KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF ENIGINEERING

DEPARTMENT OF MATERIALS ENIGINEERING

GROWTH AND PRODUCTIVITY OF *KHAYA GRANDIFOLIOLA* IN THE DRY SEMI-DECIDUOUS FOREST OF GHANA: A COMPARISON IN PURE STANDS AND IN MIXED STANDS

BY

SAMUEL MENSAH OPOKU

BSc. (HONS.) NATURAL RESOURCES MANAGEMENT,

KNUST

OCTOBER, 2012

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF ENIGINEERING

DEPARTMENT OF MATERIALS ENIGINEERING

GROWTH AND PRODUCTIVITY OF *KHAYA GRANDIFOLIOLA* IN THE DRY SEMI-DECIDUOUS FOREST OF GHANA: A COMPARISON IN PURE STANDS AND IN MIXED STANDS

A THESIS SUBMITTED TO THE DEPARTMENT OF MATERIALS

ENIGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF

MASTER OF SCIENCE DEGREE IN ENVIRONMENTAL RESOURCES

MANAGEMENT

BY

SAMUEL MENSAH OPOKU

BSc. (HONS) NATURAL RESOURCES MANAGEMENT

DECLARATION

“I hereby declare that this submission is my own work towards the MSc. Environmental Resources Management 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”.

SAMUEL MENSAH OPOKU	………………….	…………….
(STUDENT)	(SIGNATURE)	(DATE)
DR. EMMANUEL OPUNI-FRIMPONG	…………………..	…………….
(SUPERVISOR)	(SIGNATURE)	(DATE)
PROF. SAMUEL KWOFIE	………………..	…………..
(HEAD OF DEPARTMENT)	(SIGMATURE)	(DATE)

ABSTRACT

This study was aimed at assessing the performance of one of the very important indigenous species, *Khaya grandifoliola* in pure or mixed stands as well as its performance to exotic tree species, *Tectona grandis*. The study was carried out in a four year old plantation in the Tain Tributaries Block II Forest Reserve which lies in dry semi-deciduous forest zone of Ghana. The results from the study indicated that there was significant difference in diameter growth for *Khaya grandifoliola* in pure and in mixed stands with the pure stands presenting higher diameter growth of 9.15 cm and mixed stands of 7.81 cm. *Khaya grandifoliola* also recorded total height of 5.50 m and merchantable height 3.63 m in pure stands and in mixed stands *Khaya grandifoliola* produced total height of 5.04 m and merchantable height of 3.52 m. However, these values were not significantly different in both stands. *Khaya grandifoliola* performed better in pure than in mixed stands for basal area per hectare and total volume per hectare estimations. Consequently, *Khaya grandifoliola* accumulated more carbon in pure stands than in mixed stands. Overall, *Khaya grandifoliola* performed better in pure stands than in mixed stands. *Khaya grandifoliola* was more tolerant to pests' attacks in mixed stands than in pure stands. Meanwhile there was no statistical difference in diameter growth between *Khaya grandifoliola* (9.15 cm) and *Tectona grandis* (9.61 cm) in pure stands. The values of total height, merchantable height and total volume were significantly higher for *Tectona grandis*. However, there was no significant difference between the two species with respect to basal area per hectare. *Tectona grandis* generally performed better than *Khaya grandifoliola* in pure stands.

ACKNOWLEDGEMENT

I am very grateful to the Lord Almighty for giving me the strength to undertake and complete this study. My sincere appreciation goes to the ITTO Fellowship Programme (ITTO Fellowship Ref. 007/11A) for financing my research work. I acknowledge the constructive advice, support and contribution of my supervisor Dr. Emmanuel Opuni-Frimpong, without whom this work would not have been conceived and executed. I also acknowledge the advice and input of Mr Daniel Yeboah.

My sincere gratitude goes to the management and staff of ABTS Company limited in Berekum, where this study was conducted. I also wish to thank the entire team: Godwin Andoh, Kwadow Nti Baniako, Ibrahim Mohammed, Mr Sylvester Kuudaar, Felix Aboagye Bampoh, Gertrude Gyamfi, Gifty Baffour Gyau Junior, and Gifty Baffour Gyau Senior for assisting me in collecting the data for this study.

My special appreciation goes to Nana Yaa Nyarko-Dua, who helped in the analysis of the data, editing and also made significant contributions throughout the study.

I am most thankful for the help and support of my loving family; Mr. And Mrs Mensah, my mother, Margaret Osei; and my sisters and brothers. Not forgetting my roommate, Joseph A. Alhassan, and friends; Kate Akowua, Richard Opoku and Kwabena Fosu, Issac Arthur and course mates. My profound gratitude to Felix Frimpong who not only introduced me to this project, but also supported me throughout the study.

Finally, I dedicate this work to my uncle, Mr. Forkuoh K. Mensah for his financial support and advice through my MSc programme.

TABLE OF CONTENTS

DECLARATION ii
ABSTRACT iii
ACKNOWLEDGEMENT iv
LIST OF TABLES viii
LIST OF FIGURES ix
LIST OF PLATES x
CHAPTER ONE 1
1.0 INTRODUCTION 1
1.1 Background 1
1.2 Problems statement and justification 4
1.3 Objective 6
1.3.1 Specific objectives 6
CHAPTER TWO 7
2.0 LITERATURE REVIEW 7
2.1 Ghana's Forests and their importance 7
2.1.1 Deforestation 12
2.2 Measures to address forest degradation and deforestation in Ghana 14
2.2.1 Enrichment planting 14
2.2.2 Plantation development 15
2.3 Importance of Plantations 16
2.4 Environmental issues of plantations 17
2.5 Monoculture species-plantation 19
2.5.1 Advantages of monocultures 19
2.5.2 Disadvantages of monoculture plantations 20
2.6 Mixed species plantation 23
2.6.1 Advantages of mixed species plantations 23
2.6.2 Main challenge with mixed-species plantations 25
2.7 Preference of Indigenous species to exotic species 26
2.7.1 Major challenge with the use of Indigenous species in plantations 27

2.8 Carbon sequestration 28
2.9 Description of the focal indigenous tree (*Khaya grandifoliola*) 29
2.9.1 Origin and geographic distribution 29
2.9.2 Ecology and Habitat 30
2.9.3 Growth and development 31
2.9.4 Diseases and pests 31
2.9.5 Uses of *Khaya grandifoliola* 32
2.10 Brief description of *Tectona Grandis* 33
CHAPTER THREE 34
3.0 MATERIALS AND METHODS 34
3.1 Study Area 34
3.1.1 Climate 35
3.1.2 Vegetation 36
3.2 Experimental design 37
3.3 Data collection 37
3.4 Data analysis 38
CHAPTER FOUR 41
4.0 RESULTS 41
4.1 Growth and productivity of *Khayag grandifoliola* in pure and in mixed stands 41
4.2 Tolerance to pests by *Khaya grandifoliola* in pure and in mixed stands...................43
4.3 Growth and productivity of *Khaya grandifoliola* and *Tectona grandis* in pure stands 44
4.4 Growth and productivity of tree species in the mixed stands at dry semi-deciduous forest zone 46
4.5 Aboveground biomass and Carbon sequestration 48
CHAPTER FIVE 53
5.0 DISCUSSION 53
5.1 Growth and productivity of *Khaya grandifoliola* in pure and in mixed stands 53
5.2 Tolerance to *Hypsipyla* (Mahogany shoot borer) by *Khaya grandifoliola* in pure and mixed stands 55
5.3 Growth and productivity of *Khaya grandifoliola* and *T. grandis* in pure stands. 56
5.4 Aboveground biomass and carbon sequestration. 58

5.4.1 *Khaya grandifoliola* in pure and mixed stands. 58
5.4.2 *Khaya grandifoliola* and *Tectona grandis*....59
CHAPTER SIX....61
6.0 CONCLUSION AND RECOMMENDATION....61
6.1 Conclusion 61
6.2. Recommendation....62
REFERENCE 64
APPENDIX 81

LIST OF TABLES

Table 4.1. Productivity statistics of tree species in pure and in mixed stands in the dry semi-deciduous forest zone…………………………………..………………41

Table 4.2. Aboveground biomass and carbon sequestration estimations of *K. grandifoliola* in pure and mixed stands in the dry semi-deciduous forest zone.......................49

Table 4.3. Aboveground biomass and carbon sequestration estimations of the companion species in mixed stands in the dry semi-deciduous forest zone.…...50

Table 4.4. Aboveground biomass and carbon sequestration estimations of *K. grandifoliola* and *T. grandis* in the pure stands at dry semi-deciduous forest zone……………………………..……………………………………..51

Table 4.5. Summary of carbon sequestration estimates for tree species in pure and in mixed stands in the dry semi-deciduous forest zone……………..……….....52

LIST OF FIGURES

Figure 2.1. Maps of Ghana's Forest Regions...……………………………………………8

Figure 2.2. Forest Reserves in High Forest Zone of Ghana……….…………………….....9

Figure 2.3. Distribution of *Khaya grandifoliola* …………………………………….……30

Figure 4.1. Mean diameter of *Khaya grandifoliola* in pure and mixed stands..………………………………………………………………..……42

Figure 4.2. Mean height and merchantable height of *Khaya grandifoliola* in pure and mixed stands…..……………..……………………………….…………………43

Figure 4.3. Total number of shoots, number of shoots attack, number of fresh attack and number of dead shoots of *Khaya grandifoliola* in pure and mixed stands.…...44

Figure 4.4. Mean diameter of *K. grandifoliola* and *T. grandis* in pure stands…..……………………………………………………………………45

Figure 4.5. Mean height and merchantable height of *K. grandifoliola* and *T. grandis* in pure stands……...……………………………..……………….46

Figure 4.6. Mean diameter of companion species in mixed stands……………….….……...47

Figure 4.7. Mean height and merchantable height of companion species in pure stands..47

LIST OF PLATES

Plate 3.1. The four year old pure mahogany stands in the ABTS plantation established by scientist from FORIG…………………………….………....…35

Plate 3.2. The field team that collected the data for this work in the mixed experimental stand of *K. grandifoliola*, *T. superba* and *C. odorata*……………38

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

In Ghana, natural resources such as minerals, wild life, water bodies and land play a major role in, economic, social, cultural, ecological and environmental development of the country of which forest is of no exception. Around the world, mankind derives many benefits from forest. Many medicines and pharmaceuticals have been discovered in plants native to forests. The modern society depends on products like paper, wood, rubber and bamboo all emanating from the forest. Also, around the globe, other desirable products such as spices, gums and dyes are found in forests. Forests are also important to humans for the aesthetic values they provide. Sixty to seventy percent of Ghana's population depends upon the forest resources for livelihoods and cultural purposes (Amelia *et al*., 2007). At the same time, forests and the wood they produce trap and store carbon dioxide, playing a major role in mitigating climate change (FAONewsroom, 2006).

Though, the forests are essential due to the wide variety of goods and services they provide, they are under threat from especially human-induced disturbances (Appiah *et al*., 2009; Gupta *et al*., 2004). Amelia *et al.* (2007) also emphasized that over the last century the forest cover of Ghana has declined from 8,000,000 hectares to 1,600,000 hectares. The 2010 Global Forests Resources Assessment showed that there was a 2% (135, 000 ha) loss of forest annually from 1990 – 2000 in Ghana (FAO, 2010). Forestry Commission of Ghana indicated that the rate of deforestation in Ghana stands at 65,000 hectares per annum (Tropenbos, 2005). The United Nations Framework Convention on Climate Change (UNFCCC) secretariat stated that the overwhelming direct cause of deforestation is agriculture. Subsistence farming is responsible for 48% of deforestation; commercial agriculture is responsible for 32% of deforestation; logging is responsible for 14% of deforestation and fuel wood removals make up 5% of deforestation (UNFCCC, 2007).

This rapid rate of deforestation raises concern in a number of different environmental issues such as biodiversity loss and global warming. Tropical deforestation is responsible for approximately 20% of world greenhouse gas emissions (IPCC, 2007). The Intergovernmental Panel on Climate Change reported that deforestation mainly in tropical areas, could account for up to one-third of total anthropogenic carbon dioxide emissions but recent calculations suggest that carbon dioxide emissions from deforestation and forest degradation (excluding peatland emissions) contribute about 12% of total anthropogenic carbon dioxide emissions with a range from 6 to 17% (van der Werf *et al.*, 2009). With biodiversity, the influence of deforestation on indigenous tree species have been described by Wong, (1989) in Benhin and Barbier, (2004) that most of the indigenous species like, *Milicia excelsa* and *Milicia regia*, the mahoganies (*Khaya* and *Entandrophragma* species), *Pericopsis elata*, *Naucles diderrichii*, and *Triplochiton scleroxylon* which mainly generate substantial revenues for Ghana's economy, have drastically reduced over the past decades due to deforestation.

Over the world, the African mahoganies (*Khaya* and *Entandrophragma* species) are seen to be among the most valuable tropical hardwood species. *Khaya grandifoliola* wood is exported from West African countries (e.g. Ghana) in mixed consignments with other *Khaya* spp., particularly *Khaya anthotheca* (Welw.). Until the 1950s *Khaya* timber formed up to 70% of the total export from Ghana, with an annual volume of approximately 100,000 m^3, but since then its export has steadily declined (Opuni-Frimpong, 2008). The high demand for *Khaya* spp., resulting in the overexploitation of the species may be due to its appealing characteristics, including its pinkish to dark brown colour and physical properties which makes it fairly easy to work with, and the fact that the wood finishes well and takes polish (Irvine 1961; Dunisch and Ruhmann, 2006) all make mahogany a highly desired wood for furniture and carpentry.

Forest plantation development efforts meanwhile, in Ghana are skewed towards the planting of exotic monoculture *Tectona grandis* plantations. The preference for *Tectona grandis* can be attributed to its fast growing, largely free of pest, and fire tolerance characteristics compared with many indigenous species. *Tectona grandis* plantations, however, have been described not to provide for the multitude of other non-timber products that can be provided by natural forests or indigenous species plantations capable of sustaining ecological diversity as well as providing communities with sustainable livelihoods (McNamara *et al*., 2006; Lamb *et al*., 2005; Hartley, 2002; Lamb, 1998; Montagnini and Porras, 1998).

Studies have shown that indigenous species can be restored through either pure or mixed plantation development but vast majority of the world's plantations are monocultures, with just a small number of tree species in common use (FAO, 2001; Evans and Turnbull, 2004). Perhaps, the reason for this is the principal advantage of monocultures over mixed-species forests and that is ability to concentrate all site desirable characteristics, generally, relating to growth rate and wood quality (Kelty, 2006). However, most studies have suggested that native trees do almost the same or even better in mixed stand than in pure stand. For instance, in a study comparing the growth and productivity of native tree species in monocultures and mixtures, Piotto *et al* (2004) reported that although the plantations examined were still young and may be too soon to determine the behavior of the species studied, it was evident that best growth for these species was demonstrated in mixed species.

1.2 Problems statement and justification

Over the world, various governments have provided incentives for establishing tree plantations. For instance, in Costa Rica there have been government incentives for establishing and maintaining native tree species plantation since 1990s (Piotto *et al*., 2003). In Ghana, one of the priorities of the government is to curb the high rate of deforestation by establishing 200,000 hectares of forest plantations of fast growing indigenous and exotic species over a 10 year period (Ministry of Lands and Forestry, 1996) and successive governments have made several efforts towards achieving this aim through plantation development. National Forest Plantation Development Programme (NFPDP) reported that in September 2001, at Ayigbe in the Wenchi District of the Brong-Ahafo region, the government of Ghana, launched the National Forest Plantation Development Programme (NFPAD), and aimed at encouraging the development of a sustainable forest resource base that will satisfy future demand for industrial timber and enhance environmental quality. Again, in 2009, expanded National Forest Plantation Development Programme (NFPAD) was launched by the government at Abofour in the Offinso municipality with the intention of improving environmental quality, reduce the wood deficit and provide an avenue for the country to tap the emerging benefits from climate change markets for carbon sequestration projects (Daily Graphic, 2009).

Meanwhile, in Ghana, only plantations of exotic trees species have however succeeded despite efforts committed toward the establishment of indigenous species plantations (Foli *et al*., 2009; Agyeman, 2004). Foli *et al*., (2009) indicated that the lack of interests in the use of indigenous species for plantations in Ghana was mainly due to pest infestations and diseases. This has led to loss of most of the valuable native tree species such as mahogany species in plantation even to the point of extinction since the exotic species are becoming popular.

Elliot and Pleydell, (1992) reported that despite the decline of mahoganies in West Africa, demand for African mahogany is anticipated to increase further as a result of reduced supply of native mahogany timber from Southeast Asia and South America. An increase in demand will threaten the viability and sustainability of mahoganies in areas in Ghana where significant volumes of these species are still found. There is therefore a growing interest by interested stakeholders such as the government, NGOs, farmers and other research institutions in plantation development on areas where significant portions of forest cover has been lost.

Kanowski *et al*., (2005) and Piotto *et al*., (2004) have also reported that there is continued interest in mixed-species plantations amongst landowners and researchers in tropical and subtropical regions. This shift in interest may be due to benefits from the use of mixed plantation; such as better site use, improved tree nutrition and less insect to pest damage, accumulation of aboveground biomass and carbon sequestration at rates better than monocultures. However, Forester *et al*., (2005) indicate that due to a limitation in the number of studies on mixtures, it is difficult to accurately predict success of mixed-species combinations and sites, especially with regards to growth dynamics.

In order to ensure sustainable production of the mahoganies (*Khaya* spp.,) into the future, a research programme is being carried out by the Forestry Research Institute of Ghana in collaboration with timber industries in Ghana investing in plantations. Studies are being conducted to improve the successful establishment of mahogany in plantations either in pure or mixed stands. This study therefore compared the growth and productivity of *Khaya grandifoliola* in mixed and in pure plantations in one of the experimental trials established in the degraded Tain II forest reserve in Collaboration with ABTS Company limited. It also compared the growth and productivity of *Khaya grandifoliola* in pure stands to *Tectona grandis* in pure stands.

1.3 Objective

The overall objective of the study is to evaluate the productivity of *Khaya grandifoliola* as well as aspects of the environmental services provided by the plantations.

1.3.1 Specific objectives

1. To compare the growth of *Khaya grandifoliola* in pure and in mixed stands.
2. To compare the tolerance to pests attacks by *Khaya grandifoliola* in pure and in mixed stands.
3. To compare the carbon sequestered by *Khaya grandifoliola* in pure and in mixed stands.
4. To compare the growth and productivity of *Khaya grandifoliola* to *Tectona grandis* in pure stands.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Ghana's Forests and their importance

Ghana is richly endowed with forest resources, which are vital for the country's development and future economic prosperity; they contribute to the welfare of most Ghanaians. Hawthorne (1995) found that, Ghana's High Forest Zone covers approximately 82,000 km^3. It is categorized into nine vegetation zones, each with distinct association of plant species and corresponding rainfall and soil conditions as shown in Figures 2.1 and 2.2. They are grouped as follows: Wet Evergreen Zone, Moist Evergreen Zone, Moist Semi- Deciduous North East, Moist Semi- Deciduous South East, Upland Evergreen, Dry Semi-Deciduous Inner Zone, Dry Semi-Deciduous Fire Zone, Southern Marginal and Southern Outlier.

Figure 2.1: Map of Ghana’s Forest Regions. Adapted from: UNEP-WCMC (2004)

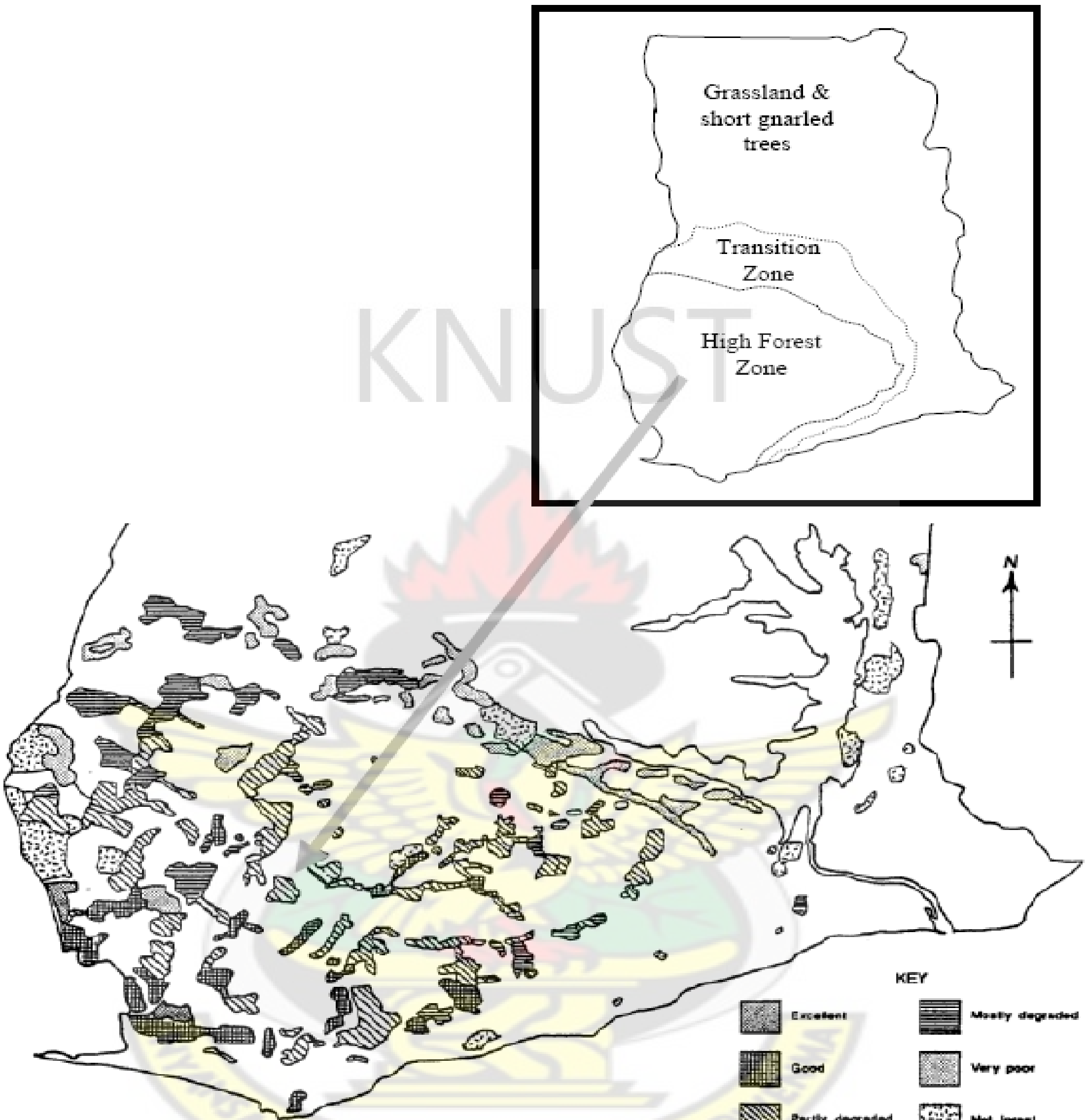


Figure 2.2: Forest Reserve in High Forest Zone of Ghana. Adapted from: Hawthorne and Abu Juam (1995).

