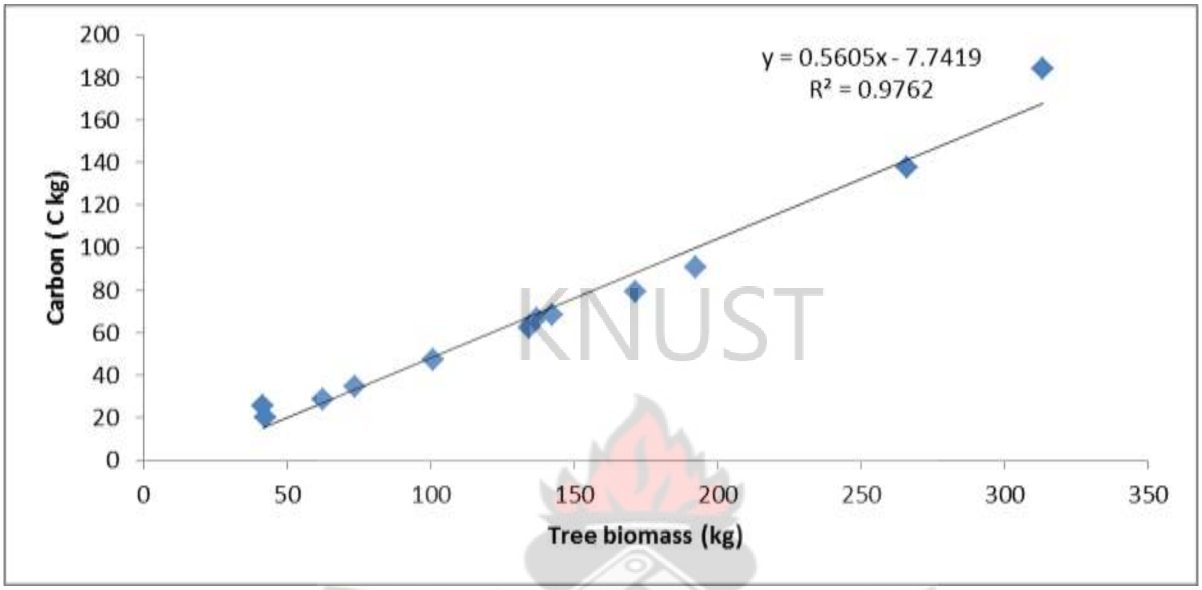

Fig. 3: Relationship between tree biomass and carbon stored in tree species in agroforestry plantation.

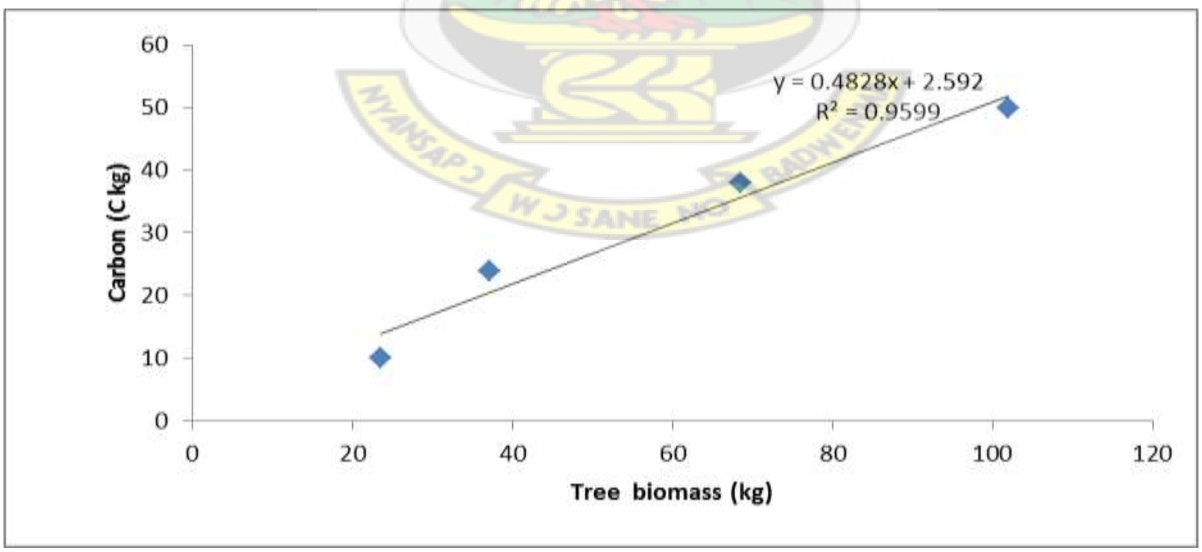

Fig. 4: Relationship between tree biomass and carbon stored in tree species in pure plantation.

4.1.2 Carbon stock among tree species occurring in mixed, agroforestry and pure plantations

Overall, results revealed that carbon accumulation per tree increased from trees in pure plantation, to mixed plantation and highest in agroforestry plantation. *Ceiba pentandra* (7yrs) in pure plantation accumulated 52.2 kg C/tree and increased to 95.6 kg C/tree in mixed plantation at age nine (9 yrs). In the agroforestry plantation of the age nine (9 yrs), carbon accumulated was 184.9 kg C/tree for *Ceiba pentandra*. In the *Khaya ivorensis* stand and *Terminalia superba* stand, the same trend was obtained (Fig. 5).

