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Variation in carbon content of tropical tree species from Ghana

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<https://doi.org/10.37099/mtu.dc.etds/161>

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VARIATION IN CARBON CONTENT OF TROPICAL TREE SPECIES FROM
GHANA

By

Daniel Yeboah

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

(Applied Ecology)

MICHIGAN TECHNOLOGICAL UNIVERSITY

2011

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This thesis, "Variation in Carbon Content of Tropical Tree Species from Ghana," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN APPLIED ECOLOGY.

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Acknowledgements

My utmost thanks go to my advisors, Dr. Andrew J. Storer and Dr. Andrew J. Burton for their advice, support and teaching that has brought me up to the level of a scientist and a professional. I thank my committee member, Dr. Amy M. Marcarelli for her advice and help throughout my research project. My profound gratitude to Dr. Emmanuel Opuni-Frimpong, Forestry Research Institute of Ghana, for serving as local advisor in Ghana and his team of students who assisted with data collection. I am grateful to the late Dr. David F. Karnosky, for his contribution in the development of this research concept. I also thank the Dean of the School of Forest Resources and Environmental Science, Dr. Margaret R. Gale for her efforts in recruiting Ghanaian students; your encouragement and dedicated professors made learning in the school enjoyable. A million thanks go to all the field technicians and managers of my former employers in Ghana, Samartex Timber and Plywood Ltd that assisted with data collection. My sincere gratitude goes to my colleague, Emmanuel Ebanyenle, for sharing key information that helped in my research. I also thank everyone who has contributed in diverse ways to this research project that helped create a wonderful and enjoyable research experience for everyone involved. I appreciate my wife, Millicent Yeboah and children for their support. Above all, I thank God for all the blessings and opportunity to be part of this great family at Michigan Tech.

Abstract

Most research on carbon content of trees has focused on temperate tree species with little information existing on the carbon content of tropical tree species. This study investigated the variation in carbon content of selected tropical tree species and compared carbon content of *Khaya* spp from two ecozones in Ghana. Allometric equations developed for mixed-plantation stands for wet evergreen forest verified the expected strong relationship between tree volumes and dbh ($r^2 > 0.93$) and volume and $\text{dbh}^2 \times \text{height}$ ($r^2 > 0.97$). Carbon concentration, wood density and carbon content differed significantly among species. Volume at age 12 ranged from 0.01 to 1.04 m³ per tree, and wood density was highly variable among species, ranging from 0.27 to 0.76 g cm⁻³. This suggests that species specific density data is critical for accurate conversion of volumes derived from allometric relationships into carbon contents. Significant differences in density of *Khaya* spp existed between the wet and moist semi-deciduous ecozones. The baseline species-level information from this study will be useful for carbon accounting and development of carbon sequestration strategies in Ghana and other tropical African countries.

Chapter 1

Introduction

Forest Estate of Ghana

Ghana is endowed with an extensive stretch of tropical forests characterized by diverse flora and fauna (Abebrese 2002). The total forest cover is about 8.2 million ha and consists of two forest types: forest reserve and off-reserve forest (Hall and Swaine 1976; Hall and Swaine 1981). These two forest types differ in many ways. The off-reserve forest is on land primarily used for agricultural purposes, and accounts for about 6.5 million ha, or about 70% of the total forests, which cover 8.2 million ha (Hall and Swaine 1976; Hall and Swaine 1981; Abebrese 2002). The reserve forests constitute about 1.2 million ha and are dedicated only for forestry purposes (Abebrese 2002). The reserve forest is further classified into wet evergreen, moist evergreen, upland evergreen, moist semi-deciduous, dry semi-deciduous, southern marginal, and south-east outlier, depending on rainfall regime (Hall and Swaine 1976). The diversity of species associated with each of these forest types is high, and each contains unique species assemblages. For example the moist-evergreen forest contains about 250 tree species per ha (Hall and Swaine 1981). The reserve and off-reserve forests serve as an economic, ecological and environmental asset to Ghana. The forestry sector employs about 75,000 people and contributes 6% to 8% to the country's Gross Domestic Product (Atuahene 2001).

Unsustainable anthropogenic activities that are known to devastate the off-reserve forest include unsustainable logging, uncontrolled fire, and conversion of forests to agricultural lands (Hawthorne and Abu-Juam 1995). International demand for timber after the Second World War also led to an expansion of timber industries in Ghana which intensified the depletion of the forest resources especially in the off-reserve forest (Hawthorne and Abu-Juam, 1995; Amanor 1997; Nanang 2010). Between 1970 and 1990, Ghana lost 1.3% of its forest each year as a result of harvesting and degradation (Dixon et al. 1996). The off-reserve forest has therefore been depleted due to a growing population and because forest products and services are of low value compared to non-forest products produced after converting the forest land. For example, people often convert forestlands to cocoa plantations, which they perceive to be of immediate benefit (Hall and Swaine 1981; Hawthorne and Abu-Juam 1995; Amanor 1997). Despite the loss of the off-reserve forest, the reserve forest remains largely intact (Amanor 1997; Sandker et al. 2010).

Atmospheric CO₂ and Climate Change

During pre-industrial times, atmospheric CO₂ concentration was about 280ppm but this has increased substantially to about 368ppm by 2000 (Malhi et al. 2002). This is largely attributed to emissions from burning of fossil fuel and vegetation (Malhi et al. 2002). This elevated atmospheric CO₂ is a contributor to global climate change, which has increased the average global temperature by about 0.74 °C over the past hundred years (IPCC 2007).

Tropical forests have been recognized for their potential to store carbon in biomass and help ameliorate the rising level of CO₂. Brown and Lugo (1982) noted that tropical

forests could be credited with about 20% of the total carbon budget of the world. The forests of Ghana contain biomass of about 1,132 MtC (FAO 2005) and the forests of Africa contain 60 GtC of biomass (FAO 2005). World soil organic matter harbors 1,500 to 2,100 Pg carbon and terrestrial plants contain 490 to 760 Pg carbon, compared to 760 Pg carbon in the atmosphere (Amthor 1995).

Many initiatives and efforts seek to harness the carbon storage capability of tropical forests. The Kyoto Protocol is an international initiative geared towards finding solutions to concerns of global warming and was adopted in 1997 by member states. To date, 193 parties, made up of 192 countries and 1 regional economic integration organisation have ratified the Kyoto Protocol (UNFCCC 1997). The Protocol placed emphases on commitments of member states to reduce their CO₂ emission by sequestering carbon in forestry and agriculture systems through Clean Development Mechanisms (UNFCCC 1997). It is therefore implied that a developed nation could partner and sponsor reforestation or afforestation projects in developing countries and obtain carbon credits (UNFCCC 1997). Major CO₂ producing countries were initially unwilling to ratify the Kyoto Protocol which delayed the commencement of the Protocol because the minimum number of member countries required for achieving a target of at least 55% reduction of CO₂ emissions had not been satisfied (UNFCCC 1997). However, the European Union and Japan signed and were followed by Canada in 2002. The threshold for the Kyoto Protocol to become binding was reached in 2005, when Russia, which accounted for 17% of the world's CO₂ emission in 2004, ratified the Protocol (UNFCCC 1997). Ghana has also signed the Kyoto Protocol and is committed to fulfil the obligations documented in the Protocol.

Management and Carbon sequestration

Forest management activities have serious repercussions for forest carbon stocks. For example, irrigation, thinning, and fertilizer application are key management actions, which can boost forest productivity and carbon stocks. Mean carbon stocks may increase following cumulative nitrogen fertilization (Hyvonen et al. 2008). Fire occurrence in forests, soil compaction during tillage and animal grazing also influences forest carbon stocks. Fire increases forest floor debris and releases soil carbon, and has been reported to increase coarse-woody debris in young forests compared to mature stands (Litton et al. 2004). This destruction can increase both heterotrophic respiration and ecosystem carbon loss (Barnes et al. 1998).

Forestry activities that increase stand density may increase below and above ground carbon (Litton et al. 2004). In addition, prolonged stand rotations result in higher carbon sequestration than do shorter rotations (Schroeder 1992).

Expansion of forests by embarking on reforestation and afforestation projects holds great potential for storing carbon in biomass in tropical regions (Winjum and Schroeder 1997; Nair et al. 2009). Restocking of degraded forests through enrichment planting programs and agroforestry intervention enhances carbon storage of forests (Schroeder 1992; Nair et al. 2009).

Carbon Projects in Africa

Many afforestation and reforestation projects have been executed in Africa as a means to sequester CO₂ in biomass and provide carbon credits for participants. Carbon trading provides an attractive economic opportunity for subsistence farmers to sell sequestered

carbon to interested partners in industrialized nations. An initiative by the World Bank has funded twelve projects in Africa through its BioCarbon fund and Global Environment facility (Jindal et al. 2008). For example, the World Bank funded a Nile Basin reforestation project in Uganda, where about 2000ha in plantations were established with timber and carbon credits shared between local communities and the bank (Jindal et al. 2008). A similar project was funded by the United States Agency for International Development (USAID). The European Union and FACE foundation are also funding other carbon projects (Jindal et al. 2008).

Carbon Analysis

Carbon (C) concentration of dry wood has generally been assumed to be 50% for most species (Matthews 1993). However, wood is comprised of a wide range of macromolecular substances such as lignin, cellulose and hemicellulose. There are varying proportions of C in each of these compounds and compound groups (Lamlom and Savidge 2006). Lamlom and Savidge (2006) reported that there is 42.1% carbon in cellobiose, the building blocks of cellulose, and 40% C in monosaccharides that are associated with hemicellulose. Different plant tissues contain varying amounts of carbon. For example, carbon contents of leaves is about, 42%, while roots contain 47 to 52% carbon (Atjay et al. 1979; Lamlom and Savidge 2006).

Tree Biomass and Allometry

Methods for estimating tree biomass have attracted much scientific attention recently because of their importance in estimating forests carbon stocks (Zianis and Mencuccini

2004). Biomass can be calculated from knowledge of both the volume and density of a tree (Zobel and van Buijtenen 1989; Brown 1997; Ketterings et al. 2001).

Using volume alone to estimate biomass may not accurately estimate the amount of substance per unit area, as it ignores significant variation in density among species (Zobel and van Buijtenen 1989; Brown 1997). Organic carbon occurs in various pools within the forest ecosystem: above and below ground biomass, woody debris, mineral soils, forest floor and heterotrophic organisms (Barnes et al. 1998). A study in the United Kingdom showed that a plantation may hold carbon in the range of about 40-80 Mg Cha⁻¹ in trees, 15-25 Mg Cha⁻¹ in above and belowground litter, and 70-90 Mg Cha⁻¹ in soil organic matter (Dewar and Cannell 1992). Above ground biomass is usually estimated with a widely applied power function model of the form: $M = aD^b$, where, a and b represent scaling coefficients, D is the diameter at breast height and M is total aboveground tree dry biomass (Ketterings et al. 2001; Zianis and Mencuccini 2004). The values of the two scaling coefficients vary with species, stand age, site quality, and climate and stand stocking (Baskerville 1965; Zianis and Mencuccini 2004). To develop allometric equations, trees are cut down from a forest stand to measure diameter at breast height (dbh) and height, which are used to estimate volumes. The calculated volumes are regressed on either dbh or the combination of dbh and height to establish the allometric equation (Brown et al. 1989; Ketterings et al. 2001; Zianis and Mencuccini 2004). The developed equation could be applied to estimate volume of all trees within an entire area based on either dbh or dbh and height, which can then be converted to biomass using wood density.