Most of the timber species are obtained from the deciduous and evergreen forests in the southwest. The main species in the deciduous forests are *Triplochiton scleroxylon* (Wawa), *Mansonia altissima* (Mansonia), *Nesogordonia papaverifera* (Danta) and *Khaya ivorensis* (mahogany); and in the evergreen forests *Guarea cedrata* (Guarea), *Tieghemella heckelii* (Makore), *Tarrietia utilis*(Niangon) and *Uapaca spp* (Assam).

The Food and Agriculture Organization's (FAO) Global Forest Resources Assessment of 2005 defines 'forests' as 'Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds *in situ*.' It does not include trees that are predominantly under agriculture or urban land use. Using this definition, the FAO reports that Ghana's forest coverage as at 2005 stood at 5,574,000 hectares. Part of this forest resource is tropical high forest which is concentrated in the central to southwestern parts of the country, and which over the last century has declined from 8,000,000 hectares to 1,600,000 hectares (Amelia *et al*, 2007). According to the Forestry Commission of Ghana, the rate of deforestation in Ghana stands at 65,000 hectares per annum (Tropenbos, 2005). These estimates all point to a severe deforestation trend. Yet, the forest and its wildlife resources are of enormous importance to the socio-economic development of the country: it contributes 6% to the country's Gross Domestic Product, and provides direct employment to over 100,000 people and indirect employment to over 2.5 million. Sixty to seventy percent of Ghana's population also depends upon the forest resources for livelihoods and cultural purposes (Amelia *et al.*, 2007). Forests contribute to livelihoods by providing food, fodder, fuel, building materials in addition to other non-quantifiable benefits such as cultural symbols, and ritual artifacts. Many non-timber products such as snails, mushrooms, chewing sponge, fruits, cola nuts, food wrapping leaves and wooden trays are very significant in the livelihoods of many urban and rural dwellers (Kotey *et al*., 1998). The Forestry Commission also reported that about 14 million m^3 of fuelwood accounts for 75% of Ghana's energy needs. Trade in non-timber forest products is a very important economic activity with a complex web of market system involving gatherers, producers, wholesalers and retailers (Kotey *et al*., 1998). Most forest fringe communities depend mostly on the products from forests to supplement their incomes (Dadebo and Shinohara, 1999), and in some cases they serve as the only source of income or livelihood for some poor or marginal families (Siry *et al*., 2005; Kotey *et al*., 1998). Bush meat which is a very important delicacy is consumed by about 75 % of the population of Ghana and is also considered as the main source of meat for about 80 % of rural populations in southern Ghana (Kotey *et al*., 1998). Current export earnings from forests and wildlife are reported to be approximately US$400 million per annum.

Environmental benefits cannot be quantified, but includes the provision of ecological stability, watershed protection, and a reliable source of food, medicinal plants, and building materials. They do not only help maintain biological diversity, but also mitigate climate change, control hydrology, mineral cycling, and soil erosion, improve air quality, create wildlife habitats and alleviate poverty (FAO, 2006; Roy *et al*., 2002). In terms of ecological benefits, these forests are important repository for genetic resources and also home to some species listed in the IUCN red list. Over 2100 plant species have been recorded in the High forest zone of Ghana, of which 23 are considered to be endemic (Hall and Swaine, 1981). The forests also support 74 species of bats, 37 species of rodents and over 200 bird species (IUCN, 1992). Out of the plants and animals listed on the IUCN red list of threatened species in Ghana, 13 mammals, 6 birds, 10 amphibian and 9 plant species are found in forests (IUCN, 2004).

2.1.1 Deforestation

Ghana was richly endowed with forest resources which were vital for her development and future prosperity. Originally, Ghana's forests covered about 36 percent of the total land area of the country (EU, 2006; Rice and Counsell, 1993). Records do indicate the existence of relatively undisturbed forests, which harboured abundant biodiversity (Alpert, 1993), which protected fragile soils (FAO, 2007; UNEP, 2002), and regulated the supply of scarce water resources (Glantz and Katz, 1985). However, deforestation and global climate change impacts are significantly causing a rapid loss of biodiversity in the country. The degradation of forests and the loss of biodiversity in Ghana have increased sharply in recent decades (Dixon *et al*., 1996).

Ghana, like many tropical countries, continues to lose its remaining closed forests at an alarming rate. The area of closed forest has reduced to less than 25% of its original value and now exists in fragmented patches estimated to be about 20 to 524 km². Between 1990 and 2005, Ghana has lost about 1.9 million hectares of forest or 26 percent of her forests cover with the annual deforestation rate of 2.0%. Most of the forests have lost their pristine interior habitats that are critical for the protection of vulnerable species (FAO 2001). In 1992, it was estimated that only about 1.5 million ha of "intact closed forest" were remaining in Ghana. It is estimated that about 20,000 hectares per annum of the reserved area are lost to agriculture or through bush fires and other human activities (Tabi, 2001; IUCN, 1992). The forests are now characterised by excessive harvesting of logs, a reduction in standing volumes of species, dwindling resource base, species depletion and loss of biodiversity. About 14% of the total permanent forest reserves in Ghana are without adequate forest cover. The worst affected areas are the moist semi-deciduous North-west and South-east subtype of forest zones (Tabi, 2001). The factors causing the depletion of the forests include excessive legal and illegal logging, unsustainable farming methods, annual bushfires, surface mining and infrastructural development. Underlying these deforestation driving forces are forest policy failures, unrealistic forest fee regimes, external prices of timber, weak institutional structures, and population pressures (FAO, 2001).

Though, there are several causes for forest loss in Ghana, they can be broadly divided into internal (country specific issues such as unsustainable agriculture, conversion to agriculture, unsustainable logging, wildfires, firewood collection and charcoal production, mining, plantation strategies and taungya, population pressure, poorly defined land and resource tenure, poverty and unemployment, weak government policies, corruption and weak institutional governance) and external (influences from outside Ghana such as foreign investments, international trade and market failures) factors (Appiah *et al.*, 2009; Codjoe and Dzanku, 2009; Awung, 1998). The internal factors can further be categorised into proximate and underlying causes. The proximate causes include, unsustainable agriculture, conversion to agriculture, unsustainable logging, wildfires, firewood collection and charcoal production, mining, and plantation strategies and taungya, whilst the underlying causes also include but not limited to population pressure, poorly defined land and resource tenure, poverty and unemployment, weak government policies, corruption and weak institutional governance (Codjoe and Dzanku, 2009; Teye, 2005; Benhin and Barbier, 2004; Palo and Yirdaw, 1996; Hawthorn and Abu-Juam, 1993). However, these distinctions are merely conceptual since none of the causes is mutually exclusive but all are interdependent and interactive (Codjoe and Dzanku, 2009; Dadebo and Shinohara, 1999).

2.2 Measures to address forest degradation and deforestation in Ghana

Several management options have been taken to rehabilitate degraded areas and to restore some of the over-exploited commercial species as a result of the continued forest loss and degradation in the country. The common approach which has been used to address this problem has been enrichment planting (line planting) and plantation establishments (Foli *et al*., 2009; Agyeman, 2004; Appiah, 2003; Odoom, 2002; FAO, 1993).

2.2.1 Enrichment planting

Enrichment planting is a technique for promoting artificial regeneration of forests in which seedlings of preferred timber trees are planted in the under-storey of existing logged-over forests and then given preferential treatment to encourage their growth (Lamprecht, 1989). Weaver (1987); International Tropical Timber Organization (ITTO) (2002), on the other hand explained enrichment planting as involving the introduction of valuable species to a degraded forest without the elimination of the valuable individuals already present. Enrichment planting combines both artificial planting and the natural management of the existing forest by mimicking natural gap dynamics, and it allows for the maintenance of the vegetation structure composed of different layers and complex assemblages of plants, thus retaining the forest character and the associated biodiversity and ecological *services* (McComb *et al*., 1993; Hansen *et al*., 1995 and Michon *et al*., 2007). Planting some species of mahoganies (*Khaya spp., Swietenia spp.* etc) under a partial forest canopy has been shown to reduce the incidence of the shoot borer (*Hypsipyla spp*.), which commonly attacks and severely retards the growth of these species when planted in the open (Newton *et. al*., 1993).

In the case of Ghana, enrichment planting was considered for commercial purposes. This management technique which was done through line planting was used in the 1940s and 1950s mainly in the Wet evergreen forest zone to improve the stocking of commercially valuable species (Appiah, 2003; Odoom, 2002; FAO, 1993). This became necessary because some of the reserves had been heavily logged with little chance for natural regeneration (FAO, 1993). Striplings (about 1m to 1.5m high) of economic trees such as *Khaya*, *Entandrophragma* and *Lovoa* species were planted at 5 m within lines that were cut 20 m. Though this approach has reportedly been successful in some secondary forests in the Amazon areas (Keefe *et al*., 2009) and Asia (Ădjers *et al*., 1995), it failed in Ghana (Appiah, 2003; Odoom, 2002). The failure was due to unfavourable results from practices such as canopy manipulation and competition from weeds (Appiah, 2003; FAO, 1993).

2.2.2 Plantation development

Plantations have been the object of renewed interest in both the public and private sectors in recent years. Leading global organizations (for examples IUCN-WWF, CIFOR, ITTO, FSC and FAO) in the international forest conservation and management sector have drawn attention to forest plantations as an alternative to natural forests for production of forest goods and services.

According to Foli *et al*., (2009); Zhang and Owiredu (2007); Agyeman (2004); Appiah (2003); Odoom (2002), plantation development is another measure which has been adopted to rehabilitate degraded areas and also to restore over-exploited commercial species in Ghana. Though plantation development is not the ultimate solution to deforestation (FAO, 1995), their role in tackling forest loss is appreciated and has become important part of national forestry strategies (Foli *et al*., 2009; Agyeman, 2004; Evans, 1999b). Programs to establish plantations in the country started in the late 1950s mainly for the production of timber and improvement in environmental quality and wildlife habitat (Foli *et al*., 2009; Appiah, 2003). Most of the plantations established in many forest reserves by the then Forestry Department (FD) were done through the Taungya system (Appiah, 2003; Odoom, 2002). This system was designed to use both exotic and indigenous hardwood species. It was developed in such a way that the FD would work with farmers to achieve the required objectives. However the Taungya system was not successful and had to be stopped in 1987 (Appiah, 2003; Odoom, 2002). The system was fraught with improper supervision, corruption and conflicting interest between food crop production and tree growth (Appiah, 2003; Odoom, 2002).

2.3 Importance of Plantations

In 1995 tropical and sub-tropical plantations comprised 45 % of the global net forest plantation area. Hardwoods covered 32.3 million hectares, 57 % of all plantations in the tropics and sub-tropics and 25 % of the global area (Pandey, 1997). It was estimated that in 1991-1995 four million hectares were planted annually (1.64 million hectares) in the tropics and (2.37 million hectares) in the sub-tropics of which reforestation of harvested areas was not specifically detailed. In an attempt to preserve the environmental functions of forests and to conserve stocks, several tropical countries have introduced logging bans, including Bangladesh, Cambodia, China, the Philippines, Thailand and Vietnam. For example, the Malaysia case study carried out for this review noted that in 1997 the country produced 35 million m^3 of sawlogs, but planned to reduce this to about 27 million m^3 in

2000 and in the long term to about 21 million m^3/year, a level that is believed to be sustainable (Krihsnapillay, 1998). Forest plantations of a wide range of species, including the valuable "luxury" hardwoods such as teak (*Tectona grandis*), mahogany (*Swietenia* spp.) and rosewood (*Dalbergia* spp.) have been established to meet anticipated shortages of log supplies from natural forests in the future. In 1995 the estimated global net areas of these three species were 2.25, 0.62 and 0.15 million hectares, respectively (Pandey, 1997). However, there is considerable uncertainty about the actual extent of these valuable hardwood plantations, and even more uncertainty about their standing volumes and thus raw material supply, and about future demand. In spite of this, when planned and designed appropriately, plantations can be used to maximize outputs such as timber production (Foli *et al*., 2009; Kelty, 2006; Siry *et al*., 2005; Sedjo, 1999; Lugo, 1997), restoration of degraded lands (Blay *et al*., 2008; Lugo, 1997; Brown and Lugo, 1994; Parrotta, 1992), restoration of biodiversity (Sayer *et al*., 2004; Lamb, 1998; Parrotta *et al*., 1997), poverty alleviation and community participation in addressing forestry issues (Blay *et al*., 2008; Blay, 2004; Agyeman, 2004; Odoom, 2002), reduction of pressure on natural forests (Kelty, 2006; Siry *et al*., 2005), sequestration of carbon (Hodgman and Munger, 2009; Kelty, 2006; Montagnini and Porras, 1998), and other specific land rehabilitation objectives (Kelty, 2006; Bowyer, 2001; Parrotta and Knowles, 1999; Lugo, 1997).

2.4 Environmental issues of plantations

Despite the fact that plantation establishments are on the rise (FAO, 1995) and are playing important roles, there are several oppositions to the prospects of plantation silviculture in the world due to certain negative ecological attributes (Cossalter and Pye-Smith, 2003; Rosoman, 1994) and the use of mostly exotic species (Powers, 1999). These oppositions are as a result of serious deleterious effects of plantations on soil fertility (van Bodegom *et al*., 2008; Bowyer, 2001; O' Loughlin, 1995; Rosoman, 1994), water resources (Cossalter and Pye-Smith, 2003; Cannell, 1999), biodiversity (Stephens and Wagner, 2007; Bowyers, 2001; Kwok and Corlett, 2000; Lamb, 1998; Lugo, 1997), native natural forests (van Bodegom *et al*., 2008; Bowyer, 2001; Powers, 1999) and are generally susceptible to disturbances such as pests and diseases (Bowyer, 2001; Powers, 1999; Lugo, 1997).

Plantations in some cases have had negative effect on soil fertility because of compaction during mechanized harvesting and site preparation (van Bodegom *et al*., 2008; O' Loughlin, 1995) and the fact that they are less efficient in trapping released nutrients (Evans, 1992). Studies have also found that plantation establishments can influence water quantity and quality (Cannell, 1999; Rosoman, 1994). Results from a 10-year study by Zhou *et al*. (2002) in Southern China showed that surface runoff was highest from bare land, followed by *Eucalyptus* plantation and least from mixed forest stands. In some cases plantation establishments are seen as a threat to biodiversity (Cossalter and Pye-Smith, 2003; Rosoman, 1994) and are considered to rarely contribute significantly to restoration of landscape biodiversity compared to natural forest (Stephens and Wagner, 2007; Siry *et al*., 2005; Lamb, 1998). Kwok and Corlett (2000) reported a much higher total bird density in secondary forest (44.5/ha) than in plantation (12.4/ha) after they compared avifaunas in a 30-40 year old secondary forest and a 25-30 year old *Lophostemon confertus* plantation in Hong Kong, South China. Furthermore plantations are sometimes considered to be a threat to the existence of original native forests (van Bodegom *et al*., 2008; Hartley, 2002; Bowyer, 2001).

2.5 Monoculture species-plantation

According to Evans (1999a) and Wormald (1992), based on their structural complexity or number of species involved, planted forests can either be classified as monoculture (monospecific species) or polyculture (mixed species) plantations. Most plantations in the world are composed of monocultures of particularly exotic species selected either for their high productivity or tolerance of degraded soils (Stephens and Wagner, 2007). Monocultures which have a long history are mostly the favoured plantation method throughout the tropics including Ghana (Foli *et al*., 2009; Odoom, 2002).

Cossalter and Pye-Smith (2003) and Sedjo (1999) indicated that the establishments of these plantations have been driven mainly by industry and governments to satisfy a growing demand for industrial wood products and dwindling supply from natural forests. Areas of plantations in the tropics show that monocultures of eucalypts, pines, acacias and teak are the frequently used species (Kelty, 2006; Wormald, 1992). In Africa, tropical Latin America and South America, monocultures of *Eucalyptus* spp. and Pines comprise about 50% and 80% respectively of plantation areas (Bragança *et al*., 1998; Wormald, 1992) and according to Foli *et al*. (2009); Odoom (2002), over 50%-70% of plantations in Ghana are composed of teak monocultures.

2.5.1 Advantages of monocultures

The advantages of monocultures (over mixed-species forests) are simplicity, uniformity and the ability to concentrate resources on one species or product (Evans and Turnbull, 2004; Kelty, 2006). Monocultures, due to their uniformity, are simpler to manage and harvest; the complexity at harvest of mixed-species stands is often reported as an impediment to their use (Hunt *et al.*, 2006; Kelty, 2006; Nichols *et al.*, 2006). For these reasons low value, high volume products such as industrial eucalypt pulp plantations are established as monoculture stands. These industrial plantations are commonly located on relatively poor soils that are unsuitable for other forms of agriculture. Efforts to improve productivity on such sites include matching site preparation, nutrient input and management techniques. Inputs of nutrients in the establishment stages are common in operational plantations (Florence, 1996; Schroth and Sinclair, 2003; Turnbull, 2003). Biomass removal at harvest results in high export of nutrients from these systems potentially leading to serious nutrient deficiencies in following rotations. This necessitates further increases of nutrient inputs in second and third rotations. Such intensive silvicultural management generates questions about the long-term site productivity and thus sustainability of such plantations (Evans, 1999b; Binkley, 2005).

2.5.2 Disadvantages of monoculture plantations

Inspite of the wide spread of these plantations, questions have been raised against their continued expansion due to their perceived negative impacts such as less support for biodiversity (Stephens and Wagner, 2007; Carnevale and Montagnini, 2002; Lamb, 1998) and low level of product diversification (Lamb *et al*., 2005; Odoom, 2002; Lamb, 1998).

2.5.2.1 Less support to biodiversity

Monoculture plantations may have a biological diversity which is a lot lower than that of a natural forest, and in the great majority of cases it is also much lower than the biodiversity of meadows with trees and other natural ecosystems. Monoculture tree plantations have contributed little to the conservation, study, and use of the biodiversity. Carrere and Lohmann (1996), present a rich compilation of examples where tree plantations have had a direct or indirect impact upon natural forests and thus upon biodiversity in general in the region. In some cases, these plantations have affected, or have been established to the detriment of, other ecosystems of great importance for biodiversity conservation, such as tropical wetlands. In the south of Costa Rica, Ston Forestry, a subsidiary of Ston Container (one of the largest wood pulp processors) is facing judicial prosecution for causing the desiccation of wetlands (van den Hombergh, 1999).

A study by Kohli *et al*., (1996) at the outskirts of Chandigarh, India showed that floor vegetation was lowest in monoculture plantations. They found 35 plant species under mixed plantations of *Albizia lebbeck*, *Dalbergia sissoo* and *Populus deltoides* against 17, 28 and 29 species under *Populus deltoides, Albizia lebbeck and Dalbergia sissoo* monocultures respectively (Kohli *et al*., 1996). In the Osa peninsula in Costa Rica, for example, some biologists are questioning the impact of hundreds of thousands of Gmelina fruit trees upon natural populations of parrots and guacamayos in the Corcovado National Park. If these populations increase due to a resource which may be cut at any time, they will have to look for refuge and food amongst the limited resources of the national park, thus affecting the equilibrium of its ecology.