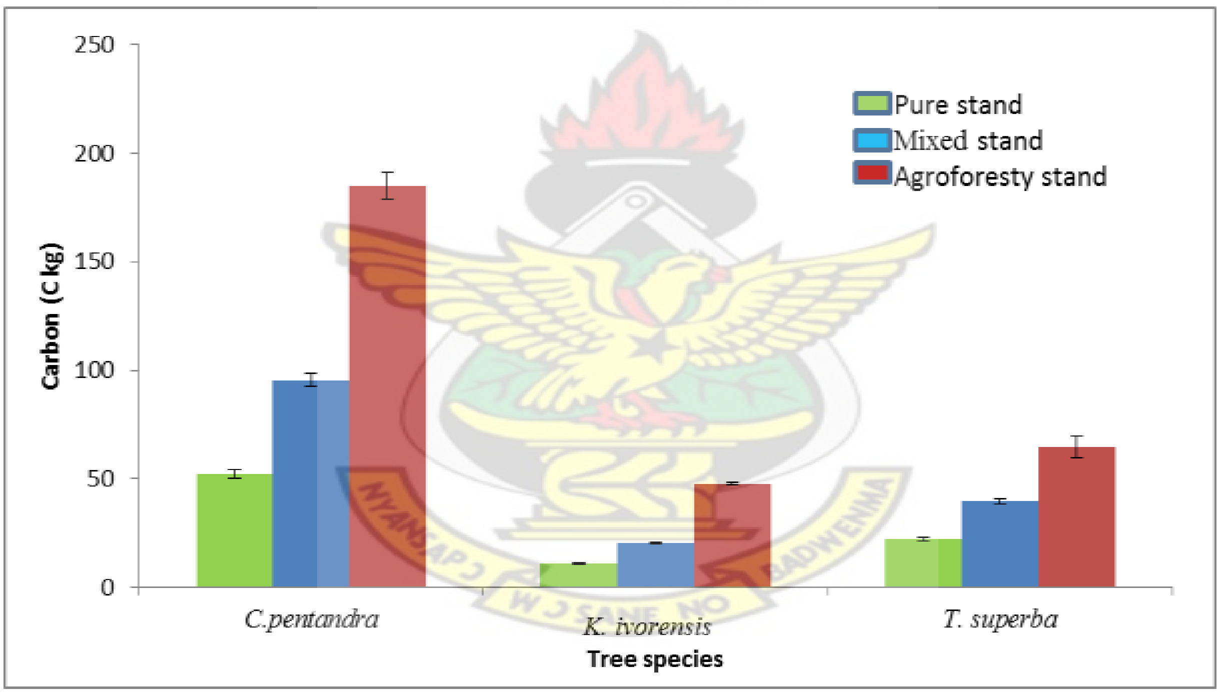

Fig. 5: Carbon stock among tree species occurring in mixed, agroforestry and pure plantations.

4.1.3 Carbon stock for trees species in mixed plantation in wet vegetation of Ghana

In mixed plantation, *Ceiba pentandra* and *Milicia excelsa* recorded the highest values for Total Above Ground Biomass (TAGB) per tree which ranged from 197.8 to 210.6 kg and 188.9 to 209.5 kg respectively (Table 2) forming more than 40% of the entire carbon in aboveground biomass in the plantation. Tree species with the lowest biomass were *Aningeria robusta*, *Entandrophragma angolense and Mammea africana* which ranged from 13.2 to 14.0 kg, 12.7 to 13.5 kg and12.6 to 13.0 kg respectively (Table 2).

Table 2: Mean carbon stock for trees species in mixed plantation in wet vegetation of Ghana.

Tree species	TAGB per tree (kg)	Carbon per tree (kg C)	Carbon per hectare (Mg C/ha)
A. robusta	13.6±0.4^{a}	6.5±0.2^{a}	0.1±0.0^{a}
A. toxicaria	22.9±1.5^{a,b}	10.8±0.7^{a,b}	0.1±0.0^{a}
C. pentandra	204.2±6.4^{e}	95.6±3.0^{e}	1.5±0.0^{e}
E. angolense	13.1±0.4^{a}	6.1±0.2^{a}	0.1±0.0^{a}
H. utilis	44.6±1.3^{b}	21.6±0.6^{b}	0.3±0.0^{b}
K. ivorensis	43.3±0.7^{b}	20.4±0.3^{b}	0.3±0.0^{b}
M. africana	11.8±0.2^{a}	5.7±0.1^{a}	0.1±0.0^{a}
M. excelsa	199.2±10.3^{e}	92.8±4.8^{e}	1.5±0.1^{e}
P. angolensis	54.7±3.5^{b}	25.2±1.6^{b}	0.4±0.0^{b}
T. ivorensis	145.6±6.8^{d}	69.8±3.2^{d}	1.1±0.1^{d}
T. superba	85.4±2.5^{c}	39.9±1.2^{c}	0.6±0.0^{c}
T. scleroxylon	89.1±3.8^{c}	42.1±1.8^{c}	0.7±0.0^{c}

Means with the same letter(s) along the columns are not significantly different ($P < 0.05$).

Ceiba pentandra and *Milicia excelsa* recorded highest values for carbon per tree at 95.6 kg C and 92.8 kg C respectively. *Aningeria robusta*, *Entandrophragma angolense* and *Mammea africana* on the other hand had the lowest amount of carbon stored with 6.5 kg C, 6.1 kg C and 5.7 kg C respectively. Data on amount of carbon per hectare showed that *Ceiba pentandra* (1.5 Mg C/ha) and *Milicia excelsa* (1.5 Mg C/ha) sequestrated the highest carbon while *Aningeria robusta, Antiaris toxicaria, Entandrophragma angolense* and *Mammea africanna* recorded the lowest carbon of 0.1 Mg C/ha each. Statistically, there was significant difference among some of tree species in carbon accumulation in mixed forest stands (P = 0.000, F-value = 255.716).

4.1.4 Carbon stock for trees species in agroforestry plantation in wet vegetation of Ghana

Results from Table 3 show that *Ceiba pentandra* grown in agroforestry plantation (on the same site with crops) had the highest above ground biomass compared to the other eleven (11) tree species under investigation. Carbon accumulation in *Aningeria robusta, Entandrophrama angolense, and Antiaris toxicaria* was very low contributing less than 10% of the entire carbon in aboveground biomass in the plantation.

The calculated biomass of *Ceiba pentandra* ranged from 382.1 to 408.1 kg/tree forming about (>20%) of the entire carbon in aboveground biomass in the plantation. *Milicia excelsa* also recorded the second highest value which ranged from 283.7 to 317.7 kg whilst *Antiaris toxicaria* and *Aningeria robusta* recorded the lowest values of 53.3 to 57.4 kg and 29.5 to 43.5 kg respectively.

Table 3: Mean carbon stock for trees species in agroforestry plantation in wet vegetation of Ghana.

Tree species	TAGB per tree (kg)	Carbon per tree (kg C)	Carbon per ha (Mg C/ha)
A. robusta	43.2±2.7^{a}	20.8±1.3^{a}	0.3±0.0^{a}
A. toxicaria	55.3±2.1^{a}	26.2±1.5^{a}	0.4±0.0^{a}
C. pentandra	395.1±13.0^{f}	184.9±6.1^{f}	3.0±0.1^{f}
E. angolense	62.7±2.3^{a}	29.0±1.1^{a}	0.5±0.0^{a}
H. utilis	138.0±5.8^{c}	67.0±2.8^{c}	1.1±0.0^{c}
K. ivorensis	101.0±1.8^{b}	47.7±0.8^{b}	0.8±0.0^{b}
M. excelsa	300.7±17.0^{e}	140.1±7.9^{e}	2.2±0.1^{e}
P. angolensis	174.4±10.1^{c,d}	80.6±4.7^{c,d}	1.3±0.1^{c,d}
T. ivorensis	145.5±9.7^{c}	69.8±4.7^{c}	1.1±0.1^{c}
T. hecklii	73.8±2.3^{a,b}	35.2±1.1^{a,b}	0.6±0.0^{a,b}
T. superba	138.2±10.6^{c}	64.5±4.9^{c}	1.0±0.1^{c}
T. scleroxylon	196.3±12.8^{d}	92.7±6.0^{d}	1.5±0.1^{d}

Means with the same letter along the columns are not significantly different ($P < 0.05$).

Analysis of variance showed a significance difference among some tree species in the agroforestry plantation ($P<0.05$). Result indicated that *Ceiba pentandra, Milicia excelsa* and *Triplochiton scleroxylon* had the highest carbon calculated per tree with values of 184.9 kg C, 140.1 kg C and 92.7 kg C respectively. The lowest values of carbon per tree species were recorded for *Entandrophrama angolense, Antiaris toxicaria,* and *Aningeria robusta* with 29 kg C, 26.2kg C and 20.8 kg C respectively.