In this thesis, the biomass and carbon content of 18 tree species from tropical forest plantations in Ghana were estimated from wood samples collected in wet and moist forest ecozones. Species-specific information on carbon concentration, and wood density and methods for calculating carbon content are described, and these will be useful for both commercial forest plantations and reforestation activities.

Chapter 2

Variation in carbon content of tropical tree species from Ghana

Abstract

Most research on the carbon content of trees has focused on temperate tree species with little information existing for tropical tree species. Questions remain regarding how much carbon can be sequestered by various tree species and in different forest climatic zones. This study was designed to investigate the variation in carbon content of selected tropical tree species and compare the carbon content of *Khaya* spp from two ecozones in Ghana. Two to three individuals of 18 tree species were randomly selected and harvested from 12-year-old and 7-year-old plantations in Ghana. The diameter at breast height (dbh at 1.3 m above ground) and length of the main stem were measured. A 2-cm thick wood disc was cut from the bottom, middle and top positions of the main stem of each tree, and used to estimate wood density and carbon concentration. Estimates of tree stem carbon were computed using tree stem volumes, density and carbon concentration. Allometric equations developed for mixed plantation stands for the wet evergreen forest verified the expected strong relationship between tree stem volumes and dbh ($r^2 > 0.93$) and between volumes and $\text{dbh}^2 \times \text{height}$ ($r^2 > 0.97$). Carbon concentration, wood density and carbon content differed significantly among tree species. Carbon concentration of the tree species ranged from 46.3 to 48.9 %. Volume for the 12-year-old trees varied widely among species, from 0.01 m³ to 1.04 m³. Wood densities differed among tree species and

the three stem positions. Differences in wood density at the three positions on the stem were independent of tree species. Wood density was highly variable among species, ranging from 0.27 g cm^{-3} to 0.76 g cm^{-3} . Species specific knowledge of wood density was much more important than knowledge of carbon concentration for ensuring accurate conversion of allometric volume estimates to tree carbon content. Significant differences in wood density did exist among *Khaya* spp from wet and moist semi-deciduous ecozones, suggesting climatic factors may also need to be considered. This study has provided baseline species-level information that will be useful for carbon accounting and development of carbon sequestration strategies in Ghana and other tropical African countries.

Introduction

Growing concerns about climate change resulting from increased concentration of greenhouse gases in the atmosphere have stimulated discussions about the importance and potential of forests for carbon sequestration. Due to anthropogenic emissions, the concentration of the major greenhouse gas, carbon dioxide (CO_2), has increased from 290 to 390 ppm within the last hundred years (Schneider 1990). Mean global temperatures have increased by 0.74°C over the same time period, as atmospheric CO_2 concentration increased (IPCC 2007). Regional temperatures may increase even by 1 to 5°C , if the current atmospheric CO_2 concentration is doubled (Mahlman 1997).

To reduce the escalating levels of greenhouse gases, in particular CO_2 , afforestation and reforestation systems have been encouraged as means to sequester CO_2 in biomass, an

idea formally endorsed by the Kyoto Protocol. The Kyoto Protocol allows for the opportunity to offset CO₂ emissions through collaboration between developed and developing nations to venture into reforestation or afforestation projects (UNFCCC 1997).

Questions regarding how much carbon can be sequestered by different tree species and if there are variations in carbon content of trees with geographical location remain to be answered. Available research has revealed significant differences among different tree species growing at various sites (Elias and Potvin 2003; Lamtom and Savidge 2003; Bert and Danjon 2006). The chemical make-up of different tree species allows them to grow in different environments (Elias and Potvin 2003; Lamtom and Savidge 2003; Bert and Danjon 2006) and results in variation in carbon content between species and at different locations for trees of similar size.

Most research estimating carbon content of trees has focused on temperate trees. Little information on the carbon content for tropical trees species exists, and such paucity of information makes estimation of the value of these species as carbon sinks difficult.

Quantifying carbon stocks in forests requires accurate estimation of aboveground biomass in addition to information about the carbon concentration (Brown et al. 1989; Ketterings et al. 2001; Elias and Potvin 2003; Lamtom and Savidge 2003; Chave et al. 2004). Several factors account for variability in tree and forest biomass, including tree species, climate, topography, soil fertility, water supply, and wood density (Fearnside 1997; Luizao et al. 2004; Sicard et al. 2006; Slik et al. 2008). Wood density is an important variable which affects biomass estimates derived by converting volumes from forest inventory data (Brown et al. 1989; Fearnside 1997). Tree species mass is known to

be influenced by factors such as architecture, size, form, health, and variation of wood density (Basuki et al. 2009). Along the main stem of a tree, wood density varies from the base to the top of the stem, and radially from pith to bark. Wood density often decreases from the stump to half of the total height of the tree, and increases afterwards towards the top (Espinoza 2004). Density also varies with species, age and geographical location in tropical forests (Fearnside 1997; Slik et al. 2008; Henry et al. 2010). However, little information exists on wood density for plantation tree species grown in Ghana and other sub-Saharan African countries.

Forest biomass estimation usually involves conducting forest inventory on sampled plots, using appropriate allometric equations to estimate tree volumes, converting volumes to biomass using wood density, and extrapolating to estimate biomass for an entire area (Brown 1997; Ketterings et al. 2001; Chave et al. 2004). The allometric equation used is the most essential input from this method (Navar 2009). Development of these equations is achieved by fitted equations using regression techniques (Parresol 1999; Wirth et al. 2004). There is a possibility of error in above ground biomass estimation by inappropriate application of the same allometric equation to different forests types (Brown et al. 1989; Clark and Clark 2000). For example, the equation may be developed based on a limited size class of trees which skews the equation towards this size class (Clark et al. 2001; Henry et al. 2010) and could introduce error when applied to trees that fall outside the range of sizes used to develop the equation. Literature is replete with several allometric equations for estimating aboveground biomass of some tropical forests (Brown et al. 1989; Chave et al. 2005). In Ghana, however, allometric equations rarely exist, especially

for plantation grown trees. Hence, the option is to apply equations from other regions, the reliability of which has not been tested for Ghana (Brown et al. 1989; Henry et al. 2010).

This research seeks to bridge the knowledge gap on the carbon content of tropical trees species from Ghana by developing allometric equations applicable for plantation grown tree species and providing information on carbon concentration, wood density, and tree carbon content. The study investigated eighteen fast growing species common to the moist semi-deciduous and wet forest ecozones of Ghana. The purpose of promoting plantation development in Ghana is to restore degraded forests, provide raw materials for industry and potentially obtain extra income from carbon credits as a means of value addition. The following research questions were addressed:

- What is the estimated average carbon content in stems of selected plantation trees species grown in Ghana?
- What is the variation in carbon content among the different tree species grown in Ghana, and how is this affected by species differences in volume, density and carbon concentration?
- What is the variation in carbon content within a species from two different ecological zones in Ghana?

Hypothesis

1. There are significant differences in carbon content among different tree species due primarily to differences in wood density.

2. There are significant differences in carbon content of the same trees species planted in different ecological zones with greater carbon content occurring in wetter zones due to differences in wood density.

Objectives

1. To estimate carbon content in selected tropical trees in Ghana.
2. To compare carbon content of plantation trees from moist semi-deciduous and wet evergreen forest zones of Ghana, and determine which species have the greatest carbon sequestration potential.

Methods

Study Area

Two study areas were used, the first in Oda-kotoamso and the second at Bobiri forest reserve. Oda kotoamso is located in the western region of Ghana, and is about 10 km from Asankraqua, the district capital of Wassa Amenfi.

Geographically, Odokoamso lies between latitude 5° 18'N and 5° 45'N and longitude 2°10'W and 2°30'W. Oda kotoamso falls within the hot humid tropical rainforest of the wet evergreen forest zone of Ghana (Hall and Swaine 1981). There are two rainfall seasons: 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). Two dry seasons prevail in the area: a major dryseason from December to March, and a minor dry season from October to November. The soil is acidic with pH of about 3

to 4 (Hall and Swaine 1981). Average annual temperature range between 28 and 32 °C and relative humidity is about 70% to 85%. The landscape of the area is characterised by undulating stretches of land with hilly and flattened mountains with an elevation ranging from about 90 to 400 m above sea level.

The plantation called Oda-kotoamso Community Agroforestry Project (OCAP) was planted in 1997 and has a total size of approximately 290 ha. To date, 23 tropical and exotic species have been successfully planted as either mixed or single species stands, with spacing from 3×3 to 4×4 m. The 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 second site for the study was Bobiri (6°40'N, 1°19'W), about 35 km from Kumasi in the Ashanti region of Ghana. Bobiri falls within the moist semi-deciduous forest, which is drier than the wet evergreen forest zone (Hall and Swaine 1981). Average annual rainfall for the moist evergreen forest ranges from 1200 to 1800 mm (Hall and Swaine 1981) and the temperature is about 32 °C. Topography of the area is moderately high with an elevation of about 150 to 600 m (Hall and Swaine 1981). The soil is slightly acidic with pH of about 5 to 6 (Hall and Swaine 1981). The Bobiri plantation consists of single species stand of *Khaya ivorensis* and *Khaya grandifoliola* on a one-hectare plot.

Data Collection

A total of sixty-six trees were randomly selected from the plantations in the wet evergreen and moist semi-deciduous forest zones. For OCAP, trees of 41, 9 and 8 from 12, 7 and 5 years-old were selected from the plantations respectively. In all cases, 2 to 3 trees per species were examined within an age class at a plantation.

Tree species collected for study from the wet evergreen forest zone at OCAP were:

Aningeria robusta, *Pycnanthus angolense*, *Tectona grandis*, *Cedrela odorata*, *Heritiera utilis*, *Antiaris toxicaria*, *Tieghemelia heckelii*, *Ceiba pentandra*, *Terminalia ivorensis*, *Terminalia superba*, *Milicia excels*, *Lophira elata*, *Triplochiton scleroxylem*, *Mammea Africana*, *Guarea thompsonii*, *Khaya ivorensis*, *khaya grandifoliola*, *Turreanthus africanus*. Eight trees of *Khaya ivorensis* and *Khaya grandifoliola* were also selected from the moist semi-deciduous forest zone at Bobiri.

The trees were cut down and their diameter at breast height (dbh, at 1.3 m) was measured. The length of the main stem from bottom to top (stump to first large branch) of individual trees was measured. Volumes of the base (stump to 1.3 m), middle (1.3 m to midpoint) and top segments (midpoint to top) were computed using Smalian's formula (Avery and Burkhart 2002) using the length and end diameters of each segment. Discs of about 2 cm thickness were cut at the base, middle, and top portion of the main stem of each tree and their diameter outside bark was measured. Strip sections of wood along the diameter of the discs were removed as samples. Volumes of these sub-samples were measured by a water displacement method. This method involves fixing the removed wedged-shaped samples on a prong attached to an adjustable clamp and submerging them into a bowl of water placed on an electronic balance. The suspended wood sample in the bowl of water was fully covered but not touching the bottom of the bowl. Sample volume (cm^3) was determined as the increase in balance reading (g) due to the suspended wood sample. The wood samples were then kept in airtight bags and stored in a freezer (0 °C) at the Forest Research Institute of Ghana, until samples could be transported to Michigan

Technological University. Wood samples were oven dried at 70 °C and weighed with an electronic scale to determine dry sample weights.

The dry weight of the wood and volume were used to determine density (g cm^{-3}), and the samples were ground to a fine powder using a ball mill (Spex certi-Prep 8000M).