2.5.2.2 Soil Deterioration: Infertility and Erosion

The forestry companies argue that the impact of tree plantations upon the soil is of relatively little importance if compared to the impact intensive agriculture has. However, there is evidence that fast-growing trees have an extractive effect upon soil fertility and that they tend to impoverish the soil and unbalance its structure (World Rainforest Movement, 1999). Moreover, some species show repressive effects on the growth of other plants through the release of certain substances. This is the case with Eucalyptus, which tends to acidify the soil, and Gmelina, which inhibits the growth of plants which are not of the same species. Other plantation practices, including preparation of the soil before planting, plantation management, and harvesting, also favor erosive processes, especially in areas with steep slopes.

2.5.2.3 Low level of product diversification

The demand people place on plantations goes beyond timber production (Blay *et al*., 2008; Lamb *et al*., 2005). Blay *et al*., (2008) found that apart from timber production, non-timber products for domestic uses were one of the major motivational factors for communities to engage in reforestation activities. However monoculture plantations do not provide many of the traditional forest goods and ecological services required by communities (Erskine *et al*., 2006). Monocultures therefore present fewer options for providing income throughout the rotation period.

2.5.2.4 Deterioration of Hydrological Systems

Tree plantations present a physiological and morphological structure which is very different from that of a forest or other natural ecosystem. Thus, their capacity to absorb and release rainwater varies a lot according to the species and climatic conditions. Species like teak (*Tectona grandis*), with its large leaves, tends to concentrate rainwater and releases it in large drops that damages the soil, promoting erosion and heavy run-off. The eucalyptus presents a case similar to that of conifers, it tends to reduce the flow of water into the aquifers. This species tends to dry wetlands and swamps, and therefore are being used to control certain plagues (mosquitoes), and to dry wetlands (Castro, 1999). One of the aspects which probably influences the regulation of the hydrological cycle the most as far as the forest is concerned is the presence of the undergrowth. This undergrowth fulfills the role of a “sponge in the shade” which retains water without evaporation, and slowly releases it to the soil. However, in a managed tree plantation the undergrowth is eliminated.

2.6 Mixed species plantation

Mixed species plantations are limited to less than 0.1% of industrial plantations worldwide (Nichols *et al.*, 2006). However, there is continued interest in mixed-species plantations amongst landowners and researchers in tropical and subtropical regions (Kanowski *et al.*, 2005; Piotto *et al.*, 2004). Benefits from the use of mixed plantation may result from better site use, improved tree nutrition, and less insect or pest damage. There may be also financial gains from combining fast-growing species that can be harvested earlier in a rotation, with more valuable species that need longer rotations. The first harvest provides an initial cash flow and also improves the growth of the remaining higher value trees (Lamb and Gilmour, 2003).

2.6.1 Advantages of mixed species plantations

Advocates of mixed species plantations offer three broad reasons for their advantages (over monocultures): greater production, environmental services (soil and water protection and/or rehabilitation, nature conservation, and aesthetic benefits), and risk aversion (contingency planning for pests and pathogens, climate change, species failure, and market fluctuations). Species mixtures can potentially increase stand-level productivity, or individual-tree growth rates and stems form, using complementary characteristics; that is reducing competition for fundamental growth-regulating resources and or, increasing facilitative interactions between species (Forrester *et al.*, 2006a; Kelty, 2006). For example mixtures may produce a greater amount of biomass per unit area because competition between individuals is reduced and the site is utilised more fully (Montagnini *et al.*, 1995). Rooting zones of different species can occupy different soil strata (Lamb and Lawrence, 1993; Jose *et al.*, 2006), or a greater amount of solar energy can be captured because different species can have different optimum light requirements and crowns can separate into different canopy strata (Forrester *et al.*, 2004; Hunt *et al.*, 2006). Species may also have differing phenologies of root or shoot growth and therefore competitive demand for soil water or nutrients may be lower than that of a monoculture plantation. Mixed plantations can be less susceptible to insect or disease problems (Nichols *et al.*, 1999; Nichols *et al.*, 2001; Bosu *et al.*, 2006), and total failure of the plantation as a result of insect pests or diseases is less likely if a mixture of tree species is used.

Furthermore, increased structural and or biological diversity in planted forests may lead not only to greater yields (Erskine *et al.*, 2006), but may increase resilience to disturbance at the stand or landscape level. The functional consequences of this diversity are beginning to be explored (Tilman, 2000; Kanowski *et al.*, 2005; Lamb *et al.*, 2005).

Managing above-ground woody biomass production involves managing competition through espacement, thinning and pruning. Wide spacing of light demanding species can promote formation of larger branches and slower crown lifts, which in most cases will require pruning to produce quality wood (Dickinson *et al.*, 2000; Montagu *et al.*, 2003; Reid, 2006). Using mixtures can increase the production of merchantable timber by improving the form and bole length of desired species though the positive effects of competition (for environmental resources such as light) with an added species (Forrester *et al.*, 2006a), although the same result may be achieved with close spacing of light demanding species. In some north Queensland mixed species plantations, species have been selected for their high-value timber characteristics; where each species is potentially commercial for its sawn timber (Keenan *et al.*, 1995). Variation in effective stand density as a result of differing species' growth rates, and positive crown competition has led to increased individual tree basal area; which may lead to greater quantity and quality of timber produced per stem (Bristow *et al.*, 2006b; Erskine *et al.*, 2006).

2.6.2 Main challenge with mixed-species plantations

There is wealth of research espousing the benefits of mixed-species plantings (e.g., Wormald, 1992; Ball *et al.*, 1995; Dupuy, 1995; Hartley, 2002; Kelty, 2006; Erskine *et al.*, 2006; Forrester *et al.*, 2006b), but a paucity of industrial polyculture plantations demonstrating commercial success. Within the community of mixed-species researchers, it is easy to gain the impression that there is widespread support and demand for mixed-species plantations, but this is not generally so in the case of commercial plantations for timber production. There is little doubt that mixed-species plantings are preferable to monocultures for restoration activities (Lamb 1998; Hooper *et al*. 2005), but the case is not so clear with commercial plantations for timber production. Nichols et al. (2006) reported that even though the basic silvicultural requirements for successful mixed-species plantations have been established, there are still challenges with many aspects of the management of these plantation types (FAO, 1993; Wormald, 1992). This is because unlike monoculture plantations, mixtures may require additional silvicultural interventions (Nichols *et al.*, 2006). Management of mixed plantations is therefore more intensive and generally requires more attention to details (Wormald, 1992). Wormald (1992) indicated that to successfully manage mixed-species plantations, there is the need for among other things a clearly defined set of objectives.

2.7 Preference of Indigenous species to exotic species

Most plantations in the tropics including Ghana are mostly exotics (Odoom, 2002; FAO, 1995) consisting of species from few genera (Evans, 1999a; 1992). In Ghana for instance statistics show that about 70% of plantations are composed of teak (Foli *et al*., 2009). While monoculture plantations of exotic species have been found to be productive (Cossalter and Pye-Smith, 2003; Powers, 1999; Sedjo, 1999) and provided wood and fibre for some industrial purposes (Bowyer, 2001), they usually fail to provide a wide variety of non-timber products and other ecological services that are essential to sustain rural communities (McNamara *et al*., 2006; Lamb *et al*., 2005; Hartley, 2002; Montagnini and Porras, 1998; Lamb, 1998). Although indigenous species have mostly been excluded in plantation establishments (Butterfield and Fisher, 1994), they have been found to have the potential to perform as well as or even better than most commonly used exotic species (Foli *et al*., 2009; Butterfield, 1995). Indigenous species with peculiar wood properties and better adaptability to sites can be identified to replace most of the exotic species and provide a wide range of quality hardwoods to increase the forestry production base (Hartley, 2002; Haggar *et al*., 1998). Studies have shown that when indigenous species are well designed and managed they can achieve sustained productivity (Foli *et al*., 2009; Redondo- Brenes and Montagnini, 2006), restore biological diversity (Stephens and Wagner, 2007; Cusack and Montagnini, 2004; Hartley, 2002; Lamb, 1998; Butterfield, 1995), support rehabilitation and reforestation programs (Blay *et al*., 2008; Petit and

Montagnini, 2006; Montagnini, 2001), and increase product diversification (Lamb *et al*., 2005; Haggar *et al*., 1998).

Research from Ghana has shown that some indigenous species are not as slow growing as previously thought (Foli *et al*., 2009) and through the use of selected and improved germplasm they may possibly exceed the productive potential of most exotic species (Haggar *et al*., 1998).

More stable indigenous species have the potential to offer greater yields especially where site conditions are poor and management is limited (Butterfield, 1996). Indigenous species are also recommended as suitable options for enhancing biological diversity conservation (Hartley, 2002). These species are valuable for biodiversity conservation because they provide resources such as mast, fruit and nectar (Hartley, 2002). Indigenous species therefore are capable of providing suitable habitat with structural and understorey conditions even similar to that which pertain in natural forests (Stephens and Wagner, 2007). Indigenous species have been used in reforestation and rehabilitation projects in Ghana (Blay *et al*., 2009; Blay et al., 2008), Costa Rica (Cusack and Montagnini, 2004; Carnevale and Montagnini, 2002; Haggar et al., 1998; Butterfield, 1996), Ecuador (Larsson, 2003) and Nigeria (FAO, 1993).

2.7.1 Major challenge with the use of Indigenous species in plantations

Attempts to establish plantations of indigenous species have either been difficult or failed due among other things to inadequate knowledge of their biology, ecology, silvicultural requirements and pests and diseases problems (Wagner *et al*., 2008; Feyera *et al*., 2002; Butterfield, 1995). Generally plantations of indigenous species are susceptible to a complex of both exotic and native pests and pathogens (Ciesla, 2001) and therefore suffer from more pest damages and diseases (Gadgil and Bain, 1999). This situation is partly due to the changes in ecological conditions which occur due to shading, competition, soil conditions, tree density and other management practices (Hosking, 1983). Plantations of indigenous species in different parts of the world have suffered from incidences of pests and diseases. In China and Vietnam for instance, the defoliating caterpillar, *Dendrolimus punctatus* is a major pest of indigenous pine plantations (Ciesla, 2001). *Hylurdrectonus araucariae* although is harmless in natural stands of hoop pines in Papua New Guinea, become epidemic in plantations by feeding on the juvenile foliage of the seedlings (Hosking, 1983).

Nun moth, *Lymantria monacha* is also a defoliating caterpillar of both *Picea abies* and *Pinus sylvestris* in Central Europe (Ciesla, 2001). Foli *et al*., (2009) indicated that the lack of interest in the use of indigenous species for plantations in Ghana is mainly due to the infestation of pests and diseases. Most mahogany plantations established in Ghana have been constrained by the larvae of the shoot borer moth, *Hypsipyla robusta* (Opuni-Frimpong *et al*., 2008; Opuni-Frimpong *et al*., 2004; Odoom, 2002). Efforts to establish *Milicia* spp. in plantations have also been hindered by the gallforming psyllids, *Phytolama lata* (Wagner *et al*., 2008; Bosu *et al*., 2006; Nichols *et al*., 1999). The psyllids attack the leaves of the seedlings resulting in death (Bosu *et al*., 2004).

2.8 Carbon sequestration

Plantations can be very important in sequestering carbon from the atmosphere (Hodgman and Munger, 2009; Kelty, 2006; Montagnini and Porras, 1998; Moura Costa, 1996). Both single and mixed species plantations have the potential to help forests maintain their contribution to carbon cycles (Hodgman and Munger, 2009; Siry *et al*., 2005). Monocultures concentrate all the site resources on growth of species improving growth rates and carbon sequestration (Hodgman and Munger, 2009; Kelty, 2006). Mixed species plantations also contain species which occupy different ecological niches on the same site and therefore have the potential to store more biomass and eventually more carbon (Hodgman and Munger, 2009). Thus growth of trees in plantations is accompanied by substantial carbon storage (Bowyer, 2001). Montagnini and Porras (1998) found that the annual biomass increments for three young mixed plantations in the humid lowlands of Costa Rica ranged from 10-13 Mg/ha. Estimates from another study involving planting of degraded forests in Sabah, Malaysia indicated that the project is likely to offset 183 Mg C/ha after a 60- year rotation or an average of 100 Mg C/ha/yr during the same rotation period (Moura Costa, 1996).

2.9 Description of the focal indigenous tree (*Khaya grandifoliola*)

2.9.1 Origin and geographic distribution

Khaya grandifoliola (also called African mahogany, Benin Mahogany, Large-leaved Mahogany, or Senegal Mahogany) is a species of plant in the Meliaceae family. It is found in Benin, the Democratic Republic of the Congo, Ivory Coast, Ghana, Guinea, Nigeria, Sudan, Togo, and Uganda (Hawthorne, 1998). Occurring in more or less the transitional zone between savanna and closed forests, *Khaya grandfoIiola* trees are predominant in the Ivory Coast, Ghana and Nigeria (Donkor B. N., 1997). The shaded regions in figure 2.3 illustrate the distribution of *K. grandifoliola* in Africa.

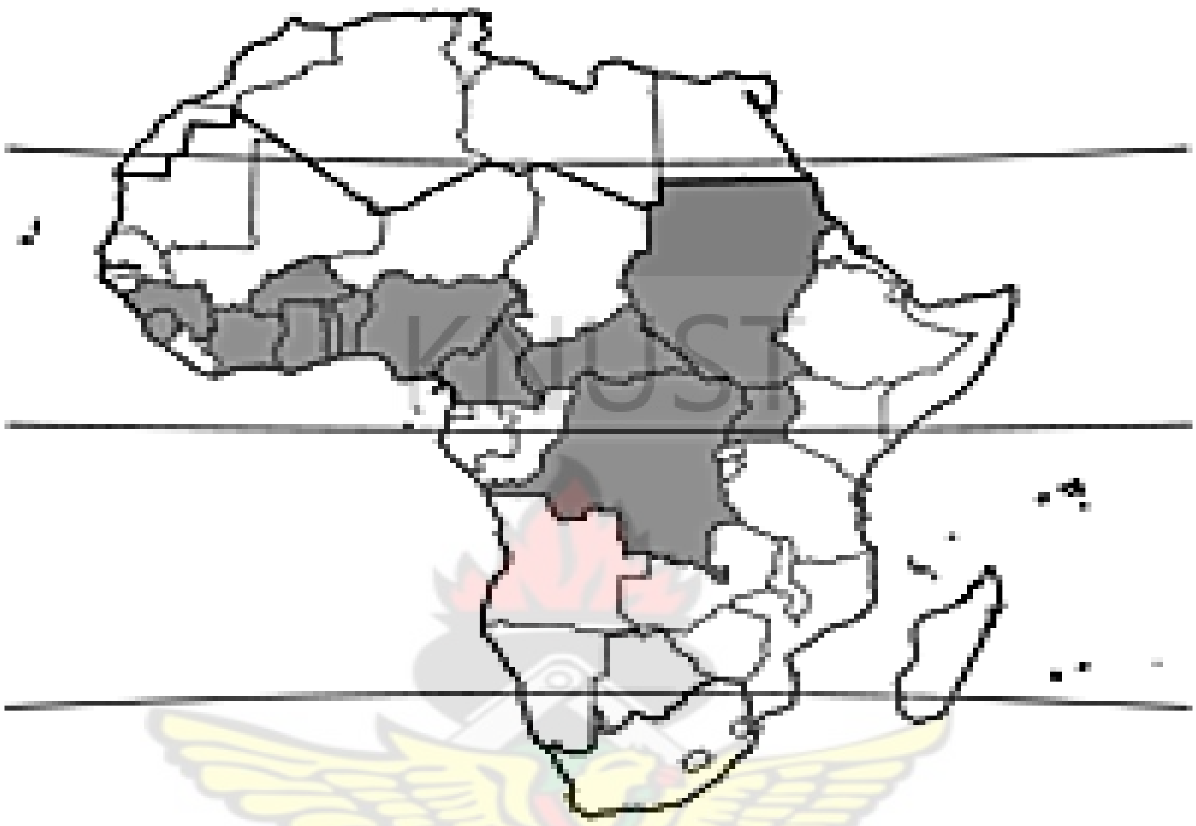


Figure 2.3. Distribution of *Khaya grandifoliola*. Adopted from: Opuni-Frimpong E. (2008).

2.9.2 Ecology and Habitat

Khaya grandifoliola occurs in semi-deciduous forest, especially in drier types and in savanna, but in the latter case usually along watercourses, in areas with 1200–1800 mm annual rainfall and a dry season of 3–5 months. It occurs up to 1400 m altitude. Sometimes it can be found in rocky and hilly parts of moist semi-deciduous forest, where *Khaya anthotheca* also occurs. In Ghana, *Khaya grandifoliola* is in drier forests of the dry semi-deciduous forest type and in rocky, hilly parts of moist semi-deciduous forests (Donkor, 1997). It prefers moist but well-drained soils, and is locally common on alluvial soils in valleys. Seeds can germinate in full sun as well as in the shade, but natural regeneration may be very sparse in the forest. In Nigeria it was found that although seedlings could become established in closed forest, they showed very poor growth and rarely survived for long. In Sudan *Khaya grandifoliola* reportedly does not regenerate under a closed forest canopy. Natural regeneration can be abundant in savanna which is close to the forest and protected from fire.

2.9.3 Growth and development

In Côte d'Ivoire *Khaya grandifoliola* trees planted in the open in the semi-deciduous forest zone reached an average height of 13.5 m and an average bole diameter of 17 cm after 10 years. However, trees planted in the evergreen forest zone only reached 9 m in height and 11.5 cm in diameter after 8 years. In Nigeria an average height of 21 m after 20 years was recorded. However, in natural forest in Nigeria the average bole diameter for trees 100 years old was estimated at only 60–70 cm. Trees are usually deciduous in the dry season; young leaves are strikingly reddish and often occur together with flowers. The flowers are pollinated by insects such as bees and moths. Dispersal of the seeds is by wind, but most seeds fall close to the parent tree. The presence of endotrophic mycorrhizal fungi in nurseries is important; inoculation with *Endogone* spores markedly improved the growth of seedlings.

2.9.4 Diseases and pests

In plantations *Khaya grandifoliola* may suffer seriously from *Hypsipyla robusta* shoot borers that kill the main stem of young trees, causing excessive branching and contributing to mortality. Entwistle (1967) indicated that the mahogany shoot borers are among the most economically significant insect pests in tropical forestry, with the most important species in Africa being *Hypsipyla robusta*. The principal damage caused by these species is from larval feeding in apical shoots. Repeated attack of the main leader results in numerous secondary shoots and stunted growth, both of which affect the quality of timber produced (Wagner *et al*., 1991; Dupuy, 1995). Despite significant research and management efforts, previous attempts to manage *Hypsipyla* spp. have largely been unsuccessful (e.g. Wanger *et al*., 1991; Newton *et al*., 1993; Mayhew and Newton, 1998; Hauxwell *et al*., 2001b). However silvicultural techniques such as overhead shading of saplings, mixed planting and removal of lateral shoots can reduce damage by shoot borers. Seeds are commonly attacked by seed-boring beetles and eaten by small rodents.

2.9.5 Uses of *Khaya grandifoliola*

The wood of *Khaya grandifoliola* is valued for carpentry, joinery, furniture, cabinet work and decorative veneer. It is suitable for light construction, light flooring, interior trim, ship building, musical instruments, toys, novelties, carving, turnery and pulpwood. Traditionally, the wood is used for furniture, household implements and dug-out canoes. It is also used as fuelwood and for charcoal production. The bitter-tasting bark is used in traditional medicine. It is widely used against fever caused by malaria. Bark decoctions are taken to treat stomach complaints including gastric ulcers, pain after childbirth, and skin diseases. In Sudan a bark infusion is used to treat diarrhoea caused by intestinal parasites. A decoction of the root bark is drunk to treat gonorrhoea and pulverized root bark is applied externally to skin diseases. In Uganda the bark is used as a fish poison, and in DR Congo the bark is used for washing cloth. *Khaya grandifoliola* is planted as a roadside tree and ornamental shade tree. In Uganda it is valued for stabilization of river banks.

2.10 Brief description of *Tectona Grandis*

Tectona grandis belongs to the family Verbenaceae and is one of the best known and most valuable tropical hard woods in the world (Raymond, 1996). It is commonly called teak, which originated from Southeast Asia. The natural range is wet tropical low and forest of Burma, India, Thailand, and on the Indonesian islands and grows in a variety of soils but deep soils with good drainage are necessary for satisfactory growth. It is a large broad-leafed and deciduous tree that shedes its leaves during the dry season. The tree ranges from 30 meters in height with a girth over one meter on good sites to 12 meters in height on poor sites (Zain, 2005). The crown opens with many small braches and the bark is brown on the bole distinctly fibrous and with shallow longitudinal fissures. (Mbuya *et al.*, 1994).

The leaves are four-sided branchlets; bear the very large leaves which are shield for three to four months during the latter half of the dry season. The leaves are shiny above and hairy below with vein network clear about 30 x 20 cm but young leaves are up to 1m long. The flowers are small about 8mm across with manve-white and are arranged in large flowering heads of about 45cm long. Teaks also have a medicinal value. The bark is bitter tonic and is considered useful in treating fever and also useful in treating headache and stomach problems.