4.1.5 Carbon stock for trees species in pure plantation in wet vegetation of Ghana

In the pure plantation, the largest TAGB calculated for *Ceiba pentandra* was 111.5 kg/tree at age seven (7yrs) (Table 4) forming more than 40% of the entire carbon in TAGB in the plantation.

Cedrela odorata (9yrs) followed with 79.5 kg/tree. The lowest TAGB (23.6 kg/tree) was recorded in *Khaya ivorensis* (6yrs).

Table 4: Mean carbon stock for trees species in pure plantation in wet vegetation of Ghana.

Tree Species	TAGB per tree (kg)	carbon per tree (kg C)	Carbon per ha (Mg C/ha)
C. odorata (9yrs)	79.5±4.0^{c}	38.4±2.0^{c}	0.6±0.0^{c}
C. pentandra (7yrs)	111.5±4.1^{d}	52.2±2.0^{d}	0.8±0.0^{d}
K. ivorensis (6yrs)	23.6±1.2^{a}	11.1±0.5^{a}	0.2±0.0^{a}
T. superba (7yrs)	47.5±2.2^{b}	22.2±1.0^{b}	0.3±0.0^{b}

Means with the same letter(s) along the columns are not significantly different ($P < 0.05$).

Results showed significance differences among tree species in pure plantation stand in term of carbon calculation (P=0.000, F=149.757). *Ceiba pentandra* had the highest value of carbon per tree of 52.2 kg C; *Cedrela odorata* accumulated 38.4 kg C while *Terminalia superba* followed with 22.2 kg C. *Khaya ivorensis* stored the least carbon per tree (11.1 kg C).

4.2 Growth of indigenous tree species in the wet vegetation of Ghana

4.2.1 Growth parameters of tree species in mixed plantation

Results of growth parameters of tree species in mixed plantation in the wet vegetation (diameter, total height, basal area and volume) are represented in Table 5. *Ceiba pentandra* had the highest volume per hectare and basal area per hectare of 3.0 m^3/ha and 0.6 m^2/ha respectively. *Terminalia ivorensis* and *Triplochiton scleroxylon* recorded the highest values for height at 11.9 m and 12.1 m respectively.

The lowest height values were recorded for *Aningeria robusta* and *Mammea africana* in all growth parameters. *Mammea africana* had the least diameter of 6.2 cm and 4.2 m high. *Aningeria robusta* performed better than *Mammea africana* with a diameter of 7.1 cm and attaining 5.1 m high (Table 5).

Table 5: Growth parameters of tree species in mixed plantation in the wet vegetation of Ghana

Tree species	Diameter (cm)	Total Height (m)	Basal Area (m^2/ha)	Volume (m^3/ha)
A. robusta	7.1 ± 0.1^{b}	5.1 ± 0.1^{b}	0.1 ± 0.0^{a}	$0.2\pm0.0^{b,c}$
A. toxicaria	9.8 ± 0.2^{c}	$7.4\pm0.1^{d,e}$	0.1 ± 0.1^{a}	$0.5\pm0.0^{b,c}$
C. pentandra	22.1 ± 0.3^{i}	10.0 ± 0.1^{f}	0.6 ± 0.0^{f}	3.0 ± 0.1^{f}
E. angolense	7.4 ± 0.1^{b}	5.9 ± 0.0^{c}	0.1 ± 0.0^{a}	0.2 ± 0.0^{a}
H. utilis	11.4 ± 0.1^{d}	$7.7\pm0.1^{d,e,f}$	0.2 ± 0.0^{b}	$0.6\pm0.0^{c,d}$
K. ivorensis	$10.8\pm0.d^{c}$	$8.1\pm0.1^{e,f}$	0.1 ± 0.0^{a}	$0.6\pm0.0^{c,d}$
M. Africana	6.2 ± 0.1^{a}	4.2 ± 0.1^{a}	0.1 ± 0.0^{a}	0.1 ± 0.0^{a}
M. excels	18.1 ± 0.3^{g}	8.3 ± 0.2^{f}	0.4 ± 0.0^{d}	1.7 ± 0.1^{e}
P. angolense	13.6 ± 0.3^{e}	7.1 ± 0.4^{d}	0.2 ± 0.0^{b}	0.9 ± 0.1^{d}
T. ivorensis	19.2 ± 0.3^{h}	11.9 ± 0.1^{h}	0.5 ± 0.0^{e}	2.8 ± 0.1^{f}
T. superb	15.2 ± 0.2^{f}	10.8 ± 0.1^{g}	0.3 ± 0.0^{c}	1.6 ± 0.0^{e}
T. scleroxylon	15.3 ± 0.4^{f}	12.1 ± 0.3^{h}	0.3 ± 0.0^{c}	1.8 ± 0.1^{e}

Means with the same letters along the columns are not significantly different ($P < 0.05$).

4.2.2 Growth parameters of tree species in agroforestry plantation

Results of growth parameters of tree species in agroforestry plantation in the wet vegetation for diameter, total height, basal area and volume are represented in Table 6. Measurements for volume per tree, basal area per hectare and volume per hectare were highest for *Ceiba pentandra* with 0.4 cm^3/tree (Fig 6), 1.0 m^2/ha and 6.0 m^3/ha respectively (Table 6). *Tieghmella hecklii* had low mean diameter of 12.7 cm but did perform better than *Aningeria robusta* which had the lowest mean diameter of 11.0 cm.

The case was different for height measurement. The *Terminalia* species had the tallest trees with 15.8 m recorded for *Terminalia ivorensis* and 13.8m for *Terminalia superba. Antiaris toxicaria* and *Aningeria robusta* had the lowest height measurements with 7.7 m and 5.2 m respectively.

Table 6: Growth parameters of tree species in agroforestry plantation in the wet vegetation of Ghana.

Tree species	Diameter (cm)	Total Height(m)	BA/ha (m^2/ha)	Volume (m^3/ha)
A. robusta	11.0 ± 0.3^{a}	5.2 ± 0.1^{a}	0.2 ± 0.0^{a}	0.4 ± 0.0^{a}
A. toxicaria	$13.7\pm0.3^{b,c}$	7.7 ± 0.2^{b}	0.2 ± 0.0^{a}	$0.9\pm0.1^{a,b}$
C. pentandra	28.4 ± 0.4^{i}	11.8 ± 0.1^{g}	1.0 ± 0.0^{f}	6.0 ± 0.2^{f}
E. angolense	13.3 ± 0.2^{b}	9.1 ± 0.1^{d}	0.2 ± 0.0^{a}	$1.0\pm0.0^{b,c}$
H. utilis	17.5 ± 0.3^{d}	12.9 ± 0.2^{h}	0.4 ± 0.0^{c}	2.5 ± 0.1^{d}
K. ivorensis	14.9 ± 0.1^{c}	10.9 ± 0.1^{f}	0.3 ± 0.0^{b}	1.5 ± 0.0^{c}
M. excels	23.4 ± 0.5^{h}	10.2 ± 0.1^{e}	0.7 ± 0.0^{e}	$3.5\pm0.2^{d,e}$
P. angolense	21.1 ± 0.5^{g}	$10.6\pm0.1^{e,f}$	0.6 ± 0.0^{d}	3.0 ± 0.1^{d}
T. ivorensis	$19.1\pm0.5^{e,f}$	15.8 ± 0.2^{j}	0.5 ± 0.0^{d}	3.7 ± 0.2^{e}
T. hecklii	12.7 ± 0.2^{b}	8.5 ± 0.2^{c}	0.2 ± 0.0^{a}	$0.9\pm0.0^{a,b}$
T. superb	$18.0\pm0.5^{d,e}$	13.7 ± 0.2^{i}	0.4 ± 0.0^{c}	2.9 ± 0.2^{d}
T. scleroxylon	$20.5\pm0.5^{f,g}$	10.9 ± 0.2^{f}	0.5 ± 0.0^{d}	2.9 ± 0.0^{d}

Means with the same letter(s) along the columns are not significantly different ($P < 0.05$).