Samples of the ground wood were then analyzed for carbon concentration using an elemental analyzer (Fisons NA 1500). The procedure used for estimating the carbon content of wood was slightly modified from similar work done by Lamlon and Savidge (2003). Density, volume and carbon concentration were used to estimate carbon content by segment, with values for the three segments summed to estimate carbon content of the entire main stem.

Data Analysis

Analysis of variance (ANOVA) was used to test for differences in carbon contents, C concentration and density of tree species investigated. Two-way ANOVA was used to test for effects of stem positions, species and their interactions in the analyses of C concentration and wood density. These analyses were performed in SAS (1997).

Contrasts among tree species were performed using Tukey's pair-wise comparison for equal sample sizes, while, Bonferroni's test was used for unequal sample size at $P < 0.05$.

The main stem height and dbh data were collected were used to develop regression relationships for predicting volume from dbh and $\text{dbh}^2 \times \text{height}$. Both linear forms and power functions were used. The power functions were in the form: $M = a(X)^b$, where, M= volume of trees, X is either the diameter at breast (dbh) or $\text{dbh}^2 \times \text{height}$, and a and b are scaling coefficients (Zianis and Mencuccini, 2004).

Results

Carbon Concentration

Carbon concentration varied significantly among species for both the 12-year-old ($P<0.001$) and 7-year-old ($P<0.001$) plantations. Mean carbon concentrations ranged from 46.3% to 48.9% (Figure 2.1; Table 2.1). Carbon concentrations were higher for 12-year-old trees than 7-year-old trees, but the difference was not statistically significant (Figure 2.2). Differences in the carbon concentration for the bottom, middle and top stem positions of 12-year-old trees were significant ($P<0.001$), but no interactions existed between species and the stem positions. Regression analysis showed a strong relationship ($P<0.0008$; $r=0.5020$) between carbon concentration and wood density for the 12-year-old trees from the wet evergreen forests ecozone.

Table 2.1
Mean carbon concentration for 12-year-r trees from OCAP
plantation the wet evergreen forest ecozone of Ghana

| Tree species | Mean C concentration (%) | Standard error of mean(SE) |
|----------------------------------|--------------------------|----------------------------|
| <i>Ceiba pentandra</i> | 46.8 | 0.3 |
| <i>Heritiera utilis</i> | 48.5 | 0.3 |
| <i>Tectona grandis</i> | 48.9 | 0.4 |
| <i>Entandrophragma angolense</i> | 46.3 | 0.4 |
| <i>Terminalia ivorensis</i> | 48.0 | 0.2 |
| <i>Terminalia superba</i> | 46.7 | 0.4 |
| <i>Milicia excelsa</i> | 46.6 | 0.3 |
| <i>Mammea africana</i> | 48.6 | 0.1 |
| <i>Khaya ivorensis</i> | 47.2 | 0.2 |
| <i>Pycnanthus angolense</i> | 46.2 | 0.2 |
| <i>Cedrela odorata</i> | 48.3 | 0.2 |
| <i>Guarea thompsonii</i> | 47.3 | 0.1 |
| <i>Lophira elata</i> | 48.4 | 0.1 |
| <i>Turreanthus africanus</i> | 48.6 | 0.1 |
| <i>Aningeria robusta</i> | 48.0 | 0.3 |
| <i>Antiaris toxicaria</i> | 47.4 | 0.2 |
| <i>Tieghemelia heckelii</i> | 47.7 | 0.3 |
| <i>Triplochiton scleroxylem</i> | 47.2 | 0.4 |

Volume and Density

Average tree volume for 12 year-old plantation tree species ranged from a minimum of 0.01 m³ to a maximum of 1.04 m³ (Figure 2.3). The species with the greatest volume at age 12 was *Ceiba pentandra*, while *Guarea thompsonii* had the lowest volume. Also, wood density differed significantly among species in the 12 year-old plantation ($P<0.001$; Figure 2.4). The mean density was highly variable among species, ranging from 0.26 to 0.76 g cm⁻³(Table 2.2). *Ceiba pentandra* had the lowest density, while *Lophira elata* had the highest density (Figure 2.4). Comparison of wood density of the same species from 12-year-old and 7-year-old plantation in the wet ecozone found not significant

differences among the two ages (Figure 2.5). There was a significant difference in wood density of *Khaya* spp of the same age but planted in different ecozones (Figure 2.6).

Density also differed significantly along the bole of the trees. Generally, the bottom positions of trees had higher mean wood density of 0.526 ± 0.02 (SE) g cm^{-3} than the middle and the top, which had mean densities of 0.444 ± 0.02 (SE) g cm^{-3} and 0.439 ± 0.02 (SE) g cm^{-3} respectively. However, no significant interactions were found between species and the three stem positions tested with two-way ANOVA. Volume of 12-year-old trees planted in the wet forest ecozone were negatively correlated ($P < 0.003$; $r = -0.5403$) to wood density.

Wood density inversely correlated with either tree's main stem height ($P < 0.0001$; $r = -0.6279$) and dbh ($P < 0.0006$; $r = -0.5114$) for the 12- year-old trees from the wet evergreen forest ecozone.

Table 2.2
Mean wood density for 12 years trees from OCAP plantation in the wet evergreen forest
ecozone of Ghana and densities in literature.

| Tree Species | Wood density in this study (g cm ⁻³) | Wood density in literature | |
|--------------------------------------|---|---|--|
| | | Reyes et al. 1992 (g cm ⁻³) | Bolza and Keating 1972 (g cm ⁻³) |
| <i>Aningeria robusta</i> | 0.497±0.03 | - | - |
| <i>Antiaris toxicaria</i> | 0.356±0.02 | 0.380 | 0.370 to 0.400 |
| <i>Cedrela odorata</i> | 0.381±0.03 | 0.430,0.440 0.450 | 0.370 to 0.400 |
| <i>Ceiba pentandra</i> | 0.273±0.01 | 0.260 | 0.270 to 0.320 |
| <i>Entandrophragma angolense</i> | 0.439±0.04 | 0.450 | 0.510 to 0.570 |
| <i>Guarea thompsonii</i> | 0.526±0.03 | 0.550 | 0.580 to 0.640 |
| <i>Heritiera utilis</i> | 0.464±0.03 | 0.560 | 0.580 to 0.640 |
| <i>Khaya ivorensis</i> | 0.523±0.03 | 0.440 | 0.460 to 0.500 |
| <i>Lophira elata</i> | 0.761±0.03 | 0.870 | 0.102 to 0.114 |
| <i>Mammea africana</i> | 0.622±0.01 | 0.620 | 0.650 to 0.720 |
| <i>Milicia excelsa</i> | 0.458±0.05 | - | - |
| <i>Pycnanthus angolensis</i> | 0.354±0.03 | 0.400 | 0.410 to 0.450 |
| <i>Tectona grandis</i> | 0.566±0.02 | 0.500,0.550+ | 0.580 to 0.640 |
| <i>Terminalia ivorensis</i> | 0.381±0.02 | - | 0.510 to 0.570 |
| <i>Terminalia superba</i> | 0.419±0.03 | 0.450 | 0.410 to 0.450 |
| <i>Tieghemella heckelii</i> | 0.581±0.05 | 0.550 | 0.580 to 0.640 |
| <i>Triplochiton scleroxylon</i> | 0.429±0.05 | 0.320 | 0.370 to 0.400 |
| <i>Turreanthus africanus</i> | 0.435±0.01 | - | 0.460 to 0.500 |

Carbon content and Guilds Classification

The mean carbon content across species at age 12 was 54.89 ± 8.16 SE kg C/tree. *Guarea thompsoni* had an extremely low average carbon content of 2kg C/tree whereas *Ceiba pentandra* sequestered the greatest carbon of 179 kg C/tree (Figure 2.7). There was significant variation in average tree carbon content among species in the 12- year-old plantation ($P < 0.001$). However, there was no significant difference among species in mean tree carbon content for the 7-year-old plantation ($P < 0.834$). Similarly, carbon content of *Khaya* spp grown in wet and moist evergreen forests zones were not significantly different at age 5.

Apart from *Tectona grandis* and *Cedrella odorata* which are exotic species, all others (i.e. indigenous) tree species were classified into three guilds; pioneers, intermediate and shade bearers (Hawthorne, 1995). The essence of this classification is to determine if there is any ecological strategy that might be related to carbon content of tropical tree species. The result showed no significant difference in carbon content for the guild classification (Table 2.3).

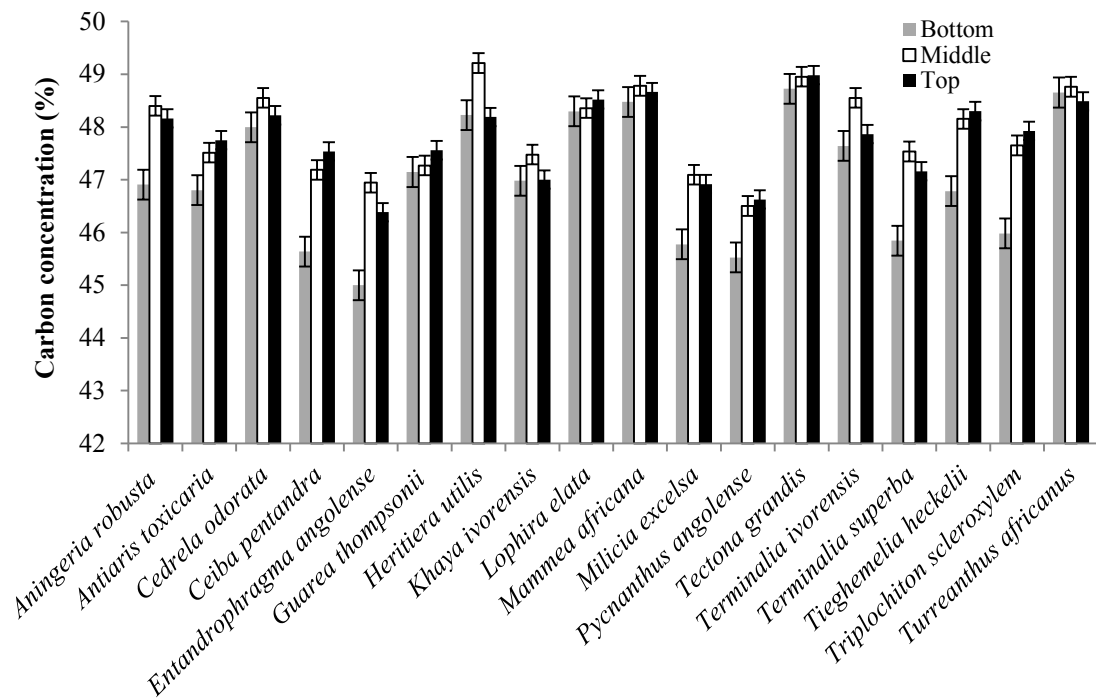


Figure 2.1 Carbon concentrations for 12 year-old-trees species from the OCAP plantation in the wet evergreen forest ecozone of Ghana.