It is useful in furniture making, boat, decks and for indoor flooring and is widely used to make doors and house windows. It is resistant to the attack of termites and its wood contains scented oil which is the repellent to insects. The leaves yield dye which is used to colour clothes.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Area

The study was conducted in the degraded portion of the Tain Tributaries Block II Forest Reserve which lies in dry semi-deciduous forest zone of Ghana. Tain Tributaries Block II Forest Reserve, with a latitude of 7.58 (7° 34' 60 N) and a longitude of -2.5 (2° 30' 0 W) has an area of 507 km^2 and last logged in 1991 (Hawthrone W. D. and Abu-Juam M., 1995). It stretches from Sunyani East and West, Berekum, and Jaman district assemblies. The study area was a research plot by Forestry Research Institute of Ghana, on the land leased to the ABTS Company Limited by the Forestry Commission for reforestation of degraded forest lands. The four year old plantation used for the study included plots of pure *Khaya grandifoliola*, mixed species (*Khaya grandifoliola*, *Terminalia superba*, *Cedrela Odorata*) and pure *Tectona grandis*.

The research being conducted by scientists of the Forestry Research Institute of Ghana with financial support from International Tropical Timber Organization (ITTO) in collaboration with Timber Industry, aims at restoring African mahogany in degraded forest landscapes of Ghana.

Plate 3.1. The four year old pure mahoganies stand in the ABTS plantation established by Scientists from FORIG.

3.1.1 Climate

Moisture laden south-west monsoons are the prevailing wind for the area during most part of the year. From late November till early March the monsoons is replaced by the desiccating harmattan wind which blow from the north east. Records from the nearest meteorological station indicate that rainfall is between 1140 mm and 1530 mm per annum but the dry semi-deciduous forest near Berekum (Brong-Ahafo Region) receives little over

1000 mm a year (Hawthrone W. D. and Abu-Juam M., 1995). Most of the time, however, the area receives between 1250 and 1500 mm. Two distinct seasons may be noticed, the rainy season (April – November) and dry season (December – March). Humidity is quite high throughout the rainy season but low in the dry season. Maximum temperature is between 30^{o}C and 34^{o}C and minimum is between 18^{o}C and 22^{o}C. Abundant sunshine and rainfall yields a warm and humid weather.

3.1.2 Vegetation

This forest reserve falls in the dry semi-deciduous vegetation zone and extends narrowly into the moist semi-deciduous zone. The area is endemic to important timber species such as *Pericopsis elata* (African teak), *Khaya anthotheca, Khaya grandifoliola, Entandrophragma utile, Argomuellera macrophylla, Ceiba pentandra, Talbotiella gentii, Nesogordonia papaverifera, Lecaniodiscus cupanioides* and *Baphia nitida* (Hall and Swaine, 1981, 1976). This area is subjected to periodic or frequent bush fires due to the fact that it is a buffer between savannah transitional zone in the north and moist semi-deciduous zone in the south. As a result of frequent incidence of bushfires and other anthropogenic disturbances most of the forests in the area have been converted to secondary forests of which the majority is degraded. The forest was classified as condition 5 by the Forest inventory carried out in 1990 by the Forest Services Division but Hawthorne W. D. and Abu-Juam M. (1995) classified it as condition 4. *Tectona grandis*, Emire and *Senna siamea* (Cassia) were planted under taungya system between 1972 and 1986 with considerable success. Natural regeneration to a large extent is suppressed and very slow, due to invasion of weeds species such as Imperata *cylindrica, Pennisetum Purpureum and Chromolaena odorata, Panicum maximum, Ageratum* conyzoides and

Adropogon gayanus. Weed invasion is one factor which has reduced the original size of the forest zone in Ghana (CSIR, 2002).

3.2 Experimental design

The area considered for the study was 2.16 ha (60 m x 360 m) with 12 plots, each measuring 20 m x 90 m with 200 trees per plot and a plant spacing of 3m x 3m. The plots were maintained by weeding *Chromolaena odorata* and other competing vegetation from the time of establishment and when needed. No other silvicultural manipulations were carried out. The plots were arranged in a Completely Randomized Design with four replicates and three treatments. The treatments included a pure *Khaya grandifoliola* stand, a mixed-species stand (including *Khaya grandifoliola*, *Terminalia superba* and *Cedrela odorata*) and a pure *Tectona grandis* stand.

3.3 Data collection

For this study, a 10 m x 80 m subplot was established within the core area of each of the 20 m x 90 m plots. All of the trees within each 10 m x 80 m plot were measured for diameter at breast height (DBH). In addition, the total height and merchantable height of all trees within 10 m x 80 m plot were measured. The impact of Mahogany shoot borer, *Hypsipyla robusta* attack on *K. grandifoliola* in pure and in mixed stands was assessed by recording the number of total shoots in response to shoot borer attack, number of shoots attacked, number of fresh shoots attacked and number of dead shoots.

Plate 3.2 The field team that collected the data for this work in the mixed experimental stand of *Khaya grandifoliola*, *Terminalia superba* and *cedrela odorata*.

3.4 Data analysis

Average diameter at breast height (DBH), total height and merchantable height, basal area, volume, aboveground biomass, and carbon sequestration were calculated for each plot. The volume of individual trees was estimated following Newbould (1967): volume = $\boldsymbol{a} \times \boldsymbol{B_{dbh}} \times \boldsymbol{H}$, where $\boldsymbol{a}$ is the stem form factor, $\mathbf{B}_{dbh}$ is the basal area and **H** is the total height. The value of $\boldsymbol{a}$ was set to 0.5 as established by Uglade, (2000); and Newbould, (1967). The aboveground biomass and carbon sequestration for the species were estimated using measurements of total height and diameter at breast height. The aboveground biomass for *Khaya grandifoliola* was estimated using the following 4 equations to compare the differences in the estimation of the biomass using different equations;

A. $Y = \mathbf{a} (DBH)^{\mathbf{b}}$**, (**a = 0.0051, b = 2.47, Yeboah D. 2011).

B. $Y = \exp[-1.996 + 2.32 \ln(DBH)]$ (Brown *et al.*, 1989).

C. $Y = \exp[-2.28 + 2.649 * \ln(DBH) - 0.021 * (\ln(DBH))^2]$ (IPCC, 2003).

D. C = Carbon concentration * Wood density * Volume (Yeboab D., 2011).

The aboveground biomass of *Tectona grandis* was estimated using $Y = 0.153 \bullet (DBH)^{2.382}$ (IPPC, 2003) while that of the companion species were estimated using $Y = \exp[-1.996 + 2.32 \ln(DBH)]$ (Brown *et al*., 1989) and $Y = \exp[-2.28 + 2.649 * \ln(DBH) - 0.021 * (\ln(DBH))^2]$ (IPCC, 2003).

Where Y is the tree biomass in kilograms, DBH the diameter at breast height in centimeters and C is carbon sequestration in Kilograms and ln is natural logarithm.

$Y = \mathbf{a} (DBH)^{\mathbf{b}}$ is a generalized equation for estimating aboveground biomass with a and b as scaling coefficients. a = 0.0051 and b = 2.47 derived by Yeboah D. (2011) for indigenous trees from a plantation in Ghana.

$Y = \exp[-1.996 + 2.32 \ln(DBH)]$ (Brown *et al*., 1989) was derived from dry forest in India and from 28 tree species with diameter range of 4 - 5 cm. The dry zones generally represent areas with rainfall greater than 900 mm/year.

$Y = \exp[-2.28 + 2.649 * \ln(DBH) - 0.021 * (\ln(DBH))^2]$ (IPCC, 2003); this model was derived from Tropical hardwoods of trees with diameter at breast height ranging from 5 –

148 cm. Tropical moist generally represent areas with rainfall of between 2000 to 4000 mm/year in the lowlands.

$Y = 0.153 \cdot (DBH)^{2.382}$; this model was derived from 87 individuals at ages of 5 to 47 years and with diameter range of 10 - 59 cm.

Carbon was assumed to equal 50% of a tree's biomass (Brown and Lugo, 1982; Schroeder, 1992; Montagnini and Porras, 1998). The basal area, total volume, aboveground biomass, and carbon sequestration per hectare were calculated in the following manner. First, for each 10 m x 80 m plot, we estimated the tree density per hectare by multiplying the number of individuals in the plot times 10,000 m^2 divided by the plot area (800 m^2). Second, the obtained density per hactare was multiplied by the individual tree average for basal area, total volume, aboveground biomass, and carbon sequestration.

One-way analysis of variance (ANOVA) was used to determinate statistically significant differences between the species growing in mixed and in pure conditions. Diameter at breast height, total height, merchantable height, basal area, total volume, and carbon sequestration were the parameters compared in the analysis. SPSS 16.0 for Windows computer software was used for all statistical analysis and differences were evaluated at 5% significance level ($P < 0.05$).

CHAPTER FOUR

4.0 RESULTS

4.1 Growth and productivity of *Khayag grandifoliola* in pure and in mixed stands

The growth and productivity performance of *K. grandifoliola* in pure and in mixed stands was generally better in pure stands than in mixed stands after four years of establishment. There was significant difference in diameter growth of *K. grandifoliola* in pure and in mixed stands (P = 0.001). *K. grandifoliola* had a better diameter growth of 9.15 cm in pure stands compared to 7.81cm of mixed stands (figure 4.1).

Table 4.1 Productivity statistics of tree species in pure and in mixed stands in the dry semi-deciduous forest zone.

Species	Condition	Density (#trees/ha)	Basal area (m^2/tree)	Basal area (m^2/ha)	Volume (m^3/tree)	Volume (m^3/ha)
K. grandifoliola	Pure	756 ± 41	.007 ± .0[a]	5.5 ± .3[a]	.023 ± .0[a]	17.8±0.9[a]
	Mixed	209 ± 71	.005± .0[b]	1.1 ± .2[b]	.016 ± .0[b]	3.4±0.6[b]
C. odorata	Mixed	178 ± 14	.016 ± .0[c]	2.9 ± .2[c]	.072 ± .0[c]	12.9±1.0[c]
T. superb	Mixed	197 ± 21	.010 ± .0[d]	2.0 ± .2[d]	.038 ± .0[d]	7.5±0.8[d]
T. grandis	Pure	584 ± 43	.008 ± .0[e]	4.8 ± .3[a]	.038 ± .0[d]	22.5±1.7[e]

Values are means and ± are standard errors.
Means along the column with the same letter are not significantly different.

K. grandifoliola in pure stands had higher total height and merchantable height of 5.50 m and 3.63 m respectively (figure 4.2) but these values however were not significantly different from the values of *K. grandifoliola* in mixed stands with total height of 5.04 m and merchantable height of 3.52 m (figure 4.2).

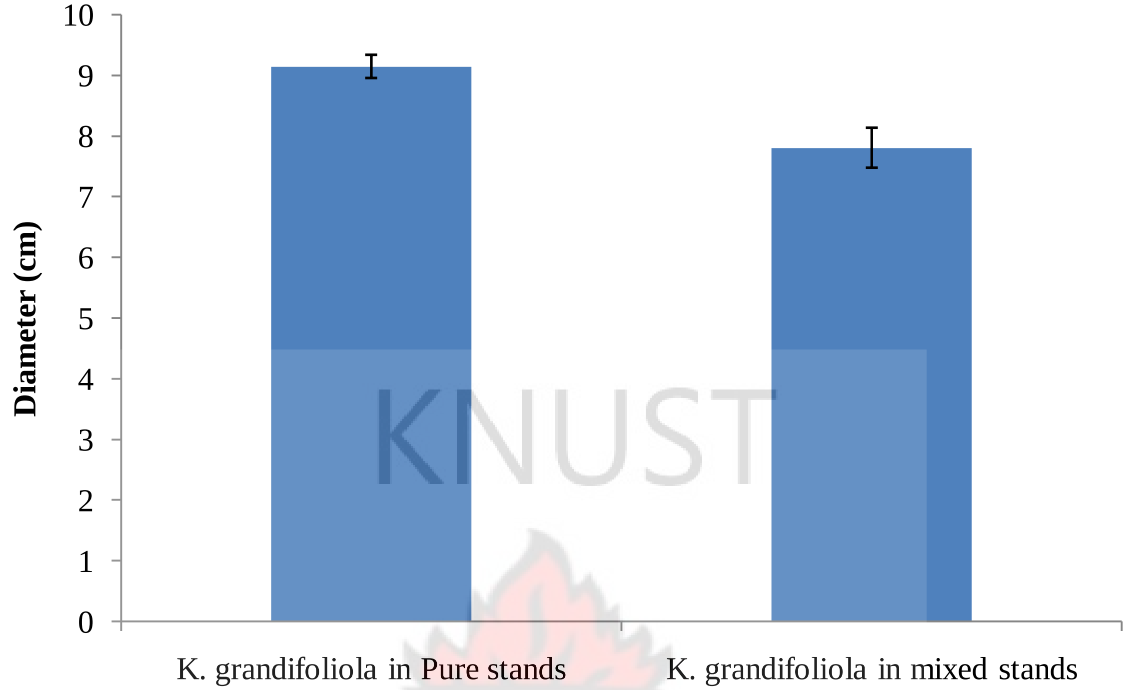


Figure 4.1. Mean diameter of *Khaya grandifoliola* in pure and in mixed stands

The basal area per tree of *K. grandifoliola* in pure stands were significantly higher than in mixed stands (P = 0.001). Subsequently basal area per hectare of *K. grandifoliola* were higher in pure than in mixed stands. *K. grandifoliola* in pure stands recorded basal area per hectare of 5.5 m^2/ha and 1.1 m^2/ha in mixed stands (Table 4.1). Also in pure stands, volume per tree of *K. grandifoliola* was statistically higher than in mixed stands (P = 0.006), consequently, *K. grandifoliola* had volume per hectare value of 17.8 m^3/ha in pure stands and 3.4 m^3/ha in mixed stands of (Table 4.1).

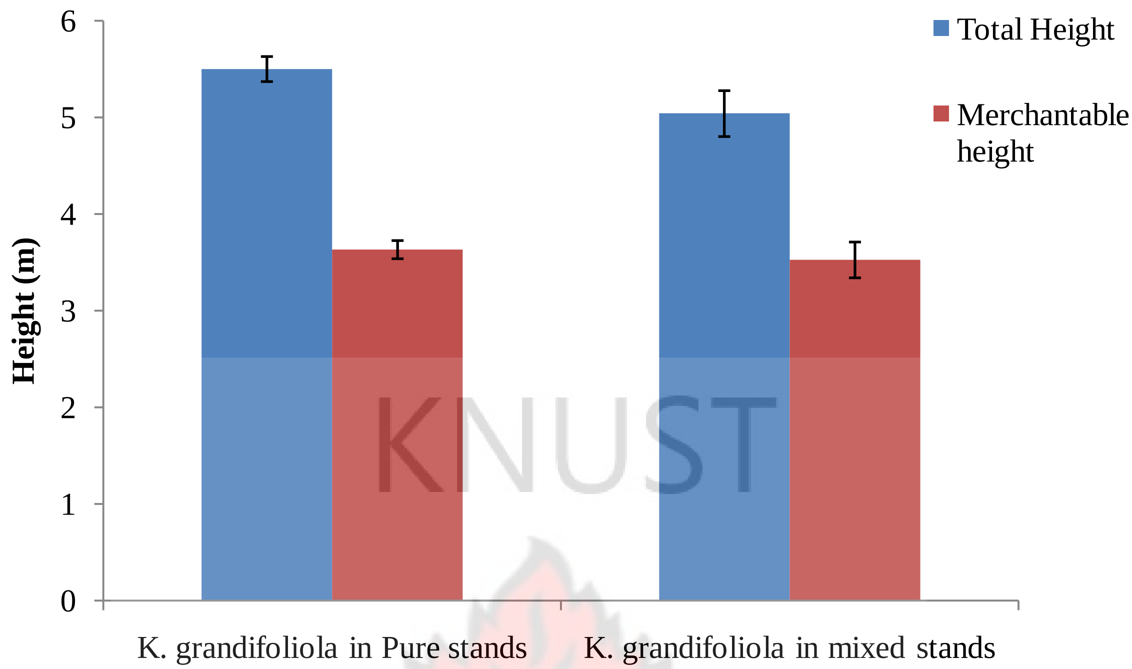


Figure 4.2. Mean height and merchantable height of *Khaya grandifoliola* in pure and in mixed stands

4.2 Tolerance to pests by *Khaya grandifoliola* in pure and in mixed stands

K. grandifoliola tolerance to mahogany shoot borer, *Hypsipyla robusta* in the two growing regimes/conditions was ascertained by collecting data on a number of total shoots sprouted in response to shoot borer attack, number of shoots attacked, number of fresh attack and number of dead shoots. Apart from the number of total shoots that presented significant difference between the two regimes with *K. grandifoliola* in pure stands recording the higher mean value of 9.9 and *K. grandifoliola* in mixed presenting 5.7 (figure 4.3), no significant differences were observed in the number of shoots attacked, number of fresh attack and number of dead shoots between the two growing regimes ($P > 0.05$). *K. grandifoliola* produced mean values of 0.95, 0.11 and 0.96 for number shoots attacked, number of fresh attack and number of dead shoots respectively in pure stands while it had mean values of 0.64, 0.19 and 0.81 for number shoots attacked, number of fresh attack and number of dead shoots respectively in mixed stands (figure 4.3).

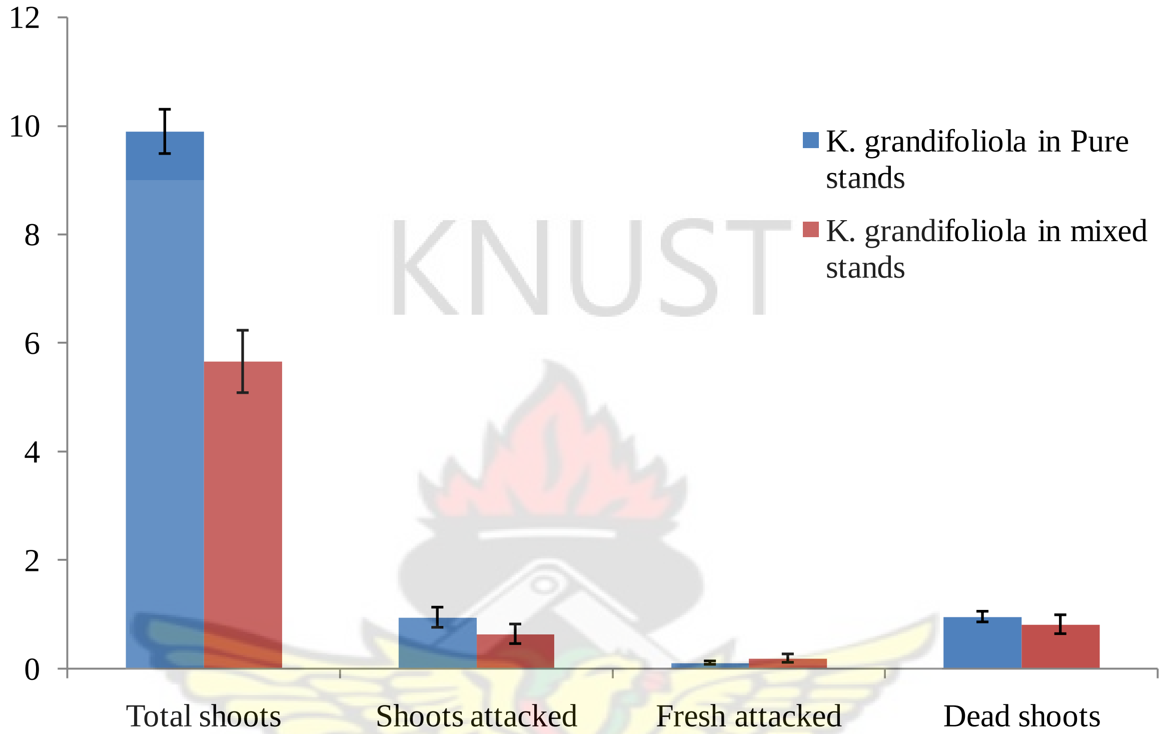


Figure 4.3. Total number of shoots, number of shoots attacked, number of fresh attacked and number of dead shoots of *Khaya grandifoliola* in pure and in mixed stands.

4.3 Growth and productivity of *Khaya grandifoliola* and *Tectona grandis* in pure stands

Four years after planting in the field, the diameter growth of *K. grandifoliola* was almost the same as that of *T. grandis* with *T. grandis* having a mean diameter of 9.61 cm and *K. grandifoliola* having a mean diameter of 9.15 cm (figure 4.4). Consequently the diameter growth of these species did not significantly differ from each other ($P > 0.05$).