4.2.3 Growth parameters of tree species in pure plantation

Results of growth parameters of tree species in pure plantation in the wet vegetation for diameter, total height, basal area and volume are represented in Table 7. The analysis of growth showed that *Ceiba pentandra* (7yrs) in pure plantation had the highest diameter of 17.7cm and attained a total height of 10.9 m. *Khaya ivorensis* (6yrs) had the least diameter of 8.6m. *Terminalia superba* (7 yrs) had a diameter of 12.2 cm attaining a total height of 6.3 m. *Ceiba pentandra* (7yrs) had the highest value for basal area and volume per hectare of 0.4 m^2/ha and 2.1 m^3/ha.

Table 7: Growth parameters of tree species in pure plantation in the wet vegetation of Ghana.

Species	Diameter (cm)	Total Height(m)	BA/ha (m^2/ha)	VOL/ha (m^3/ha)
C. odorata (9yrs)	15.3±0.3^c	10.9±0.1^c	0.3±0.0^c	1.6±0.1^c
C. pentandra (7yrs)	17.7±0.2^d	10.9±0.1^c	0.4±0.0^d	2.1±0.1^d
K. ivorensis (6yrs)	8.6±0.2^a	7.0±0.1^b	0.1±0.0^a	0.3±0.0^a
T. superba (7yrs)	12.2±0.2^b	6.3±0.1^a	0.2±0.0^b	0.6±0.0^b

Means with the same letter along the columns are not significantly different (P < 0.05).

In general tree species in agroforestry plantation recorded the highest values for growth parameters than tree species in mixed and pure plantations. *Ceiba pentandra* recorded volumes of 0.40 m^3 in agroforestry plantation, 0.19 m^3 in mixed plantation and 0.13 m^3 in pure plantation (Fig. 6).

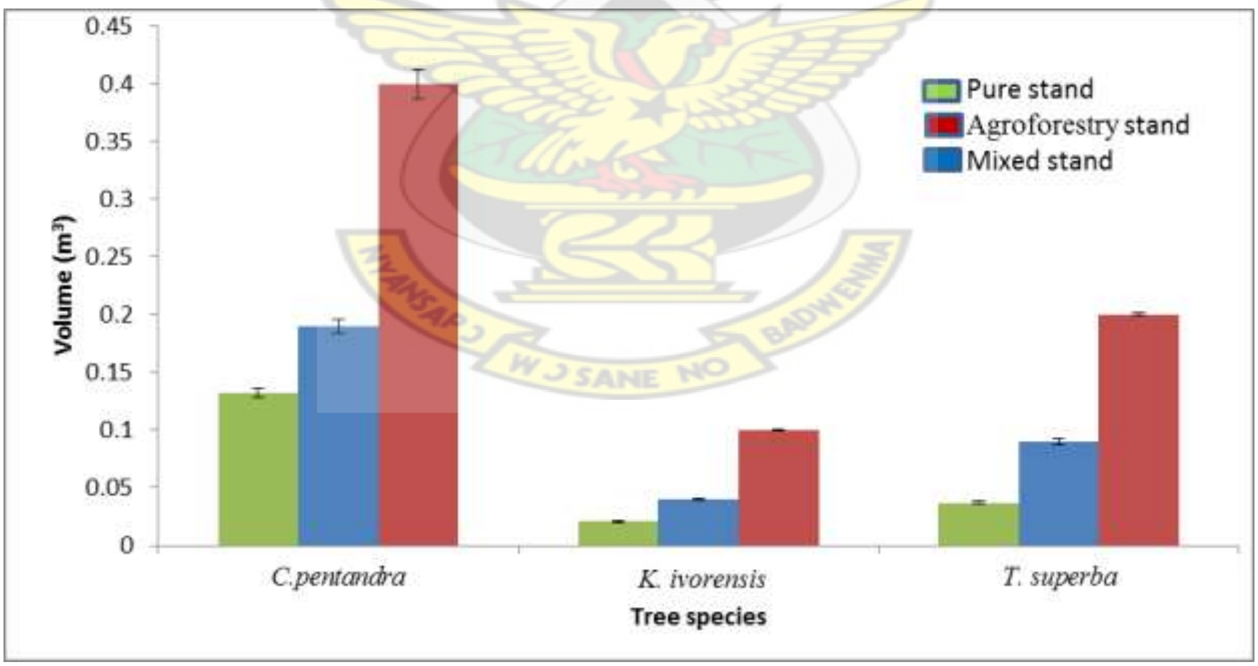

Fig. 6: Difference in volume among three tree species in mixed, agroforestry and pure plantations

4.3 Effect of different allometric equations on carbon stock

Variations in carbon stock using three different allometric equations are represented in Fig. 7. The equations were evaluated using Model 1 as standard since the wood density is a factor in this equation. Result indicates that Model 2 overestimated carbon accumulation in a tree when compared to Model 1 except for *Milicia excelsa*. However, for most of the tree species Model 3 underestimated the amount of carbon stored in them when compared to Model 1 except for *Ceiba pentandra*, *Pycnanthus angoleense* and *Terminalia ivorensis.*