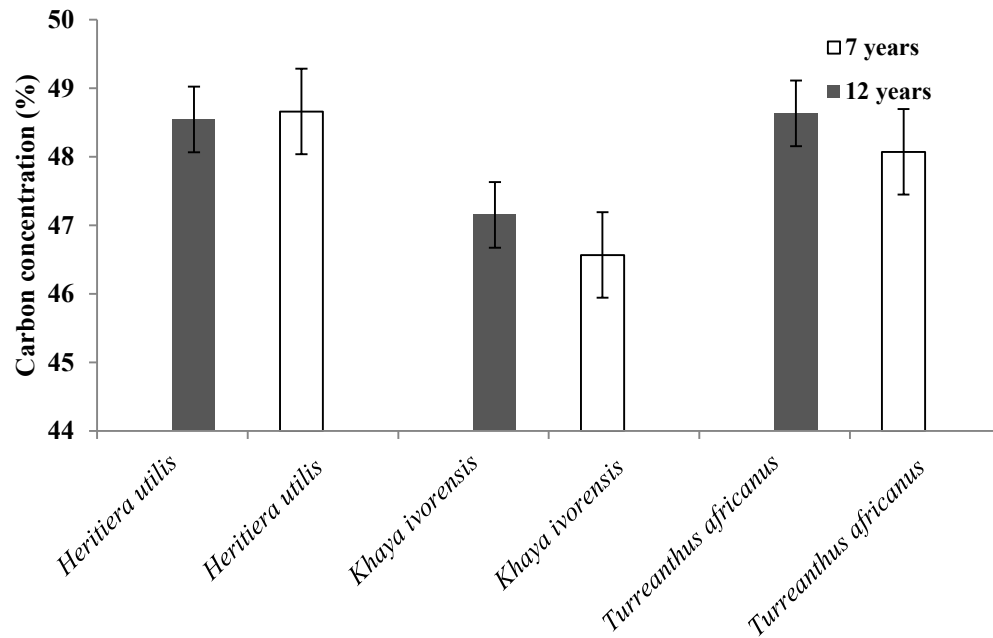


Figure 2.2 Comparison of C concentrations for 7 and 12 year-old trees of the same species from OCAP plantations in the wet evergreen forest ecozone of Ghana.

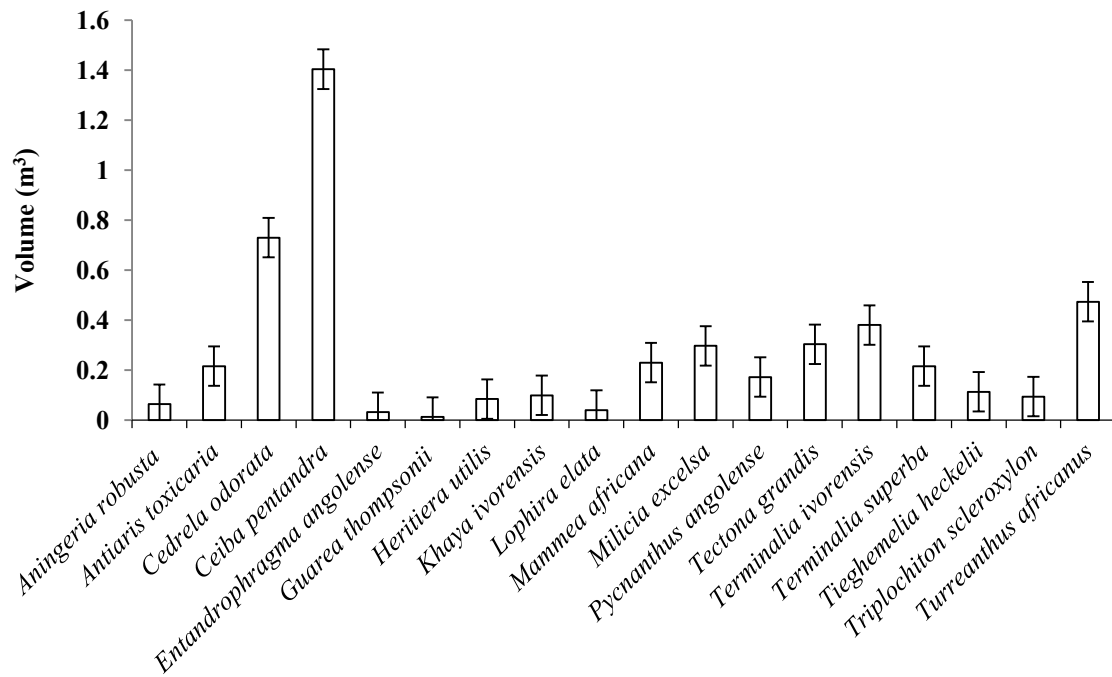


Figure 2.3 Mean volumes of species in a 12 year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

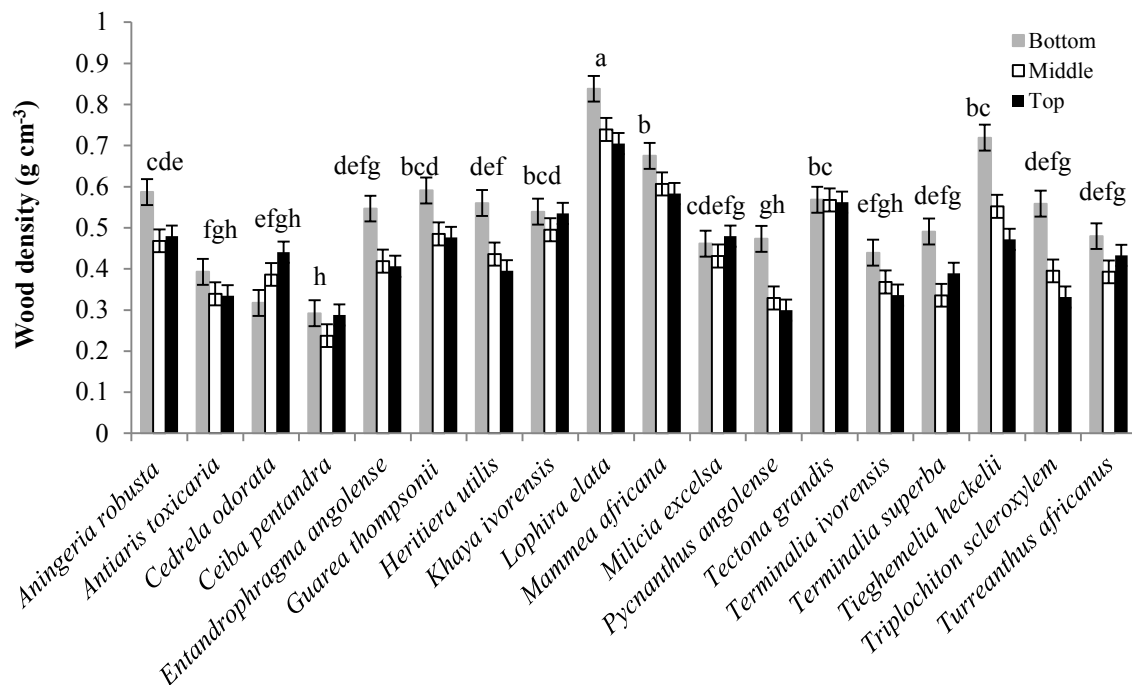


Figure 2.4 Wood density estimates of trees species from a 12 year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana. Bars with different lower case letters differ significantly ($P < 0.05$).

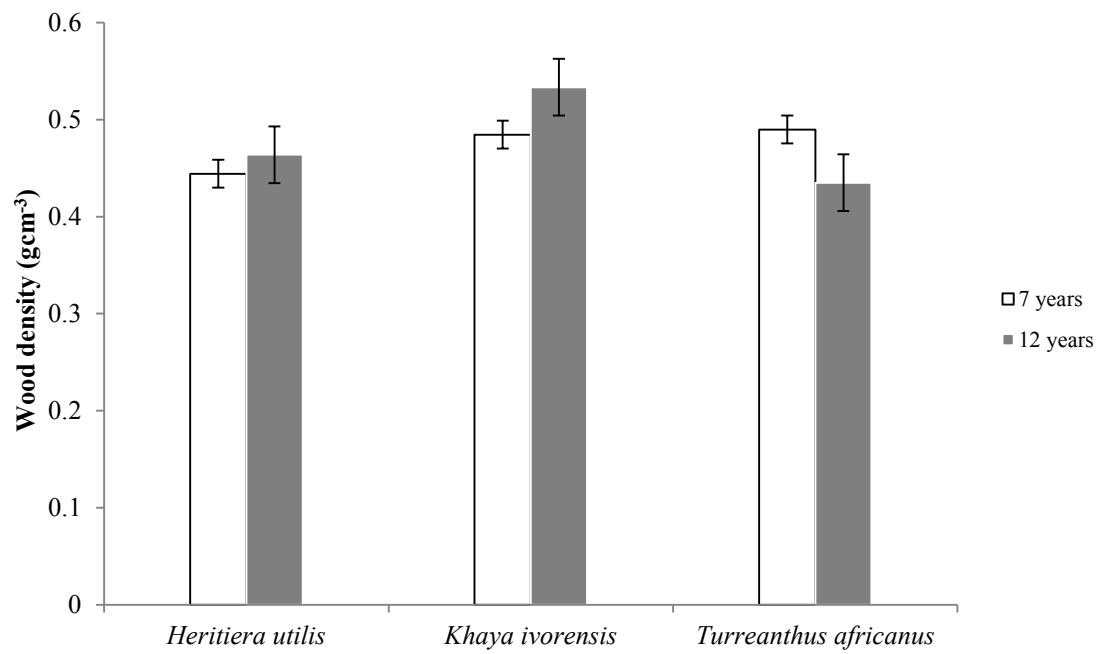


Figure 2.5 Comparison of wood density in trees from 7 and 12 year-old plantations at OCAP in the wet evergreen forest econzone of Ghana.

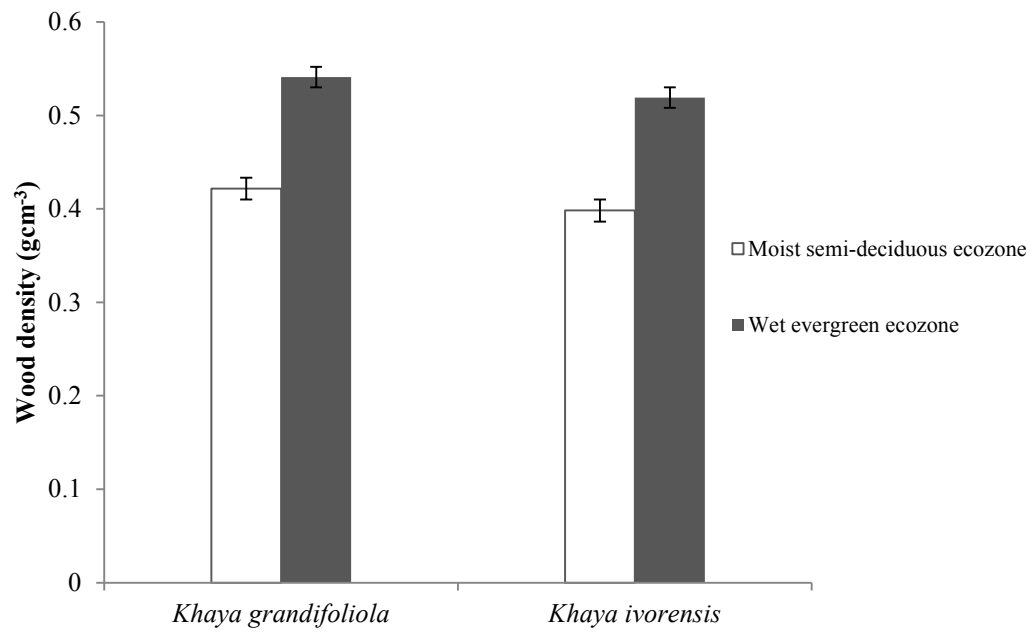


Figure 2.6 Comparison of wood density in 7-year-old *Khaya* spp from a location at OCAP in the wet evergreen forest ecozone and Bobiri in the moist semi-deciduous ecozone of Ghana.