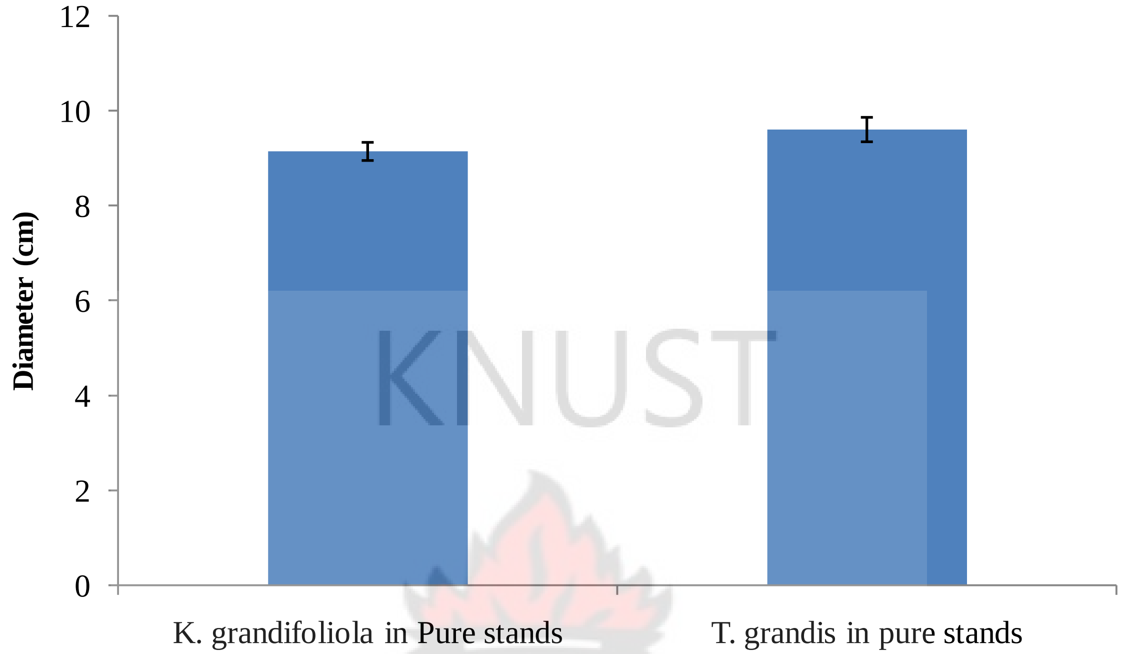


Figure 4.4. Mean diameter of *Khaya grandifoliola* and *Tectona grandis* in pure stands

K. grandifoliola and *T. grandis* significantly varied in total height (P = 0.000) and merchantable height growth (P = 0.000). *T. grandis* presented higher values for total height (8.22 m) and merchantable height (5.38 m) (figure 4.5). *K. grandifoliola* had a lower basal area per tree compared to that of *T. grandis* (Table 4.1) and the values were significantly different statistically (P = 0.045). However, there was no significant difference between the two species with respect to basal area per hectare although *K. grandifoliola* recorded a value of 5.5 m^2/ha compared to *T. grandis* of 4.8 m^2/ha (Table 4.1). On the other hand, the total volume per hectare was also significantly higher for *T. grandis* than *K.grandifoliola* (P = 0.05).

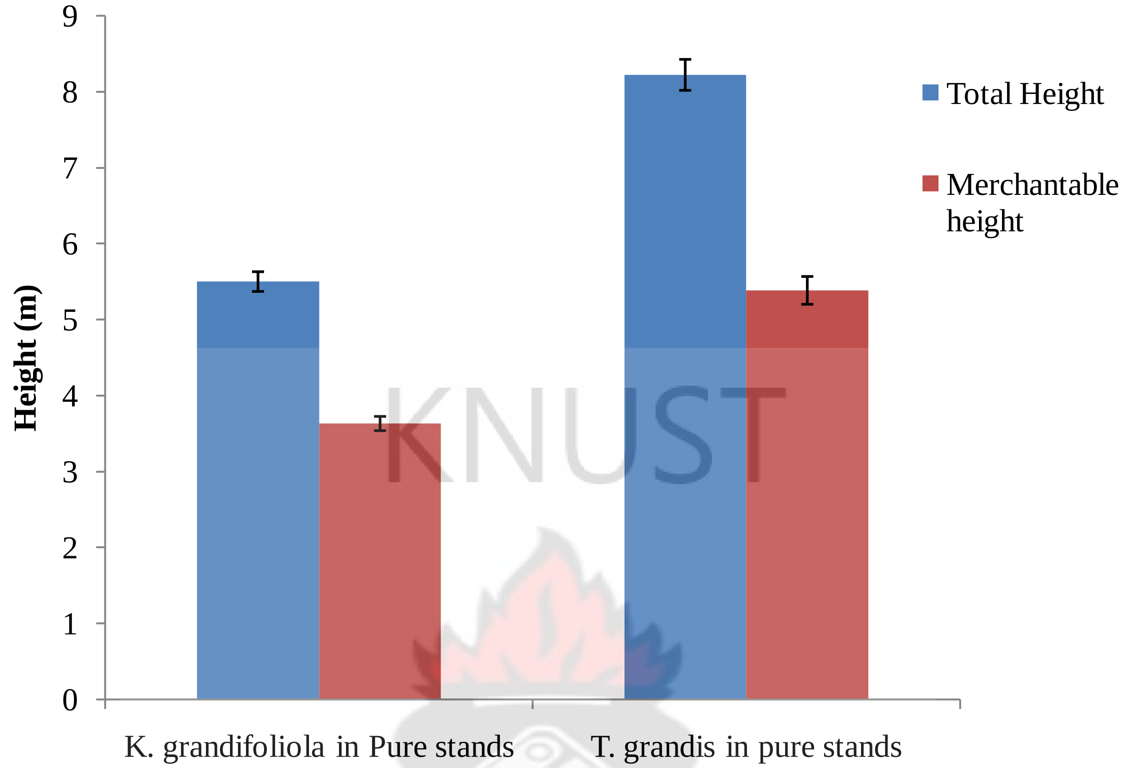


Figure 4.5. Mean total height and merchantable height of *Khaya grandifoliola* and *Tectona grandis* in pure stands.

4.4 Growth and productivity of tree species in the mixed stands at dry semi-deciduous forest zone

Cedrela which is an exotic species grew better than the two indegenous species (K. grandifoliola, C. odorata) planted in the mixed stand. Significant differences were observed among the tree species in mixed stands for the following growth variables; diameter at breast height and total height. *C. odorata* recorded the highest diameter value of 13.81 cm, followed by *T. superba* of 11.11 cm and *K. grandifoliola* of 9.15 cm (figure 4.6). The mean total height of *C. odorata* was 8.56 m, *T. superba* of 6.94 m and *K. grandifoliola* having the least of 5.50 m. For basal area per hectare, *C. odorata* recorded the highest value of 2.9 m^2/ha, *T. superba* of 2.0 m^2/ha and *K. grandifoliola* had 1.1 m^2/ha. Similarly, volume per hectare was highest in *C. odorata* with 12.9 m^3/ha, *T. superba* of 7.5 m^3/ha and *K. grandifoliola* 3.4 m^3/ha (Table 4.1).

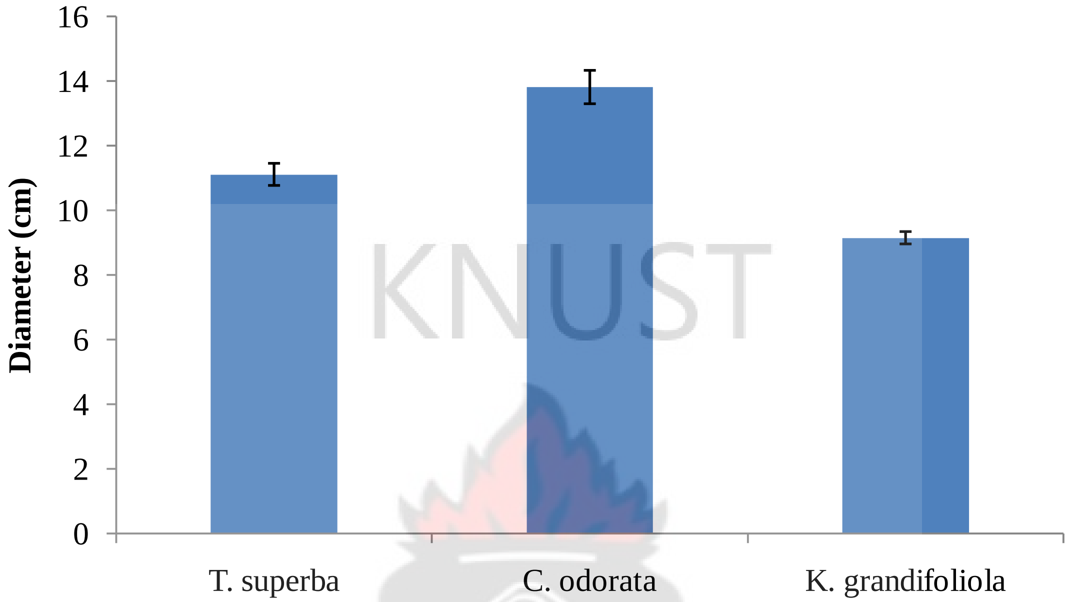


Figure 4.6. Mean diameter of companion species in mixed stands

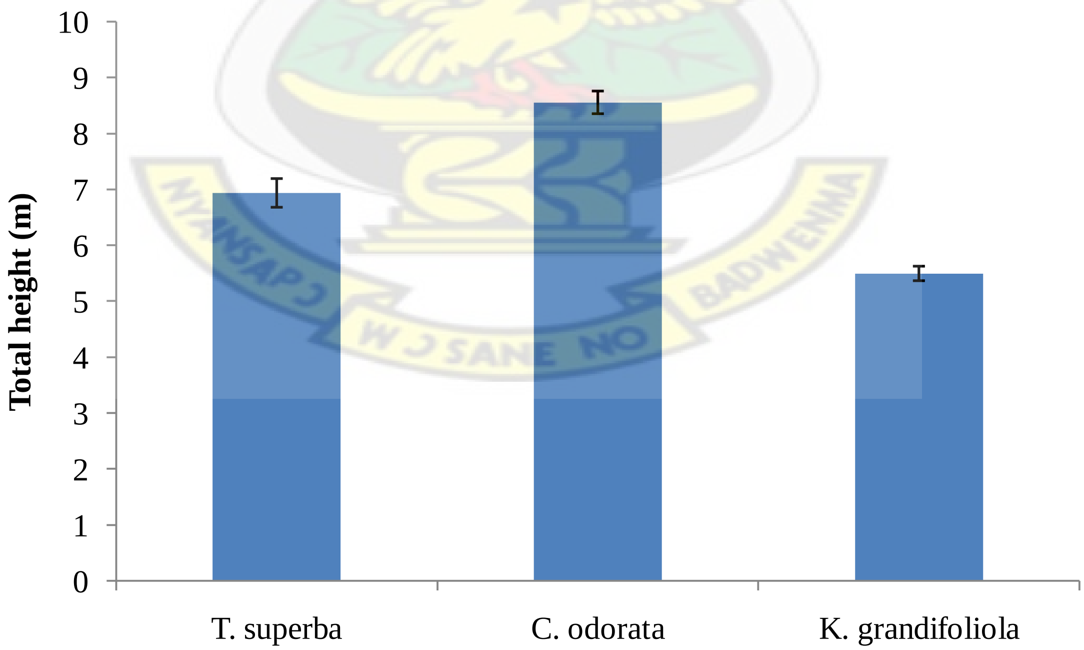


Figure 4.7. Mean total height of companion species in mixed stands

4.5 Aboveground biomass and Carbon sequestration

The results from the estimations of aboveground biomass and carbon sequestration showed that all equations used in the estimations produced higher aboveground biomass and consequently higher carbon sequestration per hectare for *K. grandifoliola* in pure than in mixed stands (Table 4.2). In addition the aboveground biomass and carbon sequestration per tree were statistically higher for *K. grandifoliola* in pure than mixed stands. Of all the equations used, equation **C** recorded the highest carbon sequestration for *K. grandifoliola* in both pure and mixed stands with equation equation **D** recording the lowest for both media (Table 4.2).

Table 4.2 Aboveground biomass and carbon sequestration estimations of *Khaya grandifoliola* in pure and in mixed stands in the dry semi-deciduous forest zone.

Allometry Models/ Equations	Species	Condition	Density (# trees/ha)	Aboveground Biomass (Kg/tree)	Aboveground Biomass (Kg/ha)	Storage Carbon (Kg/tree)	Storage Carbon (Kg/ha)
A	*K. grandifoliola*	Pure	756 ± 42	14.36 ± 0.65	10861 ± 597.6	7.18 ± 0.33	5430.4 ± 298.8
		Mixed	209 ± 36	9.93 ± 1.04	2078.4 ± 352.3	4.96 ± 0.52	1039.2 ± 176.2
B	*K. grandifoliola*	Pure	756 ± 42	26.78 ± 1.2	20252 ± 1114.4	13.39 ± 0.58	10126 ± 557.2
		Mixed	209 ± 36	18.88 ± 1.8	3953.1 ± 670.1	9.44 ± 0.92	1976.5 ± 335.1
C	*K. grandifoliola*	Pure	756 ± 42	38.77 ± 1.8	29323 ± 1613.5	19.40 ± 0.66	14661 ± 806.7
		Mixed	209 ± 36	26.51 ± 1.4	5549.8 ± 940.8	13.25 ± 1.45	2774.9 ± 470.4
D	*K. grandifoliola*	Pure	756 ± 42			4.45 ± 0.24	3363.8 ± 185.8
		Mixed	209 ± 36			3.07 ± 0.42	642.4 ± 108.9

Values are means and ± are standard errors.

* **A** is $Y = 0.005100\,(DBH)^{2.47}$

B is $Y = \exp[-1.996 + 2.32 \ln (DBH)]$

C is $Y = \exp[-2.28 + 2.649 * \ln (DBH) - 0.021 * (\ln (DBH))^2]$

D is C = Carbon concentration * Wood density * Volume

* Where Y is aboveground biomass, C is storage carbon and DBH is diameter at breast height.

Table 4.3 Aboveground biomass and carbon sequestration estimations of the companion species in the dry semi-deciduous forest zone.

Allometry Models/ Equations	Species	Condition	Density (#trees/ha)	Aboveground Biomass (Kg/tree)	Aboveground Biomass (Kg/ha)	Storage Carbon (Kg/tree)	Storage Carbon (Kg/ha)
B	*T. superba*	Mixed	197 ± 21	39.5 ± 2.7	7778.9 ± 815.9	19.7 ± 1.3	3889.5 ± 407.9
	C. odorata	Mixed	178 ± 14	67.3 ± 5.9	11999.8 ± 933.6	33.6 ± 2.9	5999.9 ± 466.8
C	*T. superba*	Mixed	197 ± 21	59.5 ± 4.4	11721.9 ± 1229.5	29.7 ± 2.2	5860.9 ± 614.8
	C. odorata	Mixed	178 ± 14	107.1 ±10.3	19082.9 ± 1484.7	53.5 ± 5.1	9541.4 ± 742.3

Values are means and ± are standard errors.

* **B** is Y= exp [-1.996 + 2.32 ln (DBH)

C is Y= exp [-2.28 + 2.649 * ln (DBH) - 0.021 * (ln (DBH))^2]

* Where Y is aboveground biomass, C is storage carbon and DBH is diameter at breast height.

The values of aboveground biomass and carbon sequestration per tree of *T. grandis* were significantly higher than *K. grandifoliola* in pure stands. However, the values of these variables per hectare were not significantly different between the two species although *T. grandis* recorded higher values for aboveground biomass and carbon sequestration per hectare than *K. grandifoliola* (Table 4.4).

Table 4.4 Aboveground biomass and carbon sequestration estimations of *Khaya grandifoliola* and *Tectona grandis* species in the dry semi-deciduous forest zone.

Species	Density (#tree/ha)	Aboveground biomass (Kg/tree)	Aboveground biomass (Kg/ha)	Carbon Storage (Kg/tree)	Carbon Storage (Kg/ha)
K. grandifoliola	756 ± 42	26.7 ± 1.2[a]	20252 ± 1114.3[a]	13.39 ± 0.5[a]	10126 ±557.2[a]
T. grandis	584 ± 43	40.9 ± 2.3[b]	23905 ± 1763.6[a]	20.45 ± 1.2[b]	11953 ±881.8[a]

Values are means and ± standard errors

Means along the column with the same letter are not significantly different.

* Y= exp [-1.996 + 2.32 ln (DBH)] was used for aboveground biomass estimation for *K. grandifoliola*

* Y = 0.153 • (DBH) $^{2.382}$ was used for aboveground biomass estimation for *T.grandis*.

Where Y is aboveground, DBH is diameter at breast height.

Table 4.5 Summary of carbon sequestration estimates for tree species in pure and in mixed stands in the dry semi-deciduous forest zone

Species	Condition	Carbon storage (Kg/ha)
K. grandifoliola	Pure	10126 ± 557.2[a]
	Mixed	1976.5 ± 335.1[b]
C. odorata	Mixed	5999.9 ± 466.8[c]
T. superb	Mixed	3889.5 ± 407.9[d]
Mix of the three species		11929.3 ± 401.3[a]
T. grandis	Pure	11953 ± 881.8[a]

Values are means and ± are standard errors.
Means along the column with the same letter are not significantly different.

* Y= exp [-1.996 + 2.32 ln (DBH) was used for aboveground biomass estimation for *K. grandifoliola, C. odorata and T. superba* and mix of the three species

* $Y = 0.153 \cdot (DBH)^{2.382}$ was used for aboveground biomass estimations for *T.grandis*

CHAPTER FIVE

5.0 DISCUSSION

5.1 Growth and productivity of *Khaya grandifoliola* in pure and in mixed stands

Several studies have shown that mixed plantations can be highly productive compared to monoculture plantations (Nadrowski *et al*., 2010; Potvin and Dutilleul, 2009; Potvin and Gotelli, 2008; Bristow *et al*., 2006a; Erskine *et al*, 2006; Forrester *et al*., 2005; Debell *et al*., 1997; Binkley *et al*., 1992). The many ecological benefits provided by mixed-species plantations according to Piotto (2008); Lamb *et al*., (2005); Kaye *et al*., (2000); Montagnini and Porras (1998) are not questionable but the fact that they achieve greater growth and productivity has been queried (Firn *et al*., 2007; Wormald, 1992).

In studying the performance of *K. grandifoliola* in pure and in mixed stands, *K. grandifoliola* did not show any differences in total height and merchantable height growth in pure and in mixed stands. The results are similar to those obtained by Parrotta (1999) and Khanna (1997), in monocultures and mixed plantations of *Eucalptus* and *Acaci*a, and Hansen and Dawson (1982) in monocultures and mixed plantations of poplar species and *Alus glotinosa*.

The higher *K. grandifoliola* diameter growth, basal area and total volume observed in pure stands suggest better performance in pure stands compared to that in mixed stands. The results seem to differ from several other studies which reported better growth in mixtures than monoculture stands (Potvin and Dutilleul, 2009; Binkely *et al*., 1992). However, it corresponds with other studies which suggested greater growth and productivity in some tree species planted in monocultures compared to mixtures. Results from Petit and Montagnini (1999) indicated that *Calophyllum brasiliense*, *Virola Koschnyi* and

Hyeronima alchorneoides significantly grew better in monocultures than in mixed plantations. Piotto *et al*., (2004) also emphasized that in the dry tropics of Costa Rica, *Tectona grandis* planted in monoculture was the most productive compared to planting in mixture with other species. *Araucana cunnighamii* planted in the humid tropics of Australia reported by Erskine *et al*., (2006) performed poorly in mixtures with average basal area and stand basal area 16% and 10% lower respectively, than in monoculture stands. Thus the concept of productivity of tree species in mixed stand or pure stand may be species specific.

Competition for resources in pure and in mixed stands is a major factor that affects growth and productivity of trees in these stands which invariably could be less in pure stands and therefore, may have contributed to the better growth of *K. grandifoliola* in pure stands. Competition occurs when two or more plants interact such that one wields a negative effect in terms of growth or mortality on the other (Furuta and Aloo, 2009; Boyden *et al*., 2005; Callaway, *et al*., 2002; Meiners and Handel, 2000; Hooper, 1998). Forrester *et al*., (2004) stated that when inter-specific competition is greater, mixed stands will be less productive than monocultures. *K. grandifoliola* is a light demanding species (Hawthorne, 1993), and therefore inter-specific competition between *K. grandifolila* and companion species in the mixed species plots for particularly light and other resources may have reduced growth (Potvin and Dutielleul, 2009; Petit and Montagnini, 2006). Moreover as morphological and physiological similarities of *K. grandifoliola* and the companion trees increase, competition between *K. grandifoliola* and companion trees intensifies (Hunt *et al*., 2006), which may eventually reduce growth and productivity (Boyden *et al*., 2008) of *K. grandifoliola* in mixed stands.

By this result, *Khaya grandifoliola* may not compete favourably when combined with these fast-growing species (*C. odorata and T. superba*), and the notable differences in growth may discourage its use in such mixtures. However the less *Hypsypyla* attack on *K. grandifoliola* in the mixed stand could lead to better tree form and may compensate for reduction in growth as mahoganies are known to be better tolerant to *Hypsipyla* in mixed stands. *K. grandifoliola* may have been suppressed under the canopy of *C. odorata and T. superba* since these species grew taller than *K. grandifoliola*. It may therefore be necessary to test this species in combination with other slower-growing species and nitrogen fixing species which may be more compatible with *K. grandifoliola*.

5.2 Tolerance to *Hypsipyla* (Mahogany shoot borer) by *Khaya grandifoliola* in pure and mixed stands

In plantations, *K. grandifoliola* may suffer seriously from *Hypsipyla robusta*, shoot borers that kill the main stem of young trees, causing excessive branching and contributing to mortality (Opuni-Frimpong, 2008). While monocultures are perceived to be prone to pest attack, mixed planting on the other hand have been suggested as silvicultural technique that can reduce damage by shoot borers (Speight and Cory, 2001; Floyd and Hauxweell, 2001; Griffiths *et al*., 2005).