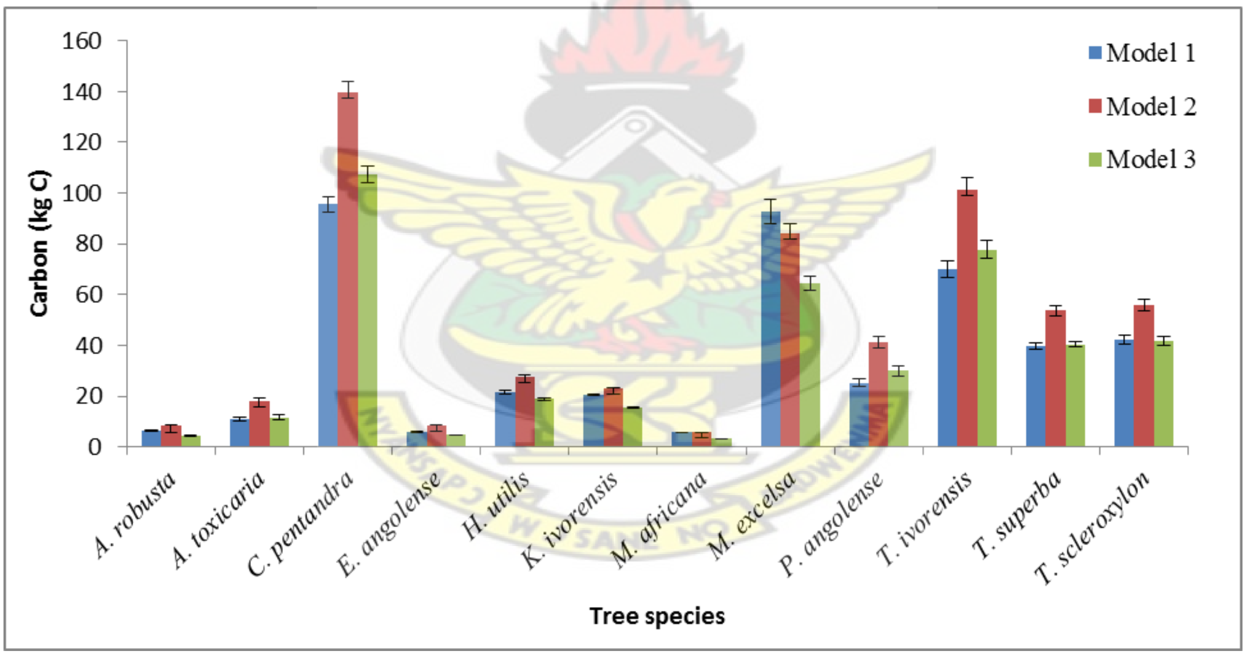

Fig.7: Variation in carbon stock using three different allometric equations.

Results from Table 8 indicated that Model 1, Model 2 and Model 3 recorded higher values for tree biomass for all tree species when compared to Yeboah (2011) except for *Pycnanthus angoleensis*. There was significant difference between biomass values for Yeboah (2011) and the other three models except *Antiatis toxicaria* for Model 1(Chave *et. al* (2005)), *Pycnanthus angoleense* for Model 2 (Brown 1997) and *Antiatis toxicaria*, *Entandrophrama angolense Heritiaris utilis, Khaya ivorensis, Mammea africana* for Model 3 (IPCC 2006).

Table 8: Total above ground biomass calculation using different allometric equations

Allometric eqn	*A. robusta*	*A. toxicaria*	*C. pentandra*	*E. angolense*	*H. utilis*	*K. ivorensis*	*M. Africana*	*P. angolense*	*M. excelsa*	*T. ivorensis*	*T. superba*	*T. scleroxylon*
Yeboah (2011)	6.6±0.1[a]	21.5±0.2[a]	160.1±2.7[a]	10.7±0.7[a]	31.2±2.4[a]	27.3±0.4[a]	6.9±0.2[a]	97.8±6.9[b]	113.1±4.5[a]	48.3±1.5[a]	63.5±2.5[a]	64.5±1.7[a]
Chave *et. al* (2005)	13.6±0.4[c]	22.9±1.5[a]	204.3±6.4[b]	13.1±0.4[b]	44.6±1.3[b]	43.3±0.7[b]	11.8±0.2[b]	53.6±3.5[a]	199.6±1.0[d]	144.0±6.8[b]	85.0±2.5[b]	88.4±3.8[b]
Brown (1997)	17.1±0.4[d]	38.6±2.3[b]	297.6±8.4[c]	18.5±0.4[c]	56.4±1.4[b]	49.1±0.6[b]	12.0±0.1[b]	87.3±7.2[b]	178.8±4.9[c]	209.3±9.0[d]	115.4±2.9[c]	117.1±4.6[c]
IPCC (2006)	9.3±0.2[b]	24.7±1.7[a]	228.6±6.3[b]	10.2±0.2[a]	38.6±1.2[a]	32.8±0.5[a]	6.6±0.1[a]	63.6±5.7[a]	137.0±4.1[b]	160.9±7.0[c]	86.4±2.4[b]	87.8±3.7[b]

Means with the same letter along the columns are not significantly different ($P < 0.05$).

4.4 Effect of carbon concentration on carbon stock

The differences in carbon stock using two different carbon concentration values are represented in Figure 8. The generalised or assumed (50%) carbon concentration (GCC) was higher than the specific carbon concentration (SCC) of the individual tree species (Fig. 8). However, there was no significant difference between the specific carbon concentration and assumed carbon concentration (50%) as a significant predictor for the amount of carbon in a tree ($P > 0.05$). *Aningeria robusta* had a TAGB of 13.6 kg, carbon values for GCC was 6.8 kg C whilst the SCC of 46.8% was calculated to be 6.5 kg C. Also the carbon value for *Triplochiton scleroxylon* was calculated to be 44.6 kg C and 42.0 kg C for GCC and SCC respectively.

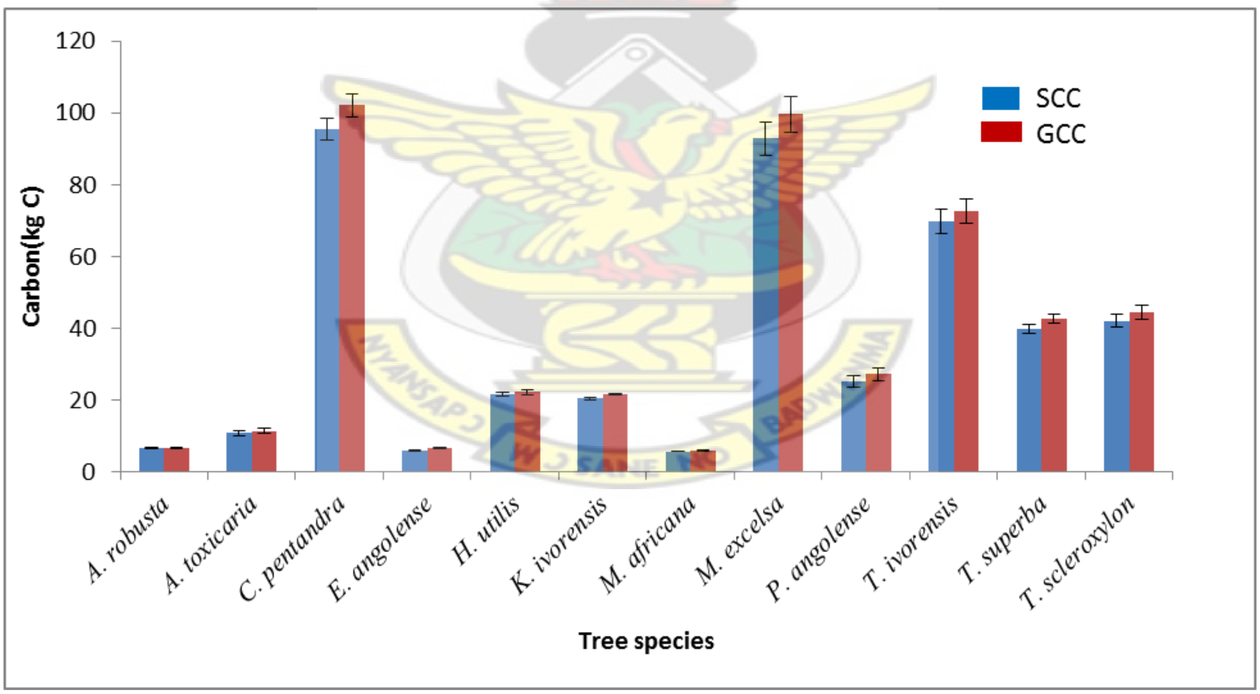

Fig. 8: Difference in carbon stock using two different carbon concentration values.