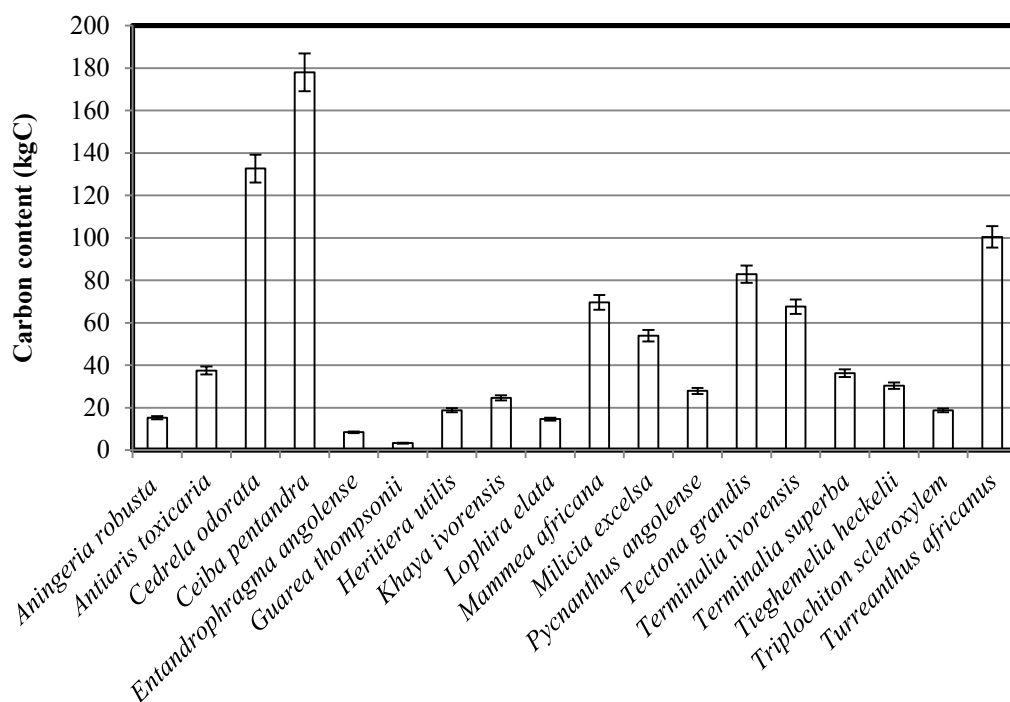


Figure 2.7 Mean C content per tree for species growing in a 12 year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

Table 2.3

Summary of carbon sequestration for trees species from OCAP plantation in the wet evergreen and Bobiri in the moist semi-deciduous forests of Ghana. SB (shade earer) NPLD (non-pioneer light demander), P (pioneers), M (moist semi-deciduous forest), W (wet evergreen forest).

| Age/ location | Guilds | Tree species | C (%) | Density (g cm ⁻³) | Volume (m ³) | Biomass (kg) | Carbon content (kgC) |
|------------------|--------|---------------------------|----------|----------------------------------|-----------------------------|-----------------|----------------------------|
| 12 years | | <i>Tectona grandis</i> | 48.9 | 0.57 | 0.304 | 172 | 84 |
| 12 years | | <i>Cedrela odorata</i> | 48.3 | 0.38 | 0.730 | 279 | 134 |
| 12 years | NPLD | <i>Heritiera utilis</i> | 48.5 | 0.46 | 0.085 | 39 | 19 |
| | | <i>Entandrophragma</i> | | | | | |
| 12 years | NPLD | <i>angolense</i> | 46.3 | 0.44 | 0.032 | 14 | 7 |
| 12 years | NPLD | <i>Khaya ivorensis</i> | 47.2 | 0.52 | 0.100 | 52 | 25 |
| | | <i>Pycnanthus</i> | | | | | |
| 12 years | NPLD | <i>angolense</i> | 46.2 | 0.43 | 0.173 | 74 | 34 |
| 12 years | NPLD | <i>Aningeria robusta</i> | 48.0 | 0.50 | 0.064 | 32 | 15 |
| 12 years | NPLD | <i>Antiaris toxicaria</i> | 47.4 | 0.36 | 0.216 | 77 | 36 |
| | | <i>Tieghemelia</i> | | | | | |
| 12 years | NPLD | <i>heckelii</i> | 47.8 | 0.58 | 0.114 | 66 | 32 |
| 12 years | P | <i>Ceiba pentandra</i> | 46.8 | 0.27 | 1.404 | 383 | 179 |
| | | <i>Terminalia</i> | | | | | |
| 12 years | P | <i>ivorensis</i> | 48.0 | 0.38 | 0.381 | 145 | 70 |
| | | <i>Terminalia</i> | | | | | |
| 12 years | P | <i>superba</i> | 46.7 | 0.42 | 0.216 | 91 | 42 |
| 12 years | P | <i>Milicia excelsa</i> | 46.6 | 0.46 | 0.297 | 136 | 63 |
| 12 years | P | <i>Lophira elata</i> | 48.4 | 0.76 | 0.040 | 31 | 15 |
| | | <i>Triplochiton</i> | | | | | |
| 12 years | P | <i>scleroxylem</i> | 47.2 | 0.43 | 0.095 | 40 | 19 |
| 12 years | SB | <i>Mammea africana</i> | 48.6 | 0.62 | 0.231 | 143 | 70 |
| | | <i>Guarea</i> | | | | | |
| 12 years | SB | <i>thompsonii</i> | 47.3 | 0.44 | 0.013 | 6 | 3 |
| | | <i>Turreanthus</i> | | | | | |
| 12 years | SB | <i>africanus</i> | 48.6 | 0.44 | 0.474 | 206 | 100 |
| 7 years | NPLD | <i>Khaya ivorensis</i> | 46.6 | 0.49 | 0.058 | 28 | 13 |
| 7 years | NPLD | <i>Heritiera utilis</i> | 48.7 | 0.44 | 0.060 | 27 | 13 |
| | | <i>Turreanthus</i> | | | | | |
| 7 years | SB | <i>africanus</i> | 48.1 | 0.49 | 0.044 | 22 | 10 |
| 5years(W) | NPLD | <i>Khaya spp</i> | 46.4 | 0.53 | 0.027 | 14 | 7 |
| 5years(M) | NPLD | <i>Khaya spp</i> | 46.0 | 0.41 | 0.020 | 8 | 4 |

Allometric Relationships

Allometric equations were developed for relationships between tree main stem volume and diameter at breast height (dbh), and volume and $\text{dbh}^2 \times \text{height}$ (D^2H). The allometric equations (Table 2.4) explained over 90% of the variation in volume across species and individual trees and thus could be applied satisfactorily to determine volume of a forest stand. Log-log relationships between dbh or D^2H and volume were also highly significant (Figures 2.9 and 2.11, $P < 0.0001$). The residual mean square error (RSME), 31% and 18%, were within the range for most allometric equations for the relationships between volume and dbh and volume and $\text{dbh}^2 \times \text{height}$ respectively (Navar 2009). The values for the scaling coefficients, a and b , were highly significant ($P > 0.0001$) for the log transformed linear regression and the power functions. The scaling coefficient for power function b , ranged from 2.3 to 2.7 (Table 2.4) as documented for other tropical forests (Brown 1989; Chave et al. 2005; Navar 2009). These scaling coefficients (a and b) vary with species, biomass and climate (Baskerville 1965; Zianis and Mencuccini 2004).

The regression analyses further verified the expected strong relationship ($r^2 > 0.93$) between tree main stem volume and dbh (Figures 2.8 and 2.9). It is imperative to note that the relationship between main stem volume and $\text{dbh}^2 \times \text{height}$ (Figure 2.10 and 2.11) was even much stronger ($r^2 > 0.97$) than volume and diameter only ($r^2 > 0.93$). The relationship ($r^2 = 0.92$) between carbon content and dbh (Figure 2.12; $r^2 > 0.92$) was smaller than the other equations ($r^2 > 0.93$ or 0.97). This is because, several species consistently had lower carbon content than others for a given size tree. By dividing species into groups of species with inherently low and high carbon content for a given diameter, stronger relationships were found (Figures 2.13 to 2.15). This differs from

results for volume, where relationships with dbh and D^2H held reasonably well across all species (compare Figures 2.13 to Figures 2.14 and 2.15).

Table 2.4
Regression equations for volume (m^3) and biomass (kg) for trees from OCAP area in the wet evergreen forest zone of Ghana. All equations are in the form $M=a(dbh)^b$ where a and b are scaling coefficients and M is volume or biomass. RMSE is residual mean square error and r^2 is the coefficient of determination.

| Equations | a | b | r^2 | RMSE |
|---|----------|------|-------|------|
| $\ln \text{ volume} = a + b \ln(dbh)$ | -9.42410 | 2.54 | 0.94 | 0.31 |
| $\ln \text{ volume} = a + b \ln(dbh^2 \times \text{height})$ | -9.29090 | 0.91 | 0.98 | 0.18 |
| $\text{Volume} = a(dbh)^b$ | 0.00007 | 2.58 | 0.94 | - |
| $\text{Volume} = a(dbh^2 \times \text{height})^b$ | 0.00008 | 0.92 | 0.98 | - |
| $\text{High volume} = a(dbh)^b$ | 0.00009 | 2.53 | 0.94 | - |
| $\text{Low volume} = a(dbh)^b$ | 0.00003 | 2.74 | 0.98 | - |
| $\text{High biomass} = a(dbh)^b$ | 0.05100 | 2.47 | 0.95 | - |
| $\text{Low biomass} = a(dbh)^b$ | 0.04170 | 2.38 | 0.97 | - |
| $\text{High carbon content} = a(dbh)^b$ | 0.02400 | 2.47 | 0.94 | - |
| $\text{Low carbon content} = a(dbh)^b$ | 0.01990 | 2.37 | 0.97 | - |
| $\ln \text{ volume} = \ln a + b \ln dbh$ | -9.57700 | 2.58 | 0.94 | - |
| $\ln \text{ volume} = \ln a + b \ln dbh^2 \times \text{height}$ | -9.39910 | 0.92 | 0.98 | - |