This study revealed that *K. grandifoliola* produced higher number of total shoots in response to *Hypsipyla* attack in pure stands than in mixed stands. The other variables like number of shoots attacked and number of dead shoots assessed in evaluating the effect of *Hypsipyla* attack on *K. grandifoliola* in pure and in mixed stands though had no significant differences between the two treatments, they were relatively higher in pure stands. On the contrary, the number of fresh attack was moderately higher in mixed stands than in pure stands.

Like other studies (Sobek *et al*., 2009; Jactel and Brokerhoff, 2007; Bosu *et al*., 2006; Jactel *et al*., 2006; Menalled *et al*., 1998) which reported lower damages by pests in mixed stands, *K. grandifoliola* seems more tolerable to *Hypsipyla* in mixed stands than in pure stands. Perhaps the principal reason for *K. grandifoliola* being tolerable to *Hypsipyla* in the mixed stands could be due to provision of shade by the companion trees. *Swietenia macrophylla* seedlings in a high light environment were found to be more susceptible to oviposition by *Hypsipyla*, and therefore to attack (Mahroof *et al*., 2002). Opuni-Frimpong *et al*. (2008) also found out that overhead canopy shade reduced the attack levels in *K. ivorensis* and *K. anthotheca*.

Again, the high tolerance to *Hypsipyla* by *K. grandifoliola* in mixed stands may be attributed to insect repellant characteristics of *C. odorata,* a companion tree. In studying the effect of insect repellent plants with *K. ivorensis* and its impact on growth and *Hypsipyla* shoot borer attack of the host species, Bosu and Nkrumah (2011) found that *C. odorata* appeared the most promising for reducing shoot borer damage to mahogany. Thus *C. odorata* could be serving as both repellent and shade tree in the mixed species stand, reducing *Hypsipyla* attack.

5.3 Growth and productivity of *Khaya grandifoliola* and *T. grandis* in pure stands.

There are many reasons for introducing exotic tree species throughout the world and their introduction has frequently been justified by their value in reclamation of disturbed areas, such as eroded lands (Zobel *et al*., 1987). However, despite their fast growing and numerous benefits of exotic species, indigenous species have been identified to have the potential to perform as well as or even better than most commonly used exotic species (Wagner *et al*., 2008; Lamb, 1998; Butterfield, 1995).

In this study, we compared the growth and productivity of *K. grandifoliola* to *T. grandis* in pure stands. The results showed no significant difference between the two species in diameter growth. This finding differs from other studies that compare *T. grandis* to *Dalbergia latifolia* (Thapa, 2004) also a tropical tree species. *K. grandifoliola* could be said to grow as fast as *T. grandis* with respect to diameter at their early stage. However, *T. grandis* had greater total height and merchantable height than *K. grandifoliola*. *K. grandifoliola* had a smaller basal per tree compare to that of *T.grandis* but the basal area per hectare of *T.grandis* however, was not significantly different from that of *K. grandifoliola*. This lack of significant difference in basal area per hectare between the two species could be attributed to their respective tree diameter and density (number of trees per hectare) (Thapa and Guatam, 2011). *T. grandis* also had higher total volume than *K. grandifoliola.*

Hypsipyla shoot borers attack in the pure stands of *K. grandifoliola* may account for the lower values of diameter, total height and merchantable height and subsequently the lower total volume of *K. grandifoliola*. *Hypsipyla* attacks have been described to result in numerous secondary shoots and reduced growth, both of which affect the quality of timber produced (Wagner *et al*., 1991; Dupuy, 1995) by mahogany species. *T. grandis* on the other hand, is described to grow very well with little or no pest problems (Bosu and Apetorgbor, 2009). However, *T. grandis* may not remain 'immune' against pests indefinitely in this new environment but over time may become more susceptible to pests attack as native pests from country of origin may accidentally be introduced into this new environment through increased global trade (Bosu and Apetorgbor, 2009).

T. grandis from the results generally demonstrated better growth and productivity performance than *K. grandifoliola*. This observation is in agreement with other studies which reported better growth and productive of exotic tree species over indigenous species. In a study comparing the growth and survival of 13 native species in pure and mixed plantations to *T.grandis*, an exotic species, Piotto *et al*. (2004) found out that, pure plantations of *T.grandis* were the most productive compared to all species and mixture of species in two other plantations. Omer *et al*. (2004) also concluded that the overall performance of an exotic species (*Eucalyptus camaldulensis*) was better than other species.

5.4 Aboveground biomass and carbon sequestration.

5.4.1 *Khaya grandifoliola* in pure and mixed stands.

Plantations can be very important in sequestering carbon from the atmosphere (Hodgman and Munger, 2009; Kelty, 2006; Montagnini and Porras, 1998; Moura Costa, 1996). Both single and mixed species plantations have the potential to help forests maintain their contribution to carbon cycles (Hodgman and Munger, 2009; Siry *et al*., 2005). Inspite of the numerous services provided by plantations in tropical Africa including Ghana, only limited studies have evaluated services attributed to native tree plantations similar to observation made in Costa Rica in Central America (Stanley and Montagnini, 1999; Montagnini, 2000; Shepherd and Montagnini, 2001).

The findings from this study is in agreement with Redondo-Brenes and Montagnini (2006) that it is important to not only evaluate the productivity of native tree plantations in pure and mixed plantings, but also carbon sequestration as a part of the environmental services that plantations can provide. With high interest in the growing of trees for mitigation against climate change, we deem it necessary to compare the carbon sequestration of *K. grandifoliola* in pure and in mixed stands. *K. grandifoliola* produced higher values of carbon sequestration for pure stands than mixed stands for all the allometric equations used to estimate carbon stocks in the stands. *K. grandifoliola* in pure stands demonstrated better growth and productivity, consequently the higher value of carbon sequestration exhibited by *K. grandifoliola* in pure stands than in mixed stands. This result corresponds to the findings of Redondo-Brenes and Montagnini (2006) who reported that *C. brasiliense, V. koschnyi, V. ferruginea* and *B. elegans* performed best in pure plantations for carbon sequestration than in mixed stands.

It should be noted that, although, *K. grandifoliola* had better carbon sequestration in pure stands than in mixed stands, a hectare of the mixture of *K. grandifoliola, C. odorata and T. superba* yielded higher value of 11,929.39 Kg of carbon sequestered compare to 10,126 Kg for a hectare of pure *K. grandifoliola* stand. Even though carbon sequestration may be secondary objective of the plantation, the mixture of the tree species of different rotation ages is expected to allow the system to retain the carbon for longer periods of time than a monoculture. Thus mixed planting may contribute more to environmental service with respect to reducing carbon accumulation in the atmosphere.

5.4.2 *Khaya grandifoliola* and *Tectona grandis*

T.grandis had higher aboveground biomass and carbon sequestration per tree values than *K. grandifoliola* but the carbon sequestration per hectare showed no difference between the two species. According to the result, *T. grandis* as a fast-growing species accumulate biomass and carbon very fast in the early stage of its lifespan while *K. grandifoliola* with moderate to fast growing character on the other hand may accumulate more biomass and carbon in the long term as it tend to have a longer rotation cycle for harvesting.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This research provides information necessary for establishing monoculture and mixed plantations as it investigated the growth and productivity of *K. grandifoliola* in pure and in mixed stands as well as the tolerance to pests attacks by *K. grandifoliola* in the two stands and the environmental services provided by the plantations and its performance compare to an exotic tree species (*T. grandis*).

Overall, the study demonstrated that *K. grandifoliola* performed better in pure than in mixed stands. *K. grandifoliola* being a light demanding tree species and the fact that companion species may have cast shade over *K. grandifoliola*, shade was attributed as the major factor to have caused the poorer performance in *K. grandifoliola* in mixed stands. Inspite of poorer growth and productivity of *K.grandifoliola* in mixed stands, it should be noted that mixed-species plantations can often provide diversification of products as well as economic incentives (Lamb and Gilmour, 2003; Kanowski *et al*., 2005; Stanley and Montagnini, 1999) than pure plantations.

Like other available literature (Watt, 1994; Mayhew and Newton, 1998; Hauxwell *et al*., 2001a), the mixed stand was effective in reducing *Hypsipyla* attacks on *K. grandifoliola* compared to the pure stands of *K. grandifoliola*. The provision of shade by the companion species and the different genetic composition of the mixed stands may have made it difficult for mahogany shoot borer to attack *K. grandifoliola* in the mixed stands. However, as Whitmore (1976) suggested, the use of shade in mixed-species plantations must be balanced to reduce shoot borer damage without excessively suppressing tree growth.

In terms of carbon sequestration, *K. grandifoliola* was shown to sequester more carbon in pure stands than in mixed stands but the mixture of the three species accumulated more carbon as much as that of the pure stands of *K. grandifoliola*. A carbon investor therefore stands to gain more by establishing mixed-species plantations since mixed-species plantations in long-term will fix more carbon due to different rotation ages of trees. *T. grandis* also accumulated more carbon as much as that of *K. grandifoliola* in pure stand. Although *T. grandis* performed better than *K. grandifoliola* in pure stands at four years, it is essential to point out that *K. grandifoliola* stands to accumulate more carbon in the long term because it has longer gestation period. Thus in the era of carbon trade *K. grandifoloiola* could provide more revenues in the long term compare to *T. grandis* which tend to have shorter gestation period may only provide revenues only in the short term. Meanwhile, information also available (Bosu and Apetorgbor, 2009) indicates that *T. grandis* and other exotic species are increasingly becoming more susceptible to pests attacks and hence establishment of exotic species plantations may not be completely free of pest in the near future.

6.2. Recommendation

1. Further studies should be carried out to assess the growth and productivity of indigenous trees in pure and mixed stands in various forest zones of Ghana. In case *K. grandifoliola* is to be used in mixed stands, it should be grown with less light demanding and slow growing species that will enhance the growth of *K. grandifoliola* and the quality of wood it provides.

2. Mixed planting should be encouraged as pests management strategy for indigenous tree species especially the mahogany species. However, species to be used in mixtures should be chosen carefully and used in a manner that they do not retard the growth of each other.
3. More research should be carried out to ascertain which stand, that is pure or mixed plantation sequester more carbon in the various forest zones of Ghana
4. Also, since allometric models are species and environment specific, several studies should be undertaken to establish specific models for estimating carbon sequestration of particular species at their various forest or environmental zones.
5. It must be made clear that the carbon sequestration values estimated in this study have to be used with caution since several studies reported overestimation of carbon sequestration with the use of allometric equations (Losi *et al*., 2003).

REFERENCE

Ădjers, G., Hadengganan, S., Kunsipalo, J., Nuryanto, K., and Vesa, L. (1995) Enrichment Planting of Dipterocarps in Logged-over Secondary Forests: effect of width, direction and maintenance method of planting line on selected *Shorea* species. *Forest Ecology and Management*, 73: 259-270

Agyeman,V.K. (2004) Plantation Development in Ghana: policy, silviculture, institutional arrangement and funding mechanism *in* Cobbinah, J.R, Ofori, D.A and Bosu, P.P. (eds.).Pest Management in Tropical Plantations. International Workshop Proceedings, 21-23 July, 2004, pp. 17-31.

Alpert, P. (1993) Conserving biodiversity in Cameroon. Ambio 22(1): 44-49.

Amelia *et al* (2007) Strengthening Voices for Better Choices' Ghana Assessment Report in REDD in Ghana, an Independent Monitoring Report by Friends of Earth-Ghana.

Appiah, M. (2003) Domestication of an Indigenous Tropical Forest Tree: silvicultural and socio-economic studies on Iroko (*Milicia excelsa*) in Ghana. PhD Thesis, Faculty of Agriculture and Forestry, University of Helsinki, Unioninkatu, pp. 104.

Appiah, M., Blay, D., Damnyag, L., Dwomoh, F.K., Pappinen, A., and Luukkanen, O. (2009) Dependence on Forest Resources and Tropical Deforestation in Ghana. *Environ. Dev. Sustain.*, 11: 471-487.

Awung, W.J. (1998) Underlying Causes of Deforestation and Forest Degradation in Cameroon. Paper presented at the Underlying Causes Initiative Workshop, 26-30 Oct., Accra, Ghana.

Ball, J.B., Wormald, T.J., and Russo, L. (1995) Experience with mixed and single species plantations. *Common For. Rev.* 74: 301–305.

Benhin, J. K. A., and Barbier, E. B. (2004) Structural Adjustment Programme,Deforestation and Biodiversity Loss in Ghana.*Environmental and Resource Economics*, 27: 337-366 FC. Robert Bamfo, Forestry Commission of Ghana, Head of Climate Change Unit.

Binkley, D. (2005) How nitrogen-fixing trees change soil carbon. In: Binkley, D., Menyailo, O. (Eds.), Tree species effects on soils: implications for global change. Kluwer Academic Publishers, Dordrecht.

Binkley, D., Dunkin, K. A., DeBell, D., and Ryan, M. G. (1992) Production and Nutrient Cycling in Mixed Plantations of *Eucalyptus* and *Albizia* in Hawaii. *Forest Science*, 38:393-408.

Blay, D. (2004) Rehabilitation of Degraded Forests through the Collaboration of Local Communities in the Dormaa District of the Brong Ahafo Region of Ghana *in* Wood, P., Atse, M.Y. (eds.). *Rehabilitation of Degraded Lands in Sub-Saharan Africa: lessons learned from selected case studies*. FORNESSA and IUFRO-SPDC pp. 104.

Blay, D., Appiah, M, Damnyag, L., Dwomoh, F. K, Luukkanen, O., and Pappinen, A. (2008) Involving Local Farmers in Rehabilitation of Degraded Forests: some lessons from Ghana. *Environ. Dev. Sustain.,* 10: 503-518.

Blay, D., Dwomoh, F. K., and Damnyag, L. (2009) Assessment of Forest Degradation by Local Communities: The Case study of Ghana. Case Studies in Measuring and Assessing Forest Degradation. Forest Resources Assessment Program. *FAO Working Paper 160,* Rome 2009.

Bosu P. P., Adu-Bredu S., and Nkrumah E. E. (2004) Observations of insect pest activities within selected nurseries in Ashanti, Ghana. Pp 154–162 in Cobbinah JR, Ofori DA & Bosu PP (eds) *Pest Management in Tropical Plantations*. *International* Workshop *Proceedings.* 21–23 July 2004, Kumasi.

Bosu, P. P. and Nkrumah, E. E. (2011) Companion planting of insect repellent plants with *Khaya ivorensis* and its impact on growth and *Hypsipyla* shoot borer attack of the host species. Ghana Journal of Journal, Vol. 27 (2), 2011, 23-39.

Bosu, P. P., and Apetorgbor (2009) Rising Pest Problems in Forest Plantations in Ghana. Technical Note No. 2. Forestry Research Institute of Ghana – CSIR.

Bosu, P.P., Cobbinah, J. R., Nichols, J. D., Nkrumah, E. E., and Wagner, M. R. (2006) Survival and Growth of Mixed Plantations of *Milicia excelsa* and *Terminalia superba* 9 years after Planting in Ghana. *Forest Ecology and Management*, 233: 352-357.

Bowyer, J. L. (2001) Environmental Implications of Wood Production in Intensively Managed Plantations. *Wood and fiber science*, 33 (3): 318-333.

Boyden, S., Binkley, D., and Senock, R. (2005) Competition and Facilitation between *Eucalyptus* and Nitrogen-fixing *Falcataria* in Relation to Soil Fertility. *Ecology*, 86(4):992-1001.

Boyden, S., Binkley, D., and Stape, J. L. (2008) Competition among *Eucalyptus* Trees Depends on Genetic Variation and Resource Supply. *Ecology*, 89(10): 2850-2859.

Bragança, M. A. L., Zanuncio, J. C., Picanço, M., and Laranjeiro, A. J. (1998) Effects of Environmental Heterogeneity on Lepidoptera and Hymenoptera Populations in *Eucalyptus* Plantations in Brazil. *Forest Ecology and Management*, 103: 287-292.

Bristow, M., Vanclay, J., Brooks, L., and Hunt, M. (2006) Growth and Species Interactions of *Eucalyptus pellita* in a Mixed and Monoculture Plantation in the Humid Tropics of North Queensland. *Forest Ecology and Management*, 233: 285-294.

Bristow, M., Vanclay, J., Brooks, L., and Hunt, M. (2006b) Growth and species interactions of *Eucalyptus pellita* in a mixed and monoculture plantation in the humid tropics of north Queensland. Forest Ecology and Management 233, 285-294.

Brown, D., and Lugo, A. E. (1982) The storage and production of organic matter in tropical forests and their role in the role in the global carbon cycle. Biotropica 14, 161–187.

Brown, S. Gillespie, A. J. R. and Ludo, A. E. (1989) Biomass estimation methods for tropical forests with applications of forest inventory data. Forest science 35:88-902.

Brown, S., and Lugo, A.E. (1994) Rehabilitation of tropical lands: a key to sustaining development. Restor. Ecol. 2:97–111.

Butterfield, R. P. (1995) Promoting biodiversity: advances in evaluating native species for reforestation. *Forest Ecology and Management*, 75:111-121.

Butterfield, R. P. (1996) Early Species Selection for Tropical Reforestation: a consideration of stability. *Forest Ecology and Management*, 81: 161-168.

Butterfield, R. P., and Fisher, R. F. (1994) Untapped Potential: native species for reforestation. *J. For*. (6): 37-40.

Callaway, R. M., Brooker, R. W., Choker, P., Kikvidze, Z., Lortie, C., Michalet, R., Paolini, L., Pugnaire, F. L., Newingham, B., Aschehoung, E.T., Armas, C., Kikodze, D., and Cook, B. J. (2002). Positive Interactions among Alpine Plants Increase with Stress. *Nature*, 417: 844-848.

Cannell, M. G. R. (1999) Environmental Impacts of Forest Monocultures: water use, acidification, wildlife conservation and carbon storage. *New Forests*, 17: 239-262.

Carnevale, N. J., and Montagnini, F. (2002) Facilitating Regeneration of Secondary Forest with the Use of Mixed and Pure plantation of Indigenous Tree Species. *Forest Ecology and Management*, 163: 217-227.

Carrere R. Y., and Lohmann L. (1996) El Papel del Sur, Plantaciones Forestales en la Estrategia Papelera Internacional . Red mexicana de acción frente al libre Comercio (RMALC) e Instituto tercer Mundo. México DF 282 pp.

Castro E. (1999) Plantaciones de Monocultivos Forestales en la Zona Norte, Una Revisión Bibliográfica. Coecoceiba-Amigos de la Tierra, Costa Rica, San José, CR,57 pp.

Ciesla, W. M. (2001) Protecting Plantations from Pest and Diseases *in* Mead, D. J. (ed.). *Forest Plantation Thematic Papers. FAO Working Paper FP/10*, Rome 2001.

Codjoe, S. N. and Dzanku, F. M. (2009) Long-term Determinants of Deforestation in Ghana: the role of Structural Adjustment policies. *African Development Review*, 21(3): 558-588.

Cossalter, C., and Pye-Smith, C. (2003). Fast-Wood Forestry. Myths and Realities. Forest Perspective, pp. 47.

CSIR (2002) Country Report on Invasive Alien Species in Ghana: Removing Barriers to Invasive Plant Management in Africa. Council for Scientific and Industrial Research, Accra, Ghana, pp. 49-57. Cusack D, Montagnini F (2004). The role of native species plantations.

Cusack, D., and Montagnini, F. (2004) The role of native species Plantation in recovery of understory woody diversity in degraded Pasturelands of Costa Rica. *Forest Ecology and Management*, 188: 1-15.

Dadebo, M. A., and Shinohara, T. (1999) Forest Resource and Timber Production of Ghana: current instruments for sustainable development. *J. For. Res*. 4: 1-12.

Daily Graphic (2009) National Forest Plantation Development Plan in Offing. www.modernghana.com/news/247251/1/national-forest-plantation-development-plan-in-off.html. Accessed on 11/4/2009.

DeBell, D. S, Cole, T. G., and Whitesell, C. D. (1997) Growth, Development, and Yield in Pure and Mixed Stands of *Eucalyptus* and *Albizia*. *Forest Science*, 43(2): 286-298.

Dickinson, G. R., Leggate, W., Bristow, M., Nester, M., and Lewty, M. J. (2000) Thinning and pruning to maximise yields of high value timber products from tropical and sub-tropical hardwood plantations. In: Snell, A., Vize, S. (Eds.), Proceedings of the Australian Forest Growers biennial conference. Opportunities for the New Millennium. Australian Forest Growers, Cairns, Queensland, pp. 32-42.

Dixon, R. K., Perry, J. A., Vanderklein, E. L. and Hiol, F. (1996) 'Vulnerability of forest resources to global climate change: case study of Cameroon and Ghana', *Climate Res.* **12**, 127–133.

Donkor B. N. (1997) Stem wood structure of four Ghanaian *khaya* species.

Dunisch O., and Ruhmanm O. (2006) Kinetics of cell formation and growth stresses in the secondary xylem of *Swietenia mahogany* (L.) Jacq. And *Khaya ivorensis* A. Chev. (Meliaceae). Wood Sci Technol cuttings. New Forest 29:105-116.

Dupuy, B. (1995) Mixed plantations in Cote d'Ivoire rain forest. Bois et Forets des Tropiques 245, 33-43.