CHAPTER FIVE

5.0 DISCUSSION

The potential capacity for different terrestrial ecosystems to sequestrate carbon is highly dependent on land-use practices and forestry activities (IPCC, 2000). The carbon sequestration potential of ecosystems depends on the type of land, while forests management determines substantially the carbon sequestration rates. This thesis has evaluated the use of four allometric equations in determining carbon stock of 14 tree species and their growth performance in three different plantations in the wet-evergreen vegetation of Ghana.

5.1 Carbon sequestration values

Values for carbon per tree species conformed to the range of values obtained by Redondo-Brenes (2007). Values of carbon per hectare for plantations from this study were lower (1.9 Mg ha^{-1} in pure plantation, 6.9 Mg ha^{-1} in mixed plantation and 13.8 Mg ha^{-1} in agroforestry plantation) compared to values obtained by Montagnini and Nair (2004) when they studied carbon content in above ground biomass of ten plantation-tree species at La Selva, Costa Rica (ie 17.3 to 82 Mg ha^{-1}). Also carbon values per hectare recorded from this study were lower (except in agroforestry plantation 13.8 Mg ha^{-1}) than values reported for tropical tree plantations that range between 8 and 78 Mg C ha^{-1} (Schroeder, 1992).

This difference could be attributed to the difference in tree density per hectare between the study area of this work, the research area at La Selva in Costa Rica and that of Schroeder (1992). The planting distance from this study allowed a limited number of trees to be selected which influenced carbon stock at the project site.

5.2 Carbon sequestration of indigenous tree species plantations

Trees in agroforestry performed better in carbon allocation compared to the same tree species in mixtures and monocultures (pure stands). All eleven (11) tree species in agroforestry plantation had highest values for carbon per tree compared to tree species in mixed and pure plantation. This justified findings by Montagnini and Nair (2004) which suggested that trees in agroforestry unlike in mixed plantations and other monoculture systems had advantage in terms of carbon sequestration. This advantage could be linked to soil nutrients provided by harvested crops left to decay in the agroforestry plantation.

Higher values in agroforestry plantation might have been caused by soil fertility improvement which Nair (1999) described as a distinct possibility in agroforestry systems. Several cash crops and short term rotational crops like yams, plantain and maize were planted in alley with tree species by farmers on OCAP plots. Harvested materials of these crops and prunes from the tree species often were returned to the soils (as in alleycropping and improved fallow systems) for soil fertility improvement.

This study also confirmed report by Budiabi and Ishii (2010) when they compared aboveground biomass between multiple crops, single crop and monoculture agroforestry system of cajaput trees (*Melaleuca leucadendron*). They indicated that carbon accumulation may be increased and a sustainable carbon cycle established by returning more biomass waste into the soil and maintaining multiple crop system.

Increases in nutrient availability associated with increased in gross primary production have been observed in fertilized *Eucalyptus saligna* by Giardina *et al.* (2003) and *Pinus radiata* plantations. Nutrient availability might have increased gross primary production in agroforestry plantation than mixtures and pure plantations.

Difference in carbon allocation among the plantations could probably be attributed to difference in age. Tree species in pure plantation were younger compared to mixed plantation and agroforestry plantation. According to Lamlon and Savidge (2003), age affects the amount of juvenile wood and mature wood present in a stem; juvenile woods are characterized by high concentration of lignin and extractives compared to matured woods. This could explain why *Ceiba pentandra* and *Khaya ivorensis* at older age nine (9 yrs) accumulating more carbon than at age seven (7 yrs) and six (6 yrs) respectively.

According to Raich (1998); McConnuaghay and Coleman (1999), increases in nutrient availability can alter the partitioning of carbon from roots and mycorrhizae to above ground biomass plant parts to increase the capture of light and CO_2. Budiabi and Ishii (2010) indicated that although crop harvesting removed large amount of carbon from the system, an almost equal amount of organic waste was returned, thus establishing carbon cycle.

5.2.1 Carbon sequestration among indigenous tree species

The fast growing species (*Ceiba pentandra, Milicia excelsa, Terminalia superba and Terminalia ivorensis*) had the highest carbon accumulation per tree (Stanley and Montagnini, 1999; Shepherd and Montagnini, 2001). This phenomenom could be influenced by species wood density and growth pattern (Redondo-Brenes, 2007). Although most fast growing species (*Ceiba pentandra*, *Terminalia superba,Terminalia ivorensis)* had low species wood density, they obtained higher growth rate and hence sequestrated high carbon. On the otherhand, *Mammea africana* and *Entandrophragma angolense* acquired the least carbon allocation tree species despite having the highest species wood density. These results therefore agreed with the report of Redondo-Brenes and Montagnini (2006) who indicated that fast growing tree species have high above ground biomass, despite having lower density.

Since above ground biomass was higher in *Ceiba pentandra* than in other tree species, it could be conjectured that photosynthesis might have been higher in *Ceiba pentandra* than the remaining tree species. Although above ground respiration was not measured, it could be a large component of gross primary production according to Ryan (1991b). Above ground biomass increased with foliage production and sapwood volume (Ryan, 1990) which were higher in *Ceiba pentandra* than the remaining tree species.

5.3 Growth of indigenous tree species plantations

Mixed and agroforestry species plantations are often promoted as being environmentally preferable to monocultures, but are rarely considered viable by commercial forest growers. The objective of much of the research into mixed and pure plantation is to examine whether mixtures can provide greater yields or other benefits at a level that may outweigh management simplicity (Kelty, 2006).

Tree species in agroforestry plantation might probably have been more productive than the monocultures and mixed because of spacing among trees in agroforestry plantation. According to Lamprecht (1986), tree species take advantage of the available growing space. The main objective for the establishment of the OCAP project by Samartex was for forest restoration and conservation. However, to better the lives of farmers, crops were interplanted between tree species until tree canopies closed. There was therefore enough spacing between tree species in Agroforestry (10m X 10m) to accommodate the crops than in mixed plantation (5m X 5m) and pure plantations (2.5mX2.5m) which had no crops. Nketia (2002) suggested that spacing of individual trees and their resultant crown development affect the rate of diameter growth and the quality of the lumber or their products which may exceed that of open grown trees. Trees like *Ceiba pentandra* require enough space for growth because they have large crowns and large stems.