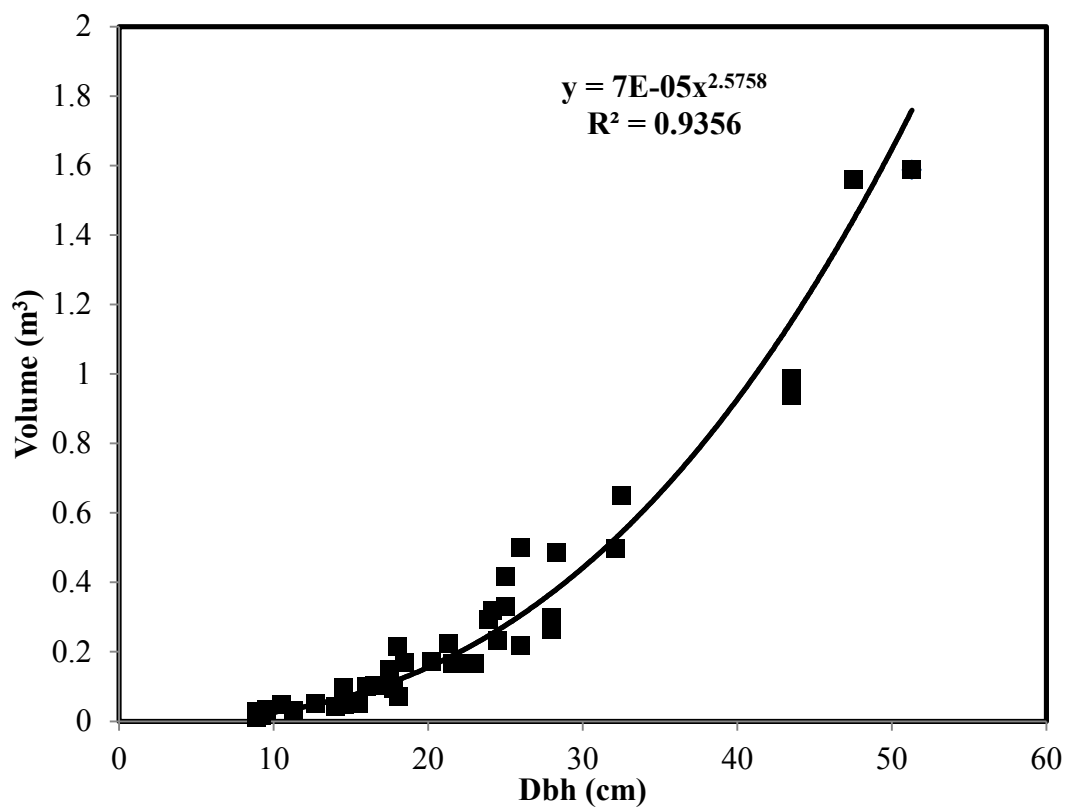


Figure 2.8 Allometric relationship between volume and dbh (power function) for 18 trees species from 12-year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

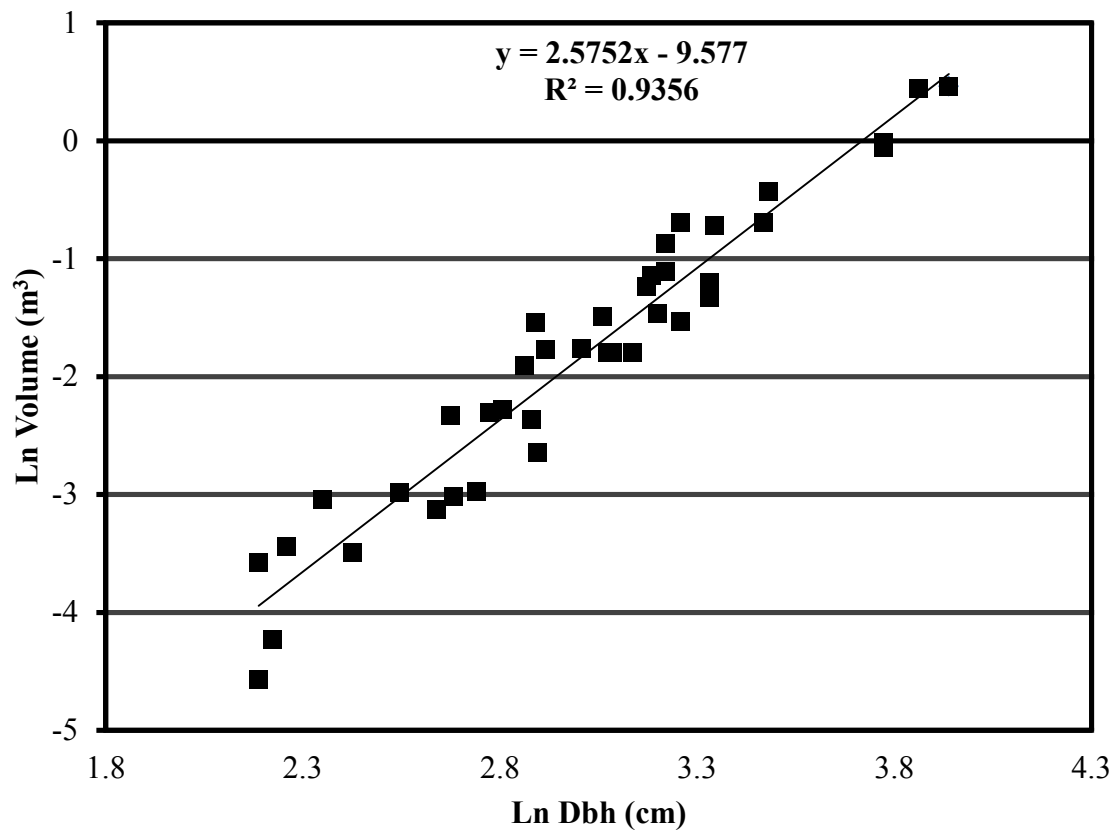


Figure 2.9 Ln- ln relationships between dbh and volume for 18 trees species from a 12-year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

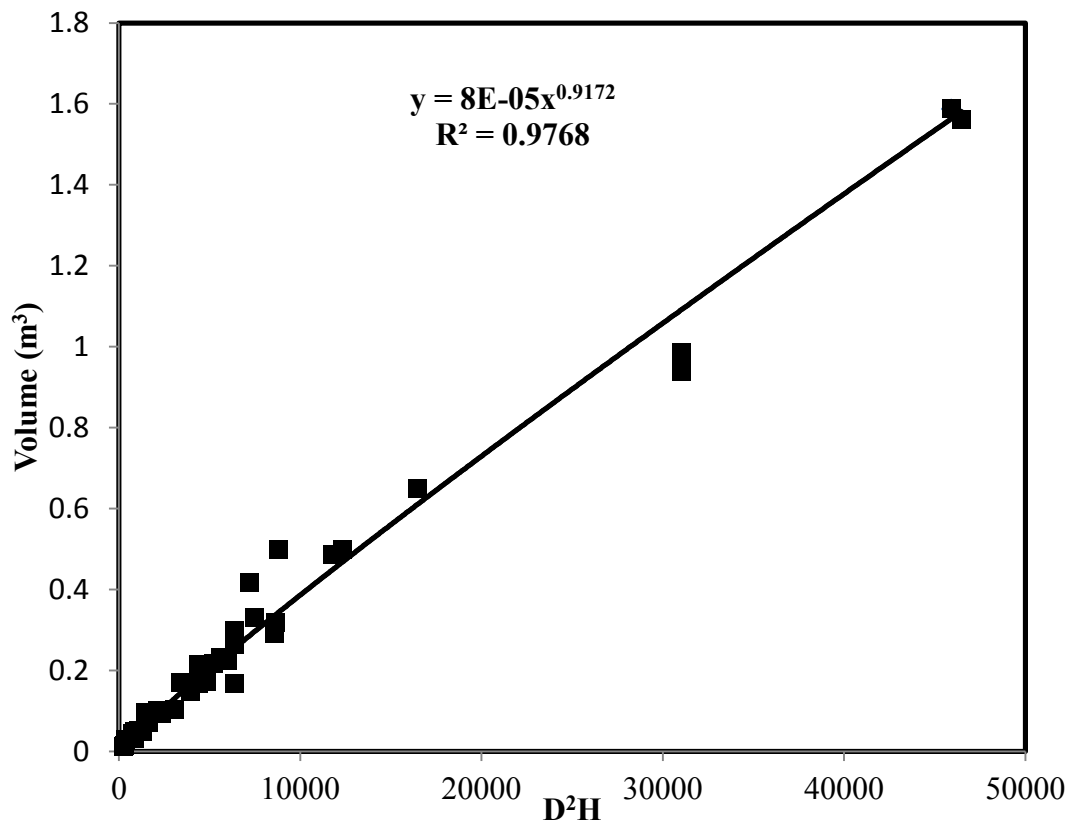


Figure 2.10 Allometric relationship (power function) between volume and $\text{dbh}^2 \times \text{height}$ (D^2H) for 18 trees species from a 12-year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

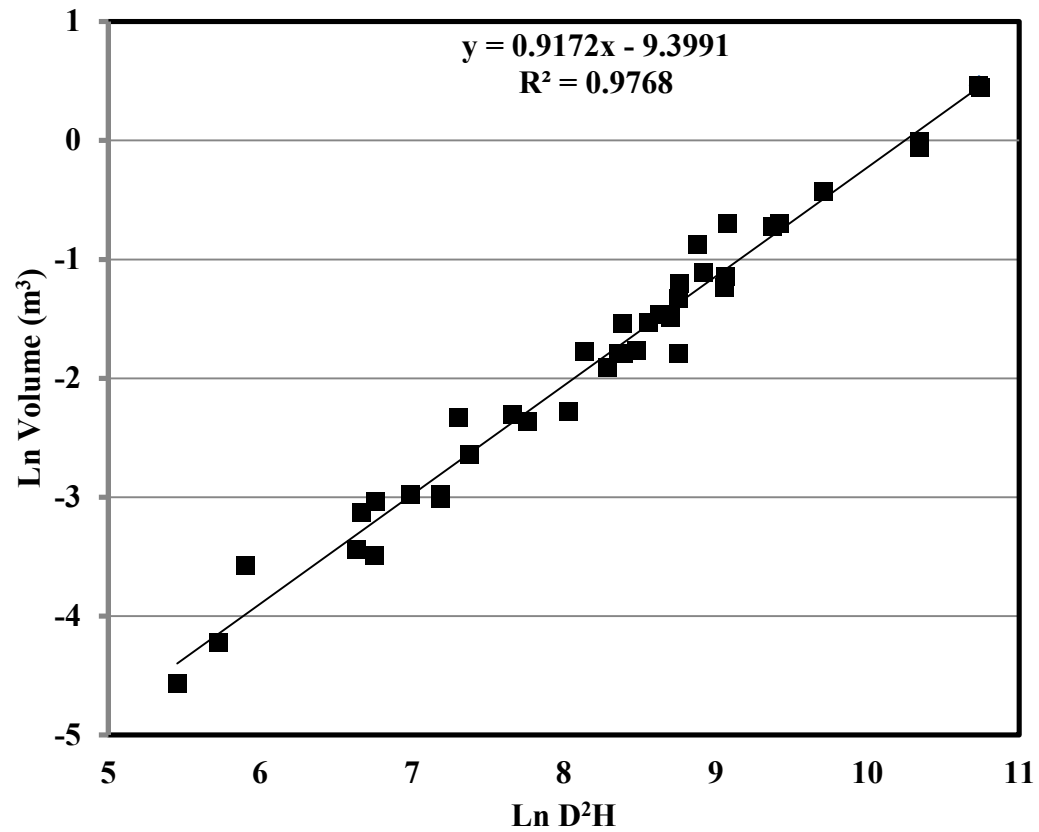


Figure 2.11 Ln-ln relationship between volume and D^2h for 18 tree species from a 12 year old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