Elliot, G., and Pleydell, G. (1992) Report on marketing and utilization of plantation species. Report for the Government of Ghana under assignment from the DFID. Unpublished.

Entwistle, P. F. (1967) The current situation on shoot, fruit and collar borers of the Meliaceae, Proceedings of the 9th British Commonwealth Forestry Conference, Commonealth Forestry Institute, Oxford, UK, 15 PP.

Erskine, P.D., Lamb, D., and Bristow, M. (2006) Tree Species Diversity and Ecosystem Function: can tropical multi-species plantation generate greater productivity. *Forest Ecology and Management,* 233: 205-210.

European Union (EU) (2006) Country Environmental Profile of Ghana, *Final Report*, Framework Contract EuropeAid/119860/C/SV/Multi - Lot N°6: Environment.

Evans, J. (1992) Plantation Forestry in the Tropics. 2nd Edition.Oxford Science Publications.

Evans, J. (1999a) Planted Forests of the Wet and Dry tropics: their variety, nature and significance. *New Forests*, 17: 25-36.

Evans, J. (1999b) Sustainability of forest plantations: the evidence. In. Department for International Development, London, pp. 1-65.

Evans, J., and Turnbull, J. W., (2004) Plantation Forestry in the Tropics, 3rd ed. Oxford University Press, Oxford, 467 pp.

FAO (1993) Timber Plantations in the Humid Tropics of Africa. *FAO Forestry Paper 98*, Rome 1993.

FAO (1995) *Forest resources assessment 1990: tropical forest plantation resources*, by D. Pandey. FAO Forestry Paper No. 128. Rome.

FAO (2001) Global Forest Resources Assessment 2000.Main Report.FAO Forestry Paper140, Food and Agriculture Organization of the United Nations, Rome, 479 pp.

FAO (2006) Global Forest Resources Assessment 2005. Progress towards Sustainable Forest Management. *FAO Forestry Paper 147*, Rome 2006.

FAO (2007) Forest and Water Forests and water, FAO, Unasylva No. 229 Vol. 58, 2007/4, Rome, 2007.

FAO, (2010) Global Resources Assessment 2010.Country Report, Ghana. *FRA 2010/077*, Rome 2010.

FAONewsroom (2006) Forests and Climate change. Food and Agriculture Organization of United Nations, helping to build a world without hunger.

Feyera, S., Beck, E., and Lüttge, U. (2002) Exotic Trees as Nurse-trees for the Regeneration of Natural Tropical Forests. *Trees,* 16: 245-249.

Firn, J., Erskine, P.D., and Lamb, D. (2007) Woody Species Diversity Influences Productivity and Soil Nutrient Availability in Tropical Plantations. *Oecologia*, 154(3):521-533.

Florence, R.G. (1996) Ecology and silviculture of eucalypt forests. CSIRO Publishing, Melbourne.

Floyd, R., and Hauxwell, C. (2001) In: Proceedings of an International Workshop on Hypsipyla Shoot Borers OF the Meliaceae at Kandy. Sri Lanka, August 20-23, 1996. Australian Centre for International Agricultural Research, Canberra, Australia.

Foli,E., Agyeman, V.K., and Pentsil, M. (2009) Ensuring Sustainable Timber Supply in Ghana: a case for plantations of indigenous timber species. Forestry Research Institute of Ghana, Technical Note No. 1, pp. 15.

Forrester, D. I., Bauhus, J., Cowie, A., and Vanclay, J. K. (2006b) Mixed-species plantations of Eucalyptus with nitrogen fixing trees: a review. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.012.

Forrester, D.I., Bauhus, J., and Cowie, A.L., (2005) On the success and failure of mixed-species tree plantations: lessons learned from a model system of Eucalyptus globulus and Acacia mearnsii. For. Ecol. Manage. 209, 147–155.

Forrester, D. I., Bauhus, J., Cowie, A. L., and Vanclay, J. K. (2006a) Mixed-species Plantations of *Eucalyptus* with Nitrogen-fixing Trees: a review. *Forest Ecology and Management*, 233: 211-230.

Forrester, D. I., Bauhus, J., and Khanna, P. K. (2004) Growth Dynamics in a Mixed-species Plantation of *Eucalyptus globulus* and *Acacia mearnsii*. *Forest Ecology and Management*, 193: 81-95.

Furuta, K., and Aloo, I. K. (2009) Between-tree Distance and Spread of the Sakhalin Fir Aphid (*Cinara todocola* Inouye) (Hom. Aphididae) within a Plantation. *Journal of Applied Entomology*, 117(1-5): 64-71.

Gadgil, P. D., and Bain, J. (1999) Vulnerability of Planted Forests to Biotic and Abiotic Disturbances. *New Forests,* 17: 227-238.

Glantz M. H., and Katz, R. W. (1985) On the economic and societal value of long-range weather prediction. *Proceedings of the Symposium on Current Problems of Medium- and Long-Range Weather Forecasts*, Budapest, Hungary, pp. 17–20.

Griffiths, M. W., Cunningham, S. A., Wylie, E. R., and Floyd, R. B. (2005) Perspectives on the management of *Hypsiplya robusta* in the Asia Pacific region. Int. Forest. Rev. 75 (5), 276.

Gupta, S., Porwal, M. C., and Roy, P. S. (2004) Human Modification of the Tropical Rain Forest of Nicobar Islands: Indicators from Land Use Land cover Mapping. *J. Hum. Ecol.,* 16 (3): 163-171.

Haggar, J. P., Briscoe, C. B., and Butterfly, R. P. (1998) Native Species: a resource for the diversification of forestry production in the lowland humid tropics. *Forest Ecology and Management,* 106:195-203.

Hall J. B., and Swaine M. D. (1976) Classification and Ecology of Closed-Canopy Forest in Ghana. J. Ecol., 64(3): 913-951.

Hall J. B., Swaine M. D. (1981) Distribution and ecology of vascular plants in a tropical rain forest: forest vegetation in Ghana. The Hague. W Junk Publishers. Hague, Netherlands, p. 383.

Hansen E. A., and Dawson J. O. (1982) Effect of Alnus glutinosa on hybrid poplar height growth in a shortrotation intensively cultured plantations. For. Sci., 28(1): 49-59.

Hansen, A. J., McComb W. C., Vega R., Raphael M. G., and Hunter M. (1995) Bird habitat relationships in natural and managed forests in the west cascades of Oregon. Ecological Applications 5:555-569.

Hartley, M. J. (2002) Rationale and Methods for Conserving Biodiversity in Plantation Forests. *Forests Ecology and Management,* 155: 81-95.

Hauxwell, C., Mayhew, J., and Newton, A. (2001a) Silvicultural management of *Hypsipyla*. In Hypsipyla *Shoot Borers in Meliaceae. ACIAR Proceedings No. 97*, eds. R.B. Floyd and C. Hauxwell, pp. 151–163. ACIAR, Canberra, Australia.

Hauxwell, C., Vargas, C., and Opuni-Frimpong, E. (2001b). Entomopathogens for control of *Hypsipyla*. In Hypsipyla *Shoot Borers in Meliaceae. ACIAR Proceedings No. 97*, eds. R.B. Floyd and C. Hauxwell, pp. 131–139. ACIAR, Canberra, Australia.

Hawthorne, W D. (1993) Forest regeneration after logging: findings of a study in the Bia South Game Production Reserve, Ghana. ODA Forestry Series No. 3, Natural Resources Institute, Chattham Maritime, London.

Hawthorne, W D. (1995) Ecological profiles of Ghanaian forest trees, tropical forestry papers- Abingdon, UK: Nuffield Press.

Hawthorne, W. (1998) *Khaya grandifoliola*. (2006) IUCN Red List of Threatened Species.

Hawthorne, W. D., and Abu-Juam, M. (1993) Forest Protection in Ghana. IUCN, Gland, Switzerland and Cambridge, UK. Xvii + pp. 203.

Hawthorne, W. D., and Abu- Juam M. (1995) Forest protection in Ghana. IUCN Gland, Switzerland and Cambridge, UK.

Hodgman, T., and Munger, J. (2009) Managing Afforestation and Reforestation Projects for Carbon Sequestration for Land managers and Policymakers *in* Tyrrell, M. L., Ashton, M. S., Spalding, D., Gentry, B. (eds.). *Forests and Carbon. A Synthesis of Science, Management, and Policy for Carbon Sequestration in Forests*. pp. 313-346.

Hooper, D. U., Chapin, F. S., Ewel., J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A. J., and Vandermeer, J., Wardle, D .A. (2005) Effects of Biodiversity on Ecosystem Functioning: a consensus of current knowledge. *Ecological Monograph*, 73: 3-35.

Hosking, G. P. (1983) Forestry Pest Problems of the South Pacific-the price of progress. *N. Z Journal of Forestry*, 185-192. humid tropics of Costa Rica. For. Ecol. Manage. 113, 91–113.

Hunt, M. A., Battaglia, M., Davidson, N. J. and Unwin, G. L. (2006) Competition between Plantation *Eucalyptus nitens* and *Acacia dealbata* Weeds in Northeastern Tasmania. *Forest Ecology and Management*, 233: 260-274.

International Tropical Timber Organization (2002) ITTO guidelines for the restoration management and rehabilitation of degraded and secondary tropical forests. ITTO Policy Development Series No 13, ITTO, Yokohama, Japan.

IPCC (2007) IPCC Fourth Assessment Report, Working Group I Report "The Physical Science Basis", Section 7.3.3.1.5 (p. 527).

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman J., Galbally M., Hiraishi T., Krug T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K and Wagner F. (Eds). *IPCC National Greenhouse Gas Inventories Programme*. IPCC/OECD/IEA/IGES, Hayama, Japan.

Irvine, F. R. (1961) Woody plants of Ghana. Oxford University Press, London, pp 868.

IUCN (1992) Protected Areas of the World: A review of national systems. Volume 3: Afrotropical. Prepared by the UNEP World Conservation Monitoring Centre (UNEP-WCMC). IUCN, Gland, Switzerland and Cambridge, UK.

IUCN, (2004) IUCN Red List of Threatened Species. Available from http://www.redlist.org.

Jactel, H., Brockerhoff, E. G. (2007) Tree Diversity Reduces Herbivory by Forest Insects. *Ecology letters*, 10: 835-848.

Jactel, H., Menassieu, P., Vetillard, F., Ganlier, A., Samalens, J. C., Brockerhoff, E. G. Jose, S., Williams, R., and Zamora, D. (2006) Belowground ecological interacions in mixed- species forest plantations. Forest Ecology and Management 233, 231-239.

Jose, S., Williams, R., Zamora, D. (2006) Belowground Ecological Interactions in Mixed-species Forest Plantations. *Forest Ecology and Management*, 233: 231-239

Kanowski, J., Catterall, C. P., and Wardell-Johnson, G. W. (2005) Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. For. Ecol. Manage. 208, 359–372.

Kaye, J. P., Resch, S. C., Kaye, M. W., and Chimmer, R. A. (2000) Nutrient and Carbon Dynamics in a Replacement Series of *Eucalyptus* and *Albizia* Trees. *Ecology*, 81: 3267-3273.

Keefe, K., Schulze, M. D., Pinheiro, C., Zweede, J. C., and Zarin, D. (2009) Enrichment Planting as a Silvicultural Option in the Eastern Amazon: Case study of Fazenda Cauaxi. *Forest Ecology and Management*, 258: 1950-1959.

Keenan, R. J., Lamb, D., and Sexton, G. (1995) Experience with mixed species rainforest plantations in north Queensland. Commonwealth Forestry Review 74, 315 – 321.

Kelty, M. (2006) The Role of Species Mixtures in Plantation Forestry. *Forest Ecology and Management*, 233: 195-204.

Khanna P. K. (1997) Comparison of growth and nutrition of young monocultures and mixed stands of Eucalyptus globules and Acacia mearnsii. For. Ecol. Manage., 94(1-3): 105-113.

Kohli, R. K., Singh, H. P., and Rani, D. (1996) Status of Floor Vegetation under Some Monoculture and Mixculture Plantations in North India. *Journal of Forest Research*,1(4): 205-209.

Kotey, E. N. A., Francois, J., Owusu, J. G. K., Yeboah, R., Amanor, K. S., and Antwi, L. (1998) Falling into Place. Policy that Works for Forests and People. Series No.4. International Institute of Environment and Development, London.

Krishnapillay, D. B (1998) A case study of the tropical forest plantations of Malaysia: Case Study for Project Timber Production from Hardwood Plantations in the Tropics and Sub-tropics: FAO GCP/INT/628/UK (*unpublished*). 58 pp.

Kwok, H. K., and Corlett, R. T. (2000) The Bird Communities of a Natural Secondary Forest and a *Lophostemon confertus* Plantation in Hong Kong, South China. *Forest Ecology and Management,* 130: 227-234.

Lamb, D. (1998) Large-Scale Ecological Restoration of Degraded tropical Forest Lands: the potential role of timber plantation. *Restoration Ecology*, 6(3): 271-279.

Lamb, D., Erskine, P., and Parrotta, J. A. (2005) Restoration of degraded tropical and forest landscapes. Science 310, 1628-1632.

Lamb, D., and Gilmour, D. (2003) Rehabilitation and restoration of degraded lands. Issues in forest conservation. IUCN-WWF, Gland, Switzerland and Cambridge, UK, p. 110.

Lamb, D., and Lawrence, P. (1993) Mixed species plantations using high value rainforest trees in Australia. In: Leith, H., Lohmann, M. (Eds.), Restoration of Tropical Forest Ecosystems. Kluwer Academic Publishers, Netherlands, pp. 101-108.

Lamprecht, H. (1989) Silviculture in the tropics. TZ-Verlagsgesellschaft mbH, Rossdorf, 296 pp. Lands in the Brazilian Amazon. *Restoration Ecology*, 7(2): 103-116.

Larsson, P. (2003) Tree Plantations as Cost-effective Tool for Reforestation of Abandoned Pastures in Amazonian Ecuador. Msc Thesis, Department of Botany, Stockholm University, S-106 91. pp. 22.

Losi, J., Siccama, T., Condit, R., and Morales, J. (2003) Analysis of alternative methods for estimating carbon stock in your plantations. For. Ecol. Manage. 184, 355-368. lowland. For. Ecol. Manage. 134, 257–270.

Lugo, A.E. (1997) The Apparent Paradox of Re-establishing Species Richness on Degraded lands with Tree Monocultures. *Forest ecology and management,* 99: 9 - 19.

Mahroof, R. M., Hauxwell, C., Edirisinghe, J. P., Watt, A. D., and Newton, A. C. (2002) Effects of artificial shade on attack by the mahogany shoot borer, Hypsipyla robusta (Moore). Agric. For. Entomol. 4, 283-292.

Mayhew, J. E. and Newton, A. C. (1998) The silviculture of mahogany. CABI Publishing, Wallingford, UK. 226 pp.

Mbuya L. P. , Msanga, H. P., Ruffo C. K., Birnie A., and Tengnas B. (1994) Useful trees and shrubs for Tanzania: Identification, Propagation and Management for Agricultural and Pastoral Communities. Regional Soil Conservation Unit (RSCU), Swedish International Development Authority (SIDA).

McComb, W., T. Spies, and Emmingham. W (1993) Douglas-fir forests: managing for timber and wildlife habitats. Journal of Forestry 91(2), 31-42.

McNamara, S., Tinh, D.V., Erskine, P.D., Lamb, D., Yates, D., and Brown, S. (2006) Rehabilitating Degraded lands in Central Vietnam with Mixed Native Species. *Forest Ecology and Management*, 233: 358-36.

Menalled, F.D., Kelty, M.J., and Ewel, J.J. (1998) Canopy Development in Tropical Tree Plantations: a comparison of species mixtures and monocultures. *Forest Ecology and Management*, 104: 249-263

Meiners, S.J., and Handel, S.N. (2000) Additive and Nonadditive Effects of Herbivory and Competition on Tree Seedling Mortality, Growth, and Allocation. *American Journal of Botany*, 87(12): 1821-1826.

Michon G., P.Levang, and F. Verdeaux (2007) Domestic forests: a new paradigm for integrating local communities' forestry into tropical forest science .Ecology and Society 12(1), 1.

Ministry of Lands and Forestry (MLF) (1996) Forestry Development Master Plan for Ghana 1996-2000.

Montagnini F., and Porras, C. (1998) Evaluating the Role of Plantation as carbon sinks: an example of an integrative approach from the humid tropics. *Environmental Management*, 22(3): 459-470.

Montagnini, F. (2000) Accumulation in above-ground biomass and soil storage.

Montagnini, F., Gonzalez, E., Porras, C., and Rheingans, R. (1995) Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest damage and establishment costs. Commonwealth Forestry Review 74, 306-314.

Montagnini. F. (2001) Strategies for the Recovery of Degraded Ecosystems: experience from Latin America. *INCI*, 26(10): 498-503.

Montagu, K.D., Kearney, D.E., and Smith, R.G.B. (2003) The biology and silviculture of pruning planted eucalypts for clear wood production—a review. Forest Ecology and Management 179, 1-13.

Moura Costa, P. (1996) Tropical Practices for Carbon Sequestration: a review and case study from southeast Asia. *Ambio*, 25(4): 279-283.

Nadrowski, K., Wirth, C., and Scherer-Lorenzen, M. (2010) Is Forest Diversity Driving Ecosystem Fucntion and Services? *Current Opinion in Environmental Sustainability*, 2:75-79.

Newbould, P.J., (1967) Methods for Estimating the Primary Production of Forest. IBP Handbook 2. Blackwell Scientific, Oxford, UK, p. 62.

Newton, A.C., P. Baker, S. Ramnarine, J.F. Mesen, and R.R.B. Leakey (1993) The mahogany shoot borer: prospects for control. Forest Ecology and Management 57,301-328.

Nichols, J. D, Bristow, M., Vanclay, J.K. (2006) Mixed-species Plantations: prospects and challenges. *Forest Ecology and Management*, 233: 383-390.

Nichols, J. D., Ofori, D. A., Wagner, M. R., Bosu, P., and Cobbinah, J. R. (1999) Survival, growth and gall formation by *Phytolyma lata* on *Milicia excelsa* established in mixed-species tropical plantations in Ghana. Agricultural and Forest Entomology 1, 137-141.

Nichols, J. D., Rosemeyer, M. E., Carpenter, F. L., and Kettler, J. (2001) Intercropping legume trees with native timber trees rapidly restores cover to eroded tropical pasture without fertilisation. Forest Ecology and Management 152, 195-209.

O'Loughlin, C. (1995) The Sustainability Paradox- a examination of *The Plantation Effect*- a review of the environmental effects of plantation forestry in New Zealand. *N.Z. Forestry*, pp. 3-8.

Odoom, F.K. (2002) Hardwood Plantations in Ghana *in* Varmola, M. (ed.). *Forest Plantations Working Papers. FAO Working Paper FP/24*, Rome 2002. of mineral nutrients in pure and mixed plantations in a humid tropical.

Omer, R. M., Faisal C. M., Ahmed W., Rashid C. A., Rahim A. and Ali Z. (2004) Choice of exotic and indigenous tree species for planting on farmlands. *Pak. J Agri. Sci, Vol.* 41(1-2).

Opuni-Frimpong, E. (2008) *Khaya grandifoliola* C.DC. In: Louppe, D., Oteng-Amoako, A.A. & Brink, M. (Editors). Prota 7(1): Timbers/Bois d'œuvre 1. [CD-Rom]. PROTA, Wageningen, Netherlands.

Opuni-Frimpong, E., Karnosky, D. F., Storer, A., and Cobbinah, J. R. (2004) Conserving African Mahogany Diversity: provenance selection and silvicultural systems to develop shoot borer tolerant trees *in* Cobbinah, J.R., Ofori, D.A., Bosu, P.P. (eds.). *Pest Management in Tropical Plantations*. International Workshop Proceedings, 21- 23 July, 2004, pp. 71-84.

Opuni-Frimpong, E., Karnosky, D. F., Storer, A. J., and Cobbinah, J. R. (2008) Silvicultural Systems for Plantation Mahogany in Africa: influences of canopy shade on tree growth and pest damage. *Forest Ecology and Management,* 255: 328-333.

Palo, M., and Yirdaw, E. (1996) Deforestation and Sustainable Forestry Challenge in Ghana in Palo, M., Mery, G. (eds.), Sustainable Forestry Challenges for Developing Countries. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 343-357.

Pandey, D. (1997) Tropical forest plantation areas 1995 Output of Project Hardwood Plantations in the Tropics and Sub-tropics: FAO GCP/INT/628/UK (*unpublished*). 61 pp.

Parrotta J. A. (1999) Productivity, nutrient cycling, and succession in single- and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta,* and *Leucaena leucocephala* in Puerto Rico. For. Ecol. Manage., 124(1): 45-77.

Parrotta, J. A. (1992) The Role of Plantation Forests in Rehabilitating Degraded Tropical Ecosystems. *Agriculture, Ecosystems and Environment*, 41:115-133.

Parrotta, J. A., Knowles, O. H. (1999) Restoration of Tropical Moist Forest on Bauxitemined.

Parrotta, J. A., Turnbull, J. W., and Jones, N. (1997) Catalyzing Native Forest Regeneration on Degraded Tropical Lands. *Forest Ecology and Management,* 99: 1-7.