According to Grant *et al.* (2006), initial plantation spacing has a major effect on the economic viability on plantations. Most organizations as a result of high initial cost of planting and sivicultural activities (thinning out) prevent them from fully stocking their plantations at the early stages. Results from this thesis show that some tree species were poor in terms of survival and growth. This agrees with Kooyman (1996) who indicated poor performance in terms of survival, growth and successful site capture in restoration rainfall plantings where initial spacing exceeded 2.5m X 2.5m. The initial stocking of the plantations (1500 trees/ha for pure stand, 400 trees/ha for mixed stand and 200 trees/ha for the agroforestry stand) were in contrast to the report by Big Scrub Rainforest Group (2005). Their study suggested that 3000 plants per ha

(1.8mX1.8m) in restoration plantings encourage site capturing by trees. As a result of establishment cost and time, most forest organizations do not plant 3000 trees/ha.

5.3.1 Growth among indigenous tree species

Ofosu (1997) suggested that the growth potential of a tree is determined genetically, but actual growth is determined largely by the environment. According to Vanclay (1994), factors that affect growth and survival of trees within its environment include soil nutrients, sunlight and shade. Competition for these resources affects productivity. Competition for resources therefore might have led to the poor performance of *Mammea africana* in the mixed plantation.

Trees also differ in their tolerance to shade and light to such a degree that subjective classification has been made by Miller (1972). The classification identified pioneer species which are light demanders and fail to establish in deep forest shade. Examples include *Ceiba pentandra* and *Milicia excelsa*. Such species are suitable for plantation conditions. They show favourable growth in gaps and are classified as such. Generally, pioneer species show the fastest growth rate and continue to respond to light more than non-pioneer species (Longman and Jenik 1987). Planting design which ensures *Triplochiton scleroxylon*, *Terminalia superba*, *Terminalia ivorensis* in mixtures on the same site would result in high height measurements of these species. Hawthorne and Gyakari (2006) described these species as light demanding. These tree species outgrow neighbouring species in height to obtain maximum sunlight for optimum growth.

Menalled and Kelty. (1998) reported that the relationship between juvenile height growth rate and degree of shade tolerance plays an important role in plantations. In general, intolerant species grow rapidly in height; allocate more growth to stem and branches (Haggar and Ewel, 1995). Light demanding tree species (*Ceiba pentandra*, *Milicia excelsa*, *Terminalia superba*, and *Terminalia ivorensis)* in this present study formed an upper canopy stratum that transmitted a substantial portion of light to shade tolerant species (*Mammea africana*) which formed a lower stratum.

5.4 Effect of different allometric equations on carbon stock

In responds to the growing concern in estimating carbon stocks in forests, several allometric equations have been designed for tropical regions. Aboveground biomass in this thesis was estimated at different plantations using four different allometric equations to indicate the proportion of carbon stock in various tree species. According to Henry *et al.* (2010), the type of tree allometric equation is important in estimating the amount of carbon in a tree. From this study there were variations among the values obtained for carbon estimation using different equations (Fig. 7) and the type of allometric equation used was a significant predictor ($P < 0.0001$) for biomass and carbon per tree. Values for tree biomass were in most cases higher for Model 2 and Model 3 as compared to that of Model 1. This difference can be attributed to the use of wood specific density in the calculation of Model 1 which was absent in the remaining two equations.

Models 2 and 3 used only DBH as a predictor. According to Basuki *et al.* (2009), tree biomass is affected by tree height and wood density as well. It was therefore important to use wood density as a predictor variable in addition to DBH. Henry *et al.* (2010) reported that wood density is known to be a strong indicator of state of succession in tropical trees and the use of average wood density instead of specific ones normally introduces a bias in biomass estimation.

In preliminary biomass equations for tropical trees, Dudley and Fownes (1991) suggested that the most important consideration in using allometric equations was that, the sampled population should be representative of the target population and that extrapolation of exponential equations beyond the range of fit may result in substantial errors. Biomass values of tree species were further compared to allometric equation designed by Yeboah (2011) from the same ecological zone. Lower biomass was recorded for the same tree species using the Yeboah equation. For example, for a tree of diameter 28.6 cm having a specific gravity of 0.271, Model 1 predicted an aboveground biomass of 220.9 kg while Model 2 predicted 434.3 kg which is significantly more than that of 160.1 kg using the Yeboah equation (Table 8). The same observation was made by Basuki *et al.* (2009). When Model 1 and Model 2 were applied to their data compared to their allometric equation, the predicted values were overestimated.

This difference among these equations could also arise from the tree sizes used in the development of the various equations. Although both equations were developed from mixed species from the wet tropics, the sample size for the equations differed. Model 1and Model 2 were fitted for larger (5 to 156 cm) trees while that of Yeboah (2011) was fitted for smaller trees (< 30 cm).

According to Dudley and Fownes (1991) sampling of a relatively small number of trees (such as 20) may improve estimates considerably. It could be inferred that Model 1 might have led to overestimation due to the large sample size (2410 trees) involved in calculation.

Model 1 was developed from diverse natural forests and specifically excluded plantation grown trees. The difference in silvicultural management and growth performance may be different between natural forest and a plantation. For example, Cole and Ewel, (2006) reported that branches are likely to be shed more in dense plantations than in a natural forest. This would also contribute to difference in values obtained from these equations.

Various authors have reported that increasing the number of predictors (and particularly incorporating the crown diameter and tree height) improves precision of the models. Chave *et al.* (2005) reported that for tropical forests, the most important predictors of tree biomass were, in decreasing order of importance, trunk diameter at 1.3 m, wood specific gravity, total height and forest type. Gibbs *et al.* (2007) reported that DBH alone explains more than 95% of the variation in aboveground tropical forest carbon stocks. While the model developed by Brown (2002) explains 95% of the variability found in less than 150 tree samples, present results based on Fig. 8 clearly illustrate that one generalised model based only on DBH cannot explain the important variability found in a single ecological zone.

5.5 Effect of carbon concentration on carbon stock

Difference in carbon concentration could cause bias in carbon estimation. The 50% carbon concentration overestimated carbon estimation by 1.8% to 3.6% per tree species. However, this degree of error could compound substantially when calculations were made on large scale. From this study, an assumed 50% carbon concentration of 192 trees in mixed stand was estimated to be 7418.57 kg C while specific carbon concentration of the same species was estimated to be 6986.48 kg C. The use of specific carbon concentration other than an assumed carbon concentration accounted for carbon values (6.9 Mg ha^{-1} in mixed stands) from this study in contrast with values by Montagnini and Nair (2004) (17.3 to 82 Mg ha^{-1}). Similar observation was made by Martin and Thomas (2011). From their study of 59 Panamanian species, the 49% conversion used by the IPCC (2006) overestimated carbon stocks by 3.3%, while assuming 50% C overestimated forest C stocks by 5.3%. Lewis *et al*. (2009) estimated tropical forests globally based on a 50% C fraction sequester C in live above ground biomass (AGB) at a rate of 0.9 Pg C yr^{-1}. When converted using specific carbon concentration values by Martin and Thomas (2011), the sink was closer to 0.85 Pg C yr^{-1} (reduction of 50 million Mg C yr^{-1}). Tropical forest accounting could be greatly influenced by carbon concentration especially carbon calculations on large scale.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Among the several methods used for carbon sequestration, the removal of carbon dioxide from the atmosphere by trees through the natural process of photosynthesis and storing the carbon in their leaves, branches, stems, barks, roots and fixing carbon in the soil is found to be efficient and less costly.