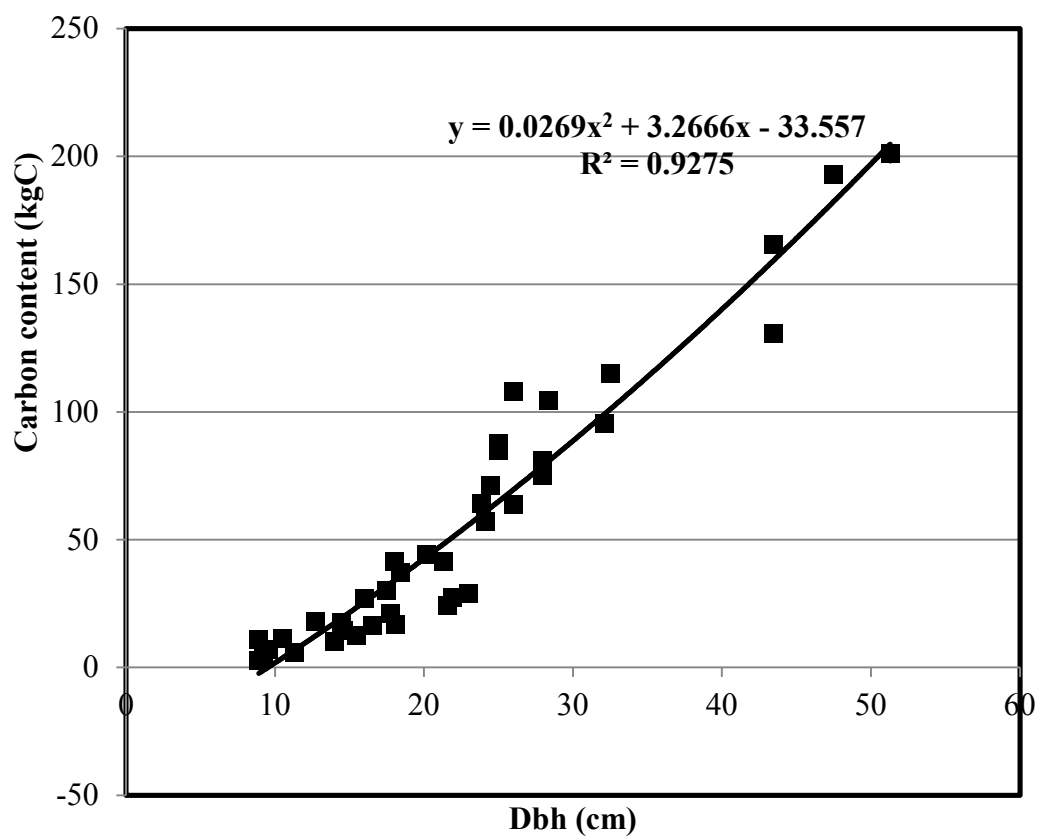


Figure 2.12 Allometric relationship between C content and dbh for 18 trees species from 12 year-old plantation at OCAP in the wet evergreen forest ecozone of Ghana.

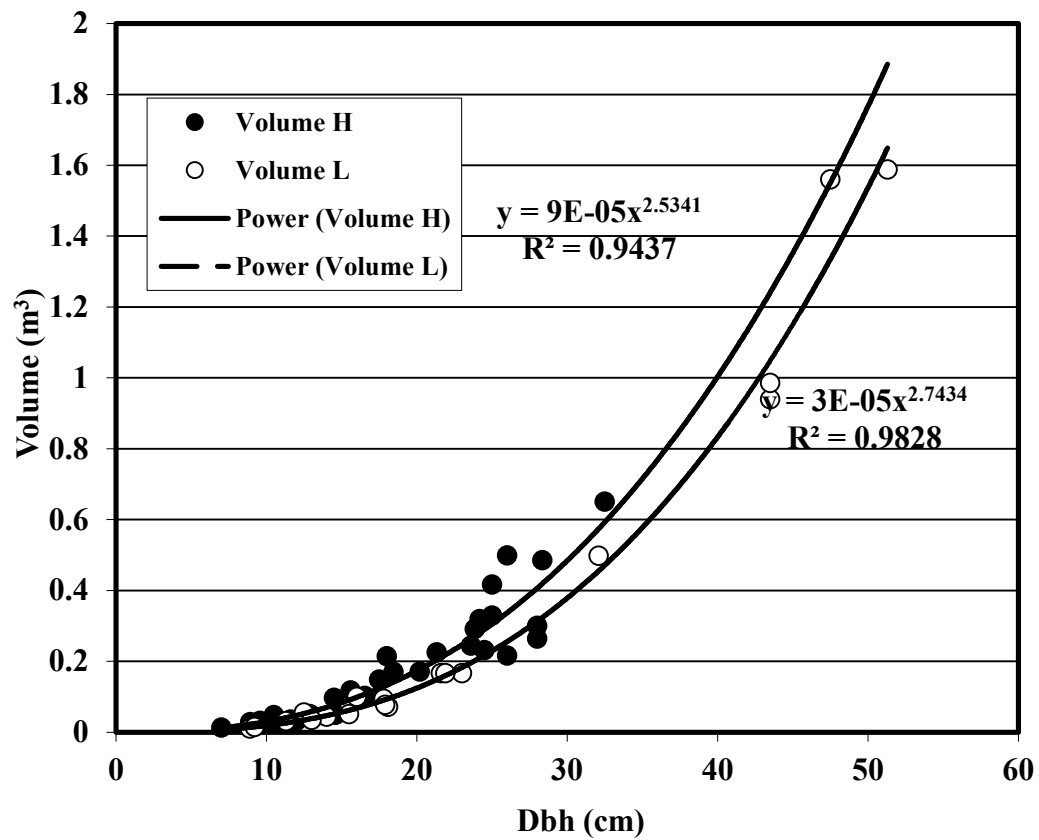


Figure 2.13 Allometric relationships between trees of high volume and dbh, and low volume and dbh (power function) from OCAP plantation 12 in the wet evergreen forest ecozone of Ghana.

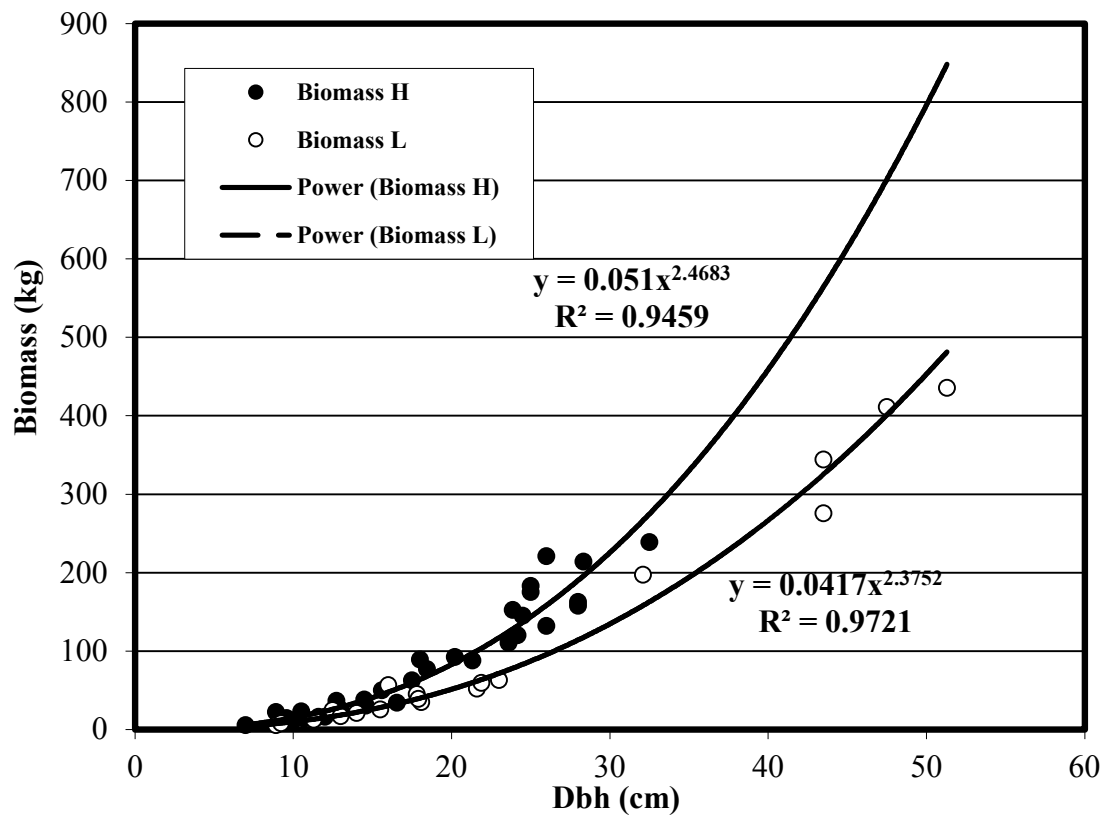


Figure 2.14 Allometric relationships between trees of high biomass and dbh, and low biomass and dbh (power function) from OCAP plantation in the wet evergreen forest ecozone of Ghana.

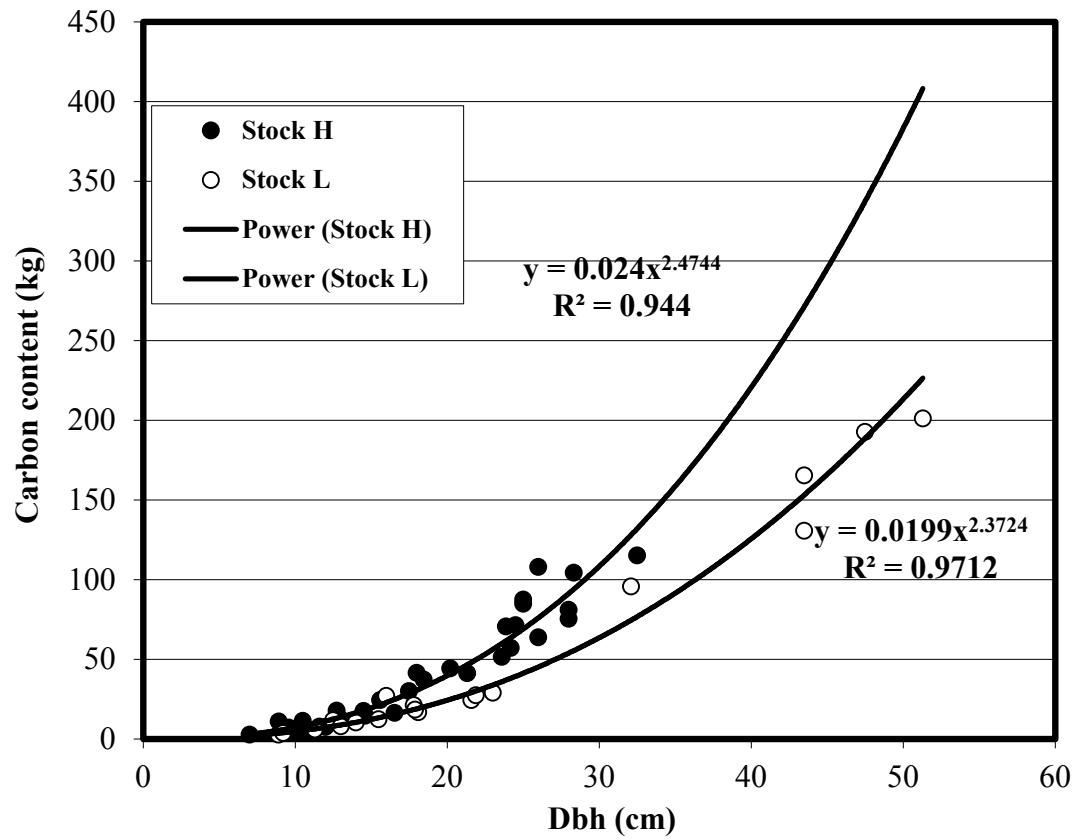


Figure 2.15 Allometric relationships between trees of high C content and dbh, and low C content and dbh (power function) from OCAP plantation in the wet evergreen forest ecozone of Ghana.