Petit, B., and Montagnini, F. (2006) Growth in Pure and Mixed Plantations of Tree Species Used in Reforesting Rural Areas of the Humid Region of Costa Rica, Central America. *Forest Ecology and Management*, 233: 338-343.

Piotto, D. (2008) A Meta-analysis Comparing Tree Growth in Monocultures and Mixed Plantation. *Forests Ecology and Management,* 225: 781-786.

Piotto, D., Montagnini, F., Ugalde, L., and Kanninen, M. (2003a) Growth and effects of thinning of mixed and pure plantations with native trees in humid tropical Costa Rica. For. Ecol. Manage. 177, 427–439.

Piotto,D., Viquez, E., Montagnini, F., and Kanninen, M. (2004) Pure and mixed forest plantations with native species of the dry tropics of Costa Rica: a comparison of growth and productivity. For. Ecol. Manage. 190, 359–372.

Potvin, C., and Dutilleul, P. (2009) Neighborhood Effects and Size-asymmetric Competition in a Plantation Varying in Diversity. *Ecology*, 90(2): 321-327.

Potvin, C., and Gotelli, N. J. (2008) Biodiversity Enhances Individual Performances But Does Not Affect Survivorship in Tropical Trees. *Ecology letters*, 11:217-223.

Powers, R. F. (1999) On the Sustainable Production of Planted Forests. *New Forests,*17: 263-306.

Raymond, K. M. (1996) A Consortium Support Model for greatly increasing the contribution of quality tropical hardwood plantations to sustainable development. The Amazon Teak Foundation. Teak 2000. Amsterdam. The Netherlands. Reafforestation with Eucalypts and Indigenous Species: a case study in southern China. Forest Ecology and Management, 167: 209-222.

Redondo-Brenes, A., and Montagnini, F. (2006) Growth, Porductivity, Aboveground Biomass, and Carbon sequestration of Pure and Mixed Native Tree Plantations in the Caribbean Lowlands of Costa Rica. *Forest Ecology and Management*, 232(1-3): 168-178.

Reid, R. (2006) Diameter-basal area ratio as a practical stand density measure for pruned plantations. Forest Ecology and Management 233, 375-382. relationships in natural and managed forests in the West Cascades of Oregon. Ecological Applications 5(3), 555-569.

Rice, T. and Counsell S. (1993) Forests Foregone : The European Community's Trade in Tropical Timbers and the Destruction of the Rainforests. Friends of the Earth. London 214 p.

Rosoman, G. (1994) The Plantation Effect-an ecoforestry review of the environmental effects of exotic monoculture tree plantation in Aotearoa / New Zealand, Greenpeace New Zealand, pp. 58.

Roy, P. S., Dutti, C. B. S., and Joshi, P. K. (2002) Tropical Forests Resource Assessment and Monitoring. *Tropical Ecology*, 43 (1):21-37.

Sayer, J., Chokkalingam, U., and Poulsen, J. (2004) The Restoration of Forest Biodiversity and Ecological Values. *Forest Ecology and Management*, 201: 3-11.

Schroeder, P. (1992). Carbon storage potential of short rotation tropical tree plantations. For. Ecol. Manage. 50, 31–41.

Schroth, G., and Sinclair, F. L. (Eds.). (2003) Trees, crops and soil fertility: concepts and research methods. CABI, Cambridge, USA.

Sedjo, R.A. (1999) The Potential of High-Yield Plantation Forestry for Meeting Timber Needs. *New Forests*, 17: 339-359.

Shepherd, D., and Montagnini, F. (2001) Above ground carbon sequestration potential in mixed and pure tree plantations in the humid tropics. J. Trop. For. Sci. 13 (3), 450–459.

Siry, J.P., Cubbage, F.W., and Ahmed, M.R. (2005) Sustainable Forest Management: global trends and opportunities. *Forest policy and Economics*, 7: 551-561.

Sobek, S., Scherber, C., Steffan-Dewenter, L., and Tscharntke, T. (2009) Sapling Herbivory, Invertebrate Herbivores and Predators across a Natural Tree Diversity Gradient in Germany's Largest Connected Deciduous Forest. *Oecologia*, 160: 279-288.

Speight, M. R., Cory, J. S. (2001) Integrated pest management of *Hysipyla* shoot borers. In: Floyd, R., Hauxwell, C. (Eds.), Proceedings of an International Workshop on Hypsipyla Shoot borers of the Meliaceae at Kandy. Sri Lanka, August 20-23, 1996. Australian Centre for International Agricultural Research, Canberra, Australian.

Stanley,W.G., and Montagnini, F. (1999) Biomass and Nutrient Accumulation in Pure and Mixed Plantations of Indigenous Tree Species Grown on Poor Soils in the Humid Tropics of Costa Rica. *Forest Ecology and Management*, 113(1): 359-372.

Stephens, S.S., and Wagner, M.R. (2007) Forest Plantation and Biodiversity: a fresh perspective. *Journal of Forestry*, pp. 307-313.

Tabi Agyarko (2001) FAO Forestry Outlook Study for Africa (FOSA) Country Report: Ghana, FAO, Rome, Pp 8-42.

Teye, J. K. (2005) Deforestation in Ghana *in* Potthoff, K. (ed.) *Human Landscape Ecology (MNFEL 330/ RFEL 303). Selected Term Papers 2003/ 2004.* Acta Geographica-Trondheim, Serie A, Nr. 10. Department of Geography, NTNU, Trondheim. ISSN 1502-2390, pp. 9-21.

Thapa H. B. and Gautam S. K. (2011) Growth performance of Tectona grandis in the western Terri of Nepal. Banko Janakari, Vol. 15, No. 2.

Thapa, H. B. (2004) Early growth, thinning yield and estimated biomass of standing trees of *Dalbergia latifolia* Roxb. in the eastern Terai, Nepal. *Banko Janakari* **14** (1):31-40.

Tilman, D. (2000) Causes, consequences and ethics of biodiversity. Nature 405, 208-211.

Tropenbos (2005) Reconciling Policy Reforms with Forest Legislation; Tropenbos International-Ghana, 2005.

Turnbull, J.W. (Ed.) (2003). Eucalypts in Asia. ACIAR Proceedings No 111.

Ugalde, L.A. (2000) El sistema MIRA. In: Componente de Silvicultura. Manual del Usuario (CATIE), Turrialba, Costa Rica, p. 82.

UNEP (2002) Africa Environment Outlook. Past, present and future perspectives,UNEP, Naroibi, Kenya. Pp131.

UNEP-WCMC. (2004) Spatial analysis of forests within protected areas in ITTO Countries. UNEPWCMC, Cambridge, UK. Data prepared for ITTO, 2004. www.unep-wcmc.org.

UNFCCC (2007) "Investment and financial flows to address climate change". *Unfccc.int.* UNFCCC. p.81.

Van Bodegon, A. J., Van den Berg, J., and Van der Meer, P. (2008) Forest Plantations for Sustainable Production in the Tropics: key issues for decision-makers. Wageningen University and Research Centre, the Netherlands, ISBN: 978-90-8585-2315.

Van den Hombergh H. (1999) Guerreros del Golfo Dulce, pag 42. DEI, Colección Universitaria, San José, Costa Rica, 339 pp.

Van der Werf G. R., Morton D. C., DeFries R. S., Olivier J. G. J., Kasibhatla P. S., Jackson R. B., Collatz G. J. and Randerson J. T. (2009) "CO_2 emissions from forest loss". *Nature Geoscience* **2** (11): 737–738 doi : 10.1038/ngeo671.

Wagner, M. R., Atuahene, S. K. N., and Cobbinah, J. R. (1991) Forest Entomology in West Tropical Africa: Forest Insects of Ghana. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Wagner, M. R., Cobbinah, J. R., and Bosu, P. P. (2008) Forest Entomology in West Africa: forest insects of Ghana. Second Edition, Springer Publishers, pp. 244.

Watt, A. D. (1994) The relevance of the stress hypothesis to insects feeding on tree foliage: In; Leather. S.R., Watt A.D., Mills, N.J., and Walters, K.F.A. (eds). Individuals, Population and patterns in Ecology. Andover, Intercept, pp. 73-85.

Weaver, P. L. (1987) Enrichment planting in tropical America. In: J.C. Figueroa Colon F.H. Wadsworth and S. Branham (Editors) Management of the Forests of Tropical

America: Prospects and Technologies. Institute of Tropical Forestry USDA Forest Service and University of Puerto Rico, Rio Piedras, pp .258-278.

Whitmore, J. L. (1976) Studies on the shoot borer Hypsipyla grandella (Zeller) Lep. Pyralidae, vol. II. IICA Miscellanceous publications No. 101, CATIE, Turrialba, Costa Rica.

Wong, J. (1989) Ghana Forest Inventory Project Seminar Proceedings, 29-30 March 1989. Accra: Ghana Forestry Department.

World Rainforest Movement (1999) Campaña Plantaciones: Plantaciones de pulpa de papel, un problema creciente. Instituto Tercer Mundo, Jacson 1136, Montevideo Uruguay, 31 pp.

Wormald, T. J. (1992) Mixed and Pure Forest Plantations in the Tropics and Subtropics. *FAO Working Paper, No. 11291*, Rome 1992.

Yeboah D. (2011) Variation in carbon content of tropical tree species from Ghana. A MSc. Thesis submitted to Michigan Technological University, Michigan, USA, 63 p.

Zain, D. K. (2005) Feasibility of Teak for smallholders in Eastern Panama. Submitted in partial fulfillment of the requirements for the degree of Master of Science in forestry. Michigan Technological University. U.S.

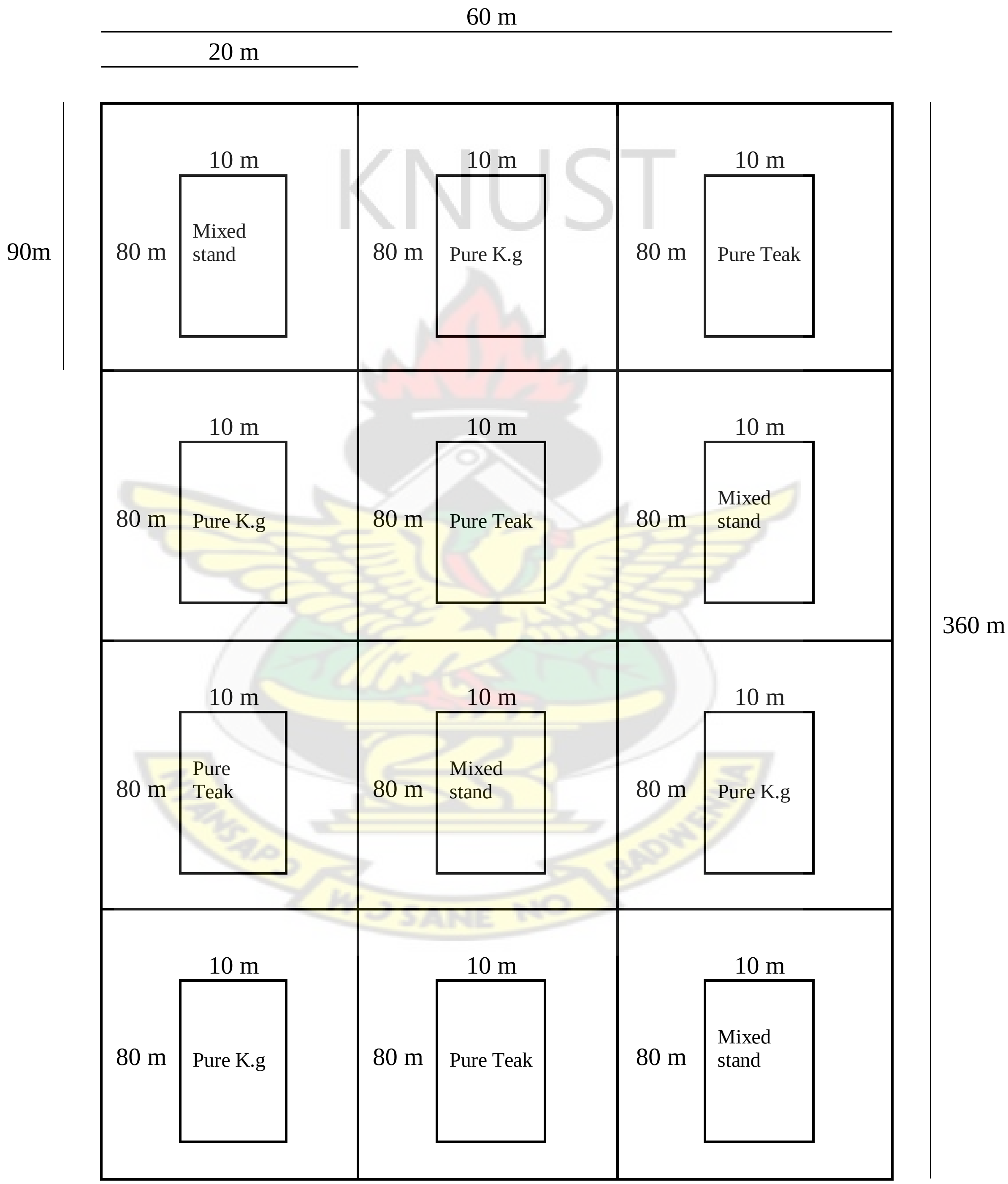
Zhang, D., and Owiredu, E. A. (2007) Land tenure, Market and the Establishment of Forest Plantation in Ghana. *Forest Policy and Economics*, 9: 602-610.

Zhou, G. Y., Morris, J. D., Yan, J. H., Yu, Z. Y., and Peng, S. L. (2002) Hydrological Impacts of Reafforestation with Eucalypts and Indigenous Species: a case study in southern China. *Forest Ecology and Management*, 167: 209-222

Zobel, B. J., Van Wyk, G. and Stahl P. (1987) Growing Exotic Forests. John Wiley and Sons, New York, USA.

APPENDIX

APPENDIX A. Layout of experimental plots at Tain II Block Forest Reserve in Berekum in the Brong Ahafo Region of Ghana.



***** K.g is *Khaya grandifoliola*.

APPENDIX B

B1 ANOVA for diameter of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	94.171	1	94.171	11.068	.001
Within Groups	2612.047	307	8.508		
Total	2706.218	308			

B2 ANOVA for total height of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	11.159	1	11.159	2.785	.096
Within Groups	1230.183	307	4.007		
Total	1241.342	308			

B3 ANOVA for merchantable height of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.593	1	.593	.273	.602
Within Groups	666.447	307	2.171		
Total	667.040	308			

B4 ANOVA for basal area per tree of *Khaya grandifolila* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	1	.000	11.146	.001
Within Groups	.005	307	.000		
Total	.005	308			

B5 ANOVA for volume per tree of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.003	1	.003	7.553	.006
Within Groups	.114	307	.000		
Total	.117	308			

B6 ANOVA for basal area per hectare of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9.458	1	9.458	11.585	.014
Within Groups	4.898	6	.816		
Total	14.356	7			

B7 ANOVA for volume per hectare of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	42.901	1	42.901	5.781	.053
Within Groups	44.528	6	7.421		
Total	87.428	7			

B8 ANOVA for diameter of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	22.374	1	22.374	2.152	.143
Within Groups	4440.133	427	10.398		
Total	4462.507	428			

B9 ANOVA for total height of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	781.160	1	781.160	137.451	.000
Within Groups	2426.721	427	5.683		
Total	3207.881	428			

B10 ANOVA for merchantable height of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	324.195	1	324.195	82.396	.000
Within Groups	1680.081	427	3.935		
Total	2004.277	428			

B11 ANOVA for basal area per tree of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	1	.000	4.043	.045
Within Groups	.010	427	.000		
Total	.010	428			

B12 ANOVA for basal area per hectare of *khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.953	1	.953	2.195	.189
Within Groups	2.605	6	.434		
Total	3.557	7			

B13 ANOVA for volume per tree of *Khaya grandifoliola* and *Tectona grandifoliola* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.023	1	.023	34.707	.000
Within Groups	.287	427	.001		
Total	.310	428			

B14 ANOVA for volume per hectare of *Khaya grandifoliola* and *Tectona grandifoliola* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	42.901	1	42.901	5.781	.053
Within Groups	44.528	6	7.421		
Total	87.428	7			

B15 ANOVA for number of total shoots of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	941.482	1	941.482	25.945	.000
Within Groups	11140.311	307	36.288		
Total	12081.793	308			

B16 ANOVA for number of shoots attack of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4.998	1	4.998	.709	.401
Within Groups	2164.808	307	7.051		
Total	2169.806	308			

B17 ANOVA for number of fresh attack of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.357	1	.357	1.328	.250
Within Groups	82.465	307	.269		
Total	82.822	308			

A18 ANOVA for number of dead shoots of *Khaya grandifoliola* in pure and in mixed stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.291	1	1.291	.570	.451
Within Groups	695.143	307	2.264		
Total	696.434	308			

B19 ANOVA for aboveground biomass per tree of *Khaya grandifoliola* in pure and in mixed stands using Y= 0.005100 (DBH) $^{2.47}$

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1032.088	1	1032.088	10.596	.001
Within Groups	29903.775	307	97.406		
Total	30935.863	308			

B20 ANOVA for sequestration carbon per tree of *Khaya grandifoliola* in pure and in mixed stands usingY = 0.005100 (DBH) $^{2.47}$

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	258.022	1	258.022	10.596	.001
Within Groups	7475.944	307	24.352		
Total	7733.966	308			

B21 ANOVA for aboveground biomass per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= 0.005100 (DBH) $^{2.47}$

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.543E8	1	1.543E8	160.255	.000
Within Groups	5775766.704	6	962627.784		
Total	1.600E8	7			

B22 ANOVA for carbon sequestration per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= 0.005100 (DBH) $^{2.47}$

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3.857E7	1	3.857E7	160.252	.000
Within Groups	1443934.257	6	240655.709		
Total	4.001E7	7			

B23 ANOVA for aboveground biomass per tree of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-1.996 + 2.32 ln (DBH)]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3274.537	1	3274.537	10.803	.001
Within Groups	93052.212	307	303.102		
Total	96326.749	308			

B24 ANOVA for carbon sequestration per tree of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-1.996 + 2.32 ln (DBH)]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	818.634	1	818.634	10.803	.001
Within Groups	23263.053	307	75.775		
Total	24081.687	308			

B25 ANOVA for aboveground biomass per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-1.996 + 2.32 ln (DBH)]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5.313E8	1	5.313E8	157.104	.000
Within Groups	2.029E7	6	3382069.177		
Total	5.516E8	7			

B26 ANOVA for carbon sequestration per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-1.996 + 2.32 ln (DBH)]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.328E8	1	1.328E8	157.104	.000
Within Groups	5073089.495	6	845514.916		
Total	1.379E8	7			

B27 ANOVA for aboveground biomass per tree of *Khaya grandifoliola* in pure and mixed stands using Y= exp [-2.28 + 2.649 * ln (DBH) - 0.021 * (ln (DBH)) ^{2}]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7896.756	1	7896.756	10.508	.001
Within Groups	230700.197	307	751.466		
Total	238596.953	308			

B28 ANOVA for carbon sequestration per tree of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-2.28 + 2.649 * ln (DBH) - 0.021 * (ln (DBH)) ^{2}]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1974.189	1	1974.189	10.508	.001
Within Groups	57675.049	307	187.867		
Total	59649.238	308			

B29 ANOVA for aboveground biomass per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-2.28 + 2.649 * ln (DBH) - 0.021 * (ln (DBH)) ^{2}]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.130E9	1	1.130E9	161.998	.000
Within Groups	4.186E7	6	6977323.799		
Total	1.172E9	7			

B30 ANOVA for carbon sequestration per hectare of *Khaya grandifoliola* in pure and in mixed stands using Y= exp [-2.28 + 2.649 * ln (DBH) - 0.021 * (ln (DBH)) ^{2}]

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.826E8	1	2.826E8	161.998	.000
Within Groups	1.047E7	6	1744320.896		
Total	2.930E8	7			

B31 ANOVA for carbon sequestration per tree of *Khaya grandifoliola* in pure and in mixed stands using concentration* wood density* volume

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	99.776	1	99.776	7.553	.006
Within Groups	4055.375	307	13.210		
Total	4155.151	308			

B32 ANOVA for carbon sequestration per hectare of *Khaya grandifoliola* in pure and in mixed stands using concentration* wood density* volume

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.481E7	1	1.481E7	160.585	.000
Within Groups	553443.282	6	92240.547		
Total	1.537E7	7			

B33 ANOVA for aboveground biomass per tree of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	21053.159	1	21053.159	33.154	.000
Within Groups	271150.044	427	635.012		
Total	292203.202	428			

B34 ANOVA for carbon sequestration per tree of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5263.410	1	5263.410	33.155	.000
Within Groups	67787.899	427	158.754		
Total	73051.309	428			

B35 ANOVA for aboveground biomass per hectare of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.669E7	1	2.669E7	3.066	.131
Within Groups	5.223E7	6	8704746.720		
Total	7.891E7	7			

B36 ANOVA for carbon sequestration per hectare of *Khaya grandifoliola* and *Tectona grandis* in pure stands

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6671791.261	1	6671791.261	3.066	.131
Within Groups	1.306E7	6	2176194.284		
Total	1.973E7	7			