The carbon storage and sequestration potential obtained varied with species, age and plantation type. It was observed that tree components in agroforestry grew better than in mixed and pure plantations. Therefore if the economic function is a priority in restoration programme, then agroforestry plantation and mixed planting should be considered. However, if the priority is with stand density and timber production, then pure plantation could be chosen.

Furthermore, if the objective is to select tree species which can accumulate carbon in the short term, then fast growing tree species like *Ceiba pentandra, Terminalia ivorensis* and *Triplochiton scleroxylon* are best options compared to *Mammea africana* and *Entandrophragma angolense.*

Finally, the type of allometric equation and carbon concentration values used influenced carbon estimation and tropical forest accounting. The involvement of wood density in the Chave *et al.* (2005) model gave a better account compared to IPCC (2006) and Brown (1997). However, the model by Yeboah (2011) showed a true reflection of carbon sequestration of the tree species because the model was designed from the same locality. The choice of allometric equation and carbon concentration values should be done with caution.

Growing native tree species in plantation is a relatively recent development in the tropics and thus, it is important to continue monitoring such plantations in order to determine the proper silvicultural treatments needed to obtain maximum economic and environmental benefit. Also climate change is creating a carbon economy. There is therefore the need for developing countries to be actively involved in carbon estimation which could earn carbon credits.

6.2 Recommendation

Further studies on carbon storage and sequestration should be carried out on below ground biomass, litter and soil to obtain a comprehensive estimate on how a given plantation sequestrates carbon on a whole. Carbon is not only stored in trunk, branches and leaves of trees alone but in soil and roots as well.

There is the need to develop species-specific allometric equations. These equations should be sensitive to geographic location, as well as differences in tree age. This will go a long way to minimize the errors and differences in carbon estimation.

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APPENDICES

Appendix 1

Volume per tree of fourteen tree species in mixtures, agroforesty and pure plantations

Tree species	Mixed stand (m^3)	Agroforestry stand (m^3)	Pure stand (m^3)
A. robusta	0.010±0.001	0.025±0.001	
A. toxicaria	0.028±0.002	0.058±0.004	
C.odorata			0.100±0.003
C.pentandra	0.190±0.006	0.376±0.128	0.132±0.004
E. angolense	0.013±0.001	0.064±0.002	
H. utilis	0.040±0.001	0.155±0.006	
K. ivorensis	0.037235113	0.095±0.001	0.021±0.001
T. hecklii		0.054±0.001	
M. Africana	0.006±0.001		
M. excelsa	0.108±0.006	0.222±0.011	
P. angolensis	0.054±0.005	0.189±0.010	
T. ivorensis	0.174±0.008	0.233±0.015	
T. superba	0.099±0.003	0.179±0.003	0.037±0.001
T. scleroxylon	0.113±0.007	0.183±0.007	

Appendix 2

ANOVA

Carbon

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	189599.136	11	17236.285	255.716	.000
Within Groups	12132.700	180	67.404		
Total	201731.837	191			

Significant level in carbon among tree species in mixed plantation.

ANOVA

Diameter

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	4588.521	11	417.138	543.107	.000
Within Groups	138.251	180	.768		
Total	4726.772	191			

Significant level in diameter among tree species in mixed plantation.

ANOVA

Biomass

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	863811.756	11	78528.341	256.921	.000
Within Groups	55017.391	180	305.652		
Total	918829.147	191			

Significant level in biomass among tree species in mixed plantation.

ANOVA

Volume

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.711	11	.065	218.712	.000
Within Groups	.053	180	.000		
Total	.764	191			

Significant level in volume among tree species in mixed plantation.

ANOVA

Height

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	1148.710	11	104.428	203.638	.000
Within Groups	92.306	180	.513		
Total	1241.017	191			

Significant level in height among tree species in mixed plantation.

ANOVA

Diameter

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	4527.639	11	411.604	177.355	.000
Within Groups	417.741	180	2.321		
Total	4945.380	191			

Significant level in diameter among tree species in agroforestry plantation.

ANOVA

Height

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	1416.911	11	128.810	318.309	.000
Within Groups	72.841	180	.405		
Total	1489.751	191			

Significant level in height among tree species in agroforestry plantation.

ANOVA

Basal Area

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.042	11	.004	165.968	.000
Within Groups	.004	180	.000		
Total	.047	191			

Significant level in basal area among tree species in agroforestry plantation.

ANOVA

Volume

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	1.764	11	.160	120.942	.000
Within Groups	.239	180	.001		
Total	2.003	191			

Significant level in volume among tree species in agroforestry plantation.

ANOVA

Biomass

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	1951998.859	11	177454.442	134.042	.000
Within Groups	238297.662	180	1323.876		
Total	2190296.520	191			

Significant level in biomass among tree species in agroforestry plantation.

ANOVA

Carbon

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	423898.881	11	38536.262	132.191	.000
Within Groups	52473.335	180	291.519		
Total	476372.216	191			

Significant level in carbon among tree species in agroforestry plantation.

ANOVA

Carbon

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	15631.741	3	5210.580	149.757	.000
Within Groups	2087.613	60	34.794		
Total	17719.354	63			

Significant level in carbon among tree species in pure plantation.

ANOVA

Diameter

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	726.665	3	242.222	293.599	.000
Within Groups	49.501	60	.825		
Total	776.166	63			

Significant level in carbon among tree species in pure plantation.

ANOVA

Height

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	290.193	3	96.731	854.609	.000
Within Groups	6.791	60	.113		
Total	296.984	63			

Significant level in height among tree species in pure plantation.

ANOVA

BA

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.003	3	.001	226.304	.000
Within Groups	.000	60	.000		
Total	.003	63			

Significant level in basal area among tree species in pure plantation.

ANOVA

Volume

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.133	3	.044	267.656	.000
Within Groups	.010	60	.000		
Total	.143	63			

Significant level in volume among tree species in pure plantation.

ANOVA

Biomass

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	70371.395	3	23457.132	151.576	.000
Within Groups	9285.305	60	154.755		
Total	79656.700	63			

Significant level in biomass among tree species in pure plantation.

ANOVA

carbon in trees

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	16474.566	2	8237.283	6.357	.002
Within Groups	742426.724	573	1295.684		
Total	758901.290	575			

Significant level in carbon estimation among tree species using three different allometric equations in mixed plantation.

ANOVA

carbon in trees

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	24711.849	3	12355.925	11.487	.000
Within Groups	1113640.1	763	1943.526		
Total	1138351.9	766			

Significant level in carbon estimation among tree species using different allometric equations in mixed plantation

ANOVA

Carbon conc

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	127.261	1	127.261	.117	.733
Within Groups	207392.790	190	1091.541		
Total	207520.051	191			

Significant level in carbon concentration among tree species in mixed plantation.