Discussion

Differences in species wood densities, carbon concentrations and carbon contents were significant for the 12-year-old trees from the wet evergreen forest ecozone. The wood density and carbon concentration for the bottom, middle and top positions of the main stem of 12-year-old trees were also significant. Wood density of *Khaya* spp from the wet evergreen forest ecozone differed significantly from those of the same age in the moist semi-deciduous forest ecozone. Wood density was negatively correlated with either height or dbh of the 12-year-old trees. Wood densities of these trees were positively correlated with carbon concentration.

Regression analysis showed a strong relationship between volume and dbh and volume and $\text{dbh}^2 \times \text{height}$ as was expected.

Carbon Concentration

Carbon concentration varied significantly among the eighteen species studied. This observation was consistent with similar studies by Elias and Potvin (2003) who reported significant variation in carbon concentration for 32 neo tropical species. The results showed a range in carbon concentration of 44-49% that was comparable to results found by other researchers (Kauppi et al. 1995; Elias and Potvin 2003). Among the eighteen species analyzed, *Tectona grandis* harbored the highest carbon concentration of 48.9% which is similar to previous reports (Kraenzel et al. 2003). The variability in carbon concentration has been attributed to inherent differences in chemical composition, which depends on type of wood, geographical location, soil and prevailing climatic conditions

(Pettersen 1984). For example, softwoods in North America have a higher carbon concentration than hardwoods because of higher proportion of lignin found in softwood species (Lamlom and Savidge 2003). Carbon concentration appeared slightly higher for 12 year-old trees than 7 year- old trees, and higher for both middle and top positions of the main stem. Perhaps age is a factor in carbon concentration of trees as it affects the amount of juvenile wood and mature wood present in the stem (Lamlom and Savidge 2003). The juvenile woods are characterized by higher concentration of lignin and extractives than mature woods (Zobel and van Buijtenen 1989; Lamlom and Savidge 2003). This could be responsible for the trend for slightly higher carbon concentration observed for both the middle and top positions of the tree.

Generally, carbon concentration of trees species has been assumed to be 50% for conversion of biomass to carbon stock (Matthews 1993). However, this work and others appears to refute this general notion as the use of this assumed figure could often overestimate actual wood carbon concentration for many species (Lamlom and Savidge 2003; Wauters et al. 2008). For example, the use of 50% as generic value for carbon accounting has been noted to potentially cause overestimation of about 2.6% in rubber trees (Wauters et al. 2008). By contrast, a possible underestimation of 6% was indicated for carbon content of 50-year-old *Pinus pinaster* stand using 50% value for carbon calculation (Bert and Danjon 2006). The observed variation in carbon concentration suggests that species differences need to be taken into account in order to have accurate estimates of carbon content of trees (Fukatsu et al. 2008). A strong positive relationship was observed between carbon concentration and wood density which corroborate previous studies (Elias and Potvin 2003).

Volume and Wood Density

Knowledge of wood density is needed in order to convert the volume of forest trees to biomass (Brown et al. 1989; Fearnside 1997) which can then be used to estimate carbon content (Brown and Lugo 1982; Brown 1997; Zianis and Mencuccini 2004). Wood density can vary greatly among species (de Castro et al. 1993; Navar 2009; Henry et al. 2010). Wood density was significantly different for the stem positions used in this study and generally increased from top to base location of the main stem. This observation has been noted in similar studies elsewhere (Espinoza 2004; Nogueira 2005). In particular, mean density of trees in Amazon forests is known to decrease from breast height to the top of the bole (Nogueira 2005). Wood density also increased from the pith to the bark of the tree (Wiemann and Williamson 2002). The differences in densities of the main stem positions observed in this study need to be taken into account in biomass estimation because these differences could potentially overestimate biomass by about 12% if densities at only the dbh are used in converting tree volumes into biomass instead of using the mean of all the three positions. Changes in wood density along the stem may be due to increasing proportions of juvenile wood from base to the top of the tree (Zobel and van Buijtenen 1989). These juvenile woods have higher moisture content than matured wood (Zobel and van Buijtenen 1989). Water content has been found to be negatively associated with density or specific gravity of tree (Suzuki 1999). This may explain the lower density at the top of the trees.

It is worth noting that estimates of wood density of species reported in this study were in agreement with wood density estimates available (Bolza and Keating 1972; Reyes et al.

1992). For instance Reyes et al. (1992) estimated density of *Ceiba pentandra* as 0.26 g cm⁻³ and 0.45 g cm⁻³ for *Entandrogma angolense*, very close to 0.27 g cm⁻³ and 0.44 g cm⁻³ respectively reported in this study. There was wide variability (0.26 to 0.761 g cm⁻³) in wood density which has also been confirmed by Suzuki (1999). Chave et al. 2009 reported that, species with thick fibers walls have higher mean wood density than species with thin fiber walls and this may account for the variation in wood density of the tree species. Fiber thickness is positively correlated with wood density (McDonald et al. 1995).

Densities of *Khaya* spp of the same age grown in moist semi-deciduous ecozone were lower than those grown in the wet evergreen forest ecozone. The wetter location displayed significantly higher density than the relatively dry location. This finding has also been observed by other authors who noted that wood density varies from one location to another (Wiemann and Williamson 2002; Baker et al. 2004). According to Wiemann and Williamson (2002) density has positive association with precipitation and this could be responsible for high density for the wetter forest zone. However, Steege and Hammond (2001) reported that wood density is not correlated with precipitation or soil fertility.

It is also known that there is often an inverse relationship between wood density and rate of volume growth (Thomas 1996). This reason may account for both fast and slow growth rate observed with relatively low and high wood density for *Ceiba pentandra* and *Guarea Thompsonii* respectively. *Ceiba pentandra* and *Guarea Thompsonii* may be adapted to low light regimes with slowing growth and high density. However, the

majority of the species were quite unique in their behavior as they exhibited either relatively high density coupled with fast volume growth or low density and slow volume growth rate, regardless of whether they were classified as light demanders or shade bearers.

Carbon Stock and Guilds Classification

Tree carbon content was significantly different among species in the 12 year-old plantation but did not differ for the guilds classification (pioneer, non-pioneer light demanders, and shade bearers). *Ceiba pentandra* had the greatest carbon content, belonged to the pioneer category, and had the highest growth rate volume and relatively low density. However, other pioneer species such as *Lophira elata* and *Triplochiton scleroxylem* had very low volume, biomass and carbon content at age 12. These results are thus only in partial agreement with Redondo-Brenes and Mongnini (2006) who showed that fast growing trees contain extremely high aboveground biomass, despite often having lower density. The fast growing species (*Ceiba pentandra*, *Tectona grandis*, *Cedrella odorata*) seems to accumulate high biomass and carbon due to their life strategy of rapid rates of photosynthesis and rapid vertical growth (Barnes et al. 1998).

Overall, the results from this study demonstrated that wood density was highly variable among the tree species (0.26 to 0.76 g cm^{-3}), and this had much greater influence on the carbon content differences among species than did carbon concentration. Thus, it seems that species wood density and volume growth rate are the driving factors in the determination of biomass or carbon content. Plantation development in Ghana has focused on promoting mixtures of fast growing species primarily to provide raw material

for industry. The development of these plantations can play a useful environmental role in carbon storage (Schroeder 1992; Winjum and Schroeder 1997; Nair et al. 2009).

Allometric Relationships

Site specific equations typically provide the most accurate estimate of forest biomass (Ketterings et al. 2001; Basuki et al. 2009). For example, aboveground biomass estimated from data with a local allometric equation from the wet natural forest of Ghana were significantly different, when similar equations from different regions were applied to the same data (Henry et al. 2010).

Allometric equations were developed for mixed-plantation forests of the wet evergreen zone of Ghana. The equation developed looked at the relationship between tree volume and other easily measured forest inventory data such as height and diameter (Chave et al. 2005). Likewise, relationships between carbon content, biomass, and dbh and height were established. The strong relationship between either biomass or volume and diameter-height was comparable to similar studies (Brown 1997; Ketterings et al. 2001; Navar 2009; Henry et al. 2010). Diameter has been noted as a key parameter used for tree allometry (Zianis and Mencuccini 2004), but equations based on diameter only are often site specific. Relationships based on a combination of height and diameters allow potential application to sites of differing quality (Ketterings et al. 2001). There was improved accuracy of the various equations when tree height was incorporated which was consistent with other studies (Henry et al. 2010). Height growth of trees reflects productivity at a particular site that could be attributed to its specific nutrient and/or moisture availability. The use of mixed-species equation may be desirable in most cases

because it mimics real natural forest situation, where there are several species per unit area. As many as 250 species per hectare could be found in forests of Ghana (Hall and Swaine 1981). However, species-specific equations have been reported to provide high accuracy of biomass estimation (Basuki et al. 2009). The equation developed here could be applied to plantation grown trees whose diameter range fall between 10cm to 60 cm.

It is important to realize that biomass equations often used for estimating carbon content across species are not as accurate as volume equations which are largely due to the high variability among species wood density. The volume equations that combined tree height and diameter were more accurate than diameter alone. Nevertheless, equations that consist of diameter only are important because data for forest inventories does not always include tree height, but virtually always includes diameter. Tree height data are usually not available because it takes more time to collect tree height data. This could be due in part to poor light penetration underneath most forest canopy which makes measurement of top of trees from below the canopy extremely difficult. The volume equations developed in this study and other similar ones are recommended for use in Ghana and could be adopted for other tropical countries with similar environments to estimate tree volume. Carbon contents for the trees can then be obtained by species specific density data (and percent carbon concentration if available) to the volume estimates.

Conclusion and Recommendations

This research was undertaken to provide information needed for determining the carbon content of tropical trees grown in forest plantations of Ghana and the surrounding region. Species differences information necessary for estimating carbon content such as wood

density, carbon concentration and volume, were investigated. The results of this study revealed significant differences among tree species in wood density, carbon concentration and carbon content at a given age. Wood density varied significantly for three stem positions (bottom, middle and top) and appeared relatively higher at lower locations on the stem. It is imperative to reiterate that there was wide variability in wood density among species which suggests it was a more important factor than carbon concentration for carbon accounting and that general values should not be applied across all species when calculated volumes are converted to biomass. Wood densities of *Khaya* spp grown in the moist semi-deciduous ecozone were lower than those of the same age grown in wet forest area. This is likely due to the higher amount of rainfall in the wet forest ecozones. Wiemann and Williamson (2002) have indicated that density is positively related to amount of rainfall. However, precipitation has often been found not to have any bearing with density as discussed earlier (Steege and Hammond 2001). To clarify the cause of the differences related to ecozone, further research targeted at disentangling the likely environmental and edaphic factors influencing wood density in Ghana is needed. Particularly, efforts should be geared towards scrutinizing the effects of soil, rainfall and elevation on wood density.

Common relationship existed across species between tree dimensions and volume, but species specific information on wood density was needed for determining carbon content. To improve accuracy of allometric equations for carbon accounting in Ghana and other tropical countries, local equations have been suggested as such equations fall within the range of diameter classes of trees in that particular locality (Brown et al. 1989; Henry et al. 2010). The various volume equations developed in this research are recommended for

use in estimating carbon content of forest plantations in Ghana and if possible can be adopted for other tropical countries. Development of these volume equation and species specific wood density and carbon concentration has laid a foundation for improving the accuracy of carbon accounting in tropical Africa, including Ghana. Still, more research is needed to investigate other above ground carbon pools, including carbon contained in leaves and branches, and below ground carbon in fine and coarse roots and soil.

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