Survival and Growth in a Moist-semi Deciduous Forest in Ghana: comparison of monoculture and mixed-species plantations

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Survival and Growth in a Moist-semi Deciduous Forest in Ghana: comparison of monoculture and mixed-species plantations

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Declaration

I hereby declare that this thesis is the result of my own research and that it has not been submitted for any degree elsewhere. I have also not used any other sources and materials than those indicated and have properly cited the materials I relied upon.

……………………………………………………………………

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LIST OF MAIN ABBREVIATIONS AND ACRONYMS

AAC	Annual Allowable Cut
ADA	Asunafo District Assembly
AGC	Ashanti Goldfields Company Ltd.
ANOVA	Analysis of Variance
CIRAD	Centre of Agricultural Research for Development
CITES	Convention on International Trade in Endangered Species
DBH	Diameter at reference height, at Breast Height (1.3m)
DI	Darwin Initiative
EP	Enrichment Planting
FAO	Food and Agriculture Organisation
FD	Forestry Department
FPDF	Forest Plantation Development Fund
FSD	Forest Services Division
GNA	Ghana News Agency
GDP	Gross Domestic Product
HIPC	Highly Indebted Poor Countries Initiative

IMF	International Monetary Fund
ISSER	Institute for Statistical Social and Economic Research
ISSS	International Society of Soil Science
IUCN	International Union of Conservation of Nature
ITTO	International Tropical Timber Organisation
NPDP	National Plantation Development Program
NTFP	Non-Timber Forest Product
PTC	Pioneer Tobacco Company Ltd.
RGR	Relative Growth Rate
RHGR	Relative Growth Rate in Height
RDGH	Relative Growth Rate in Diameter
SAP	Structural Adjustment Program
SIPL	Subri Industrial Plantation Ltd.
TIDD	Timber Industry Development Division
WRB	World Reference Base for Soil Resource

ABSTRACT

One major challenge of using indigenous species like *Nauclea diderrichii* and *Pericopsis elata* in plantations is the high incidences and damages from pests and pathogens. *Nauclea diderrichii* (De Wild.) and *Pericopsis elata* (Harms.) are adversely affected by damages from *Orygmophora mediofoveata* Hamps (Lepidoptera: Noctuidae) and *Lamprosema lateritialis* Hampson (Lepidoptera: Pyralidae), respectively when used in plantations. However no information exists in Ghana on alternative pest management options for these insect herbivores. The general recommendation which is gaining much attention is that planting these high-risk species in mixtures with companion species has the potential to reduce pest damages. This study which was part of a large scale restoration program in Ghana was therefore carried out to find out whether tree species diversity can reduce the susceptibility of *N. diderrichii* and *P. elata* to their respective primary pests, and also assess the growth performance of these species in monocultures and mixtures. *N. diderrichii, P. elata* and companion species (*Albizia adianthifolia*, *Terminalia superba*, and *Tetrapleura tetraptera*) were planted in various mixtures (0:100, 50:50, and 25:25:25:25%) in a replacement design in the Bia Tano Forest Reserve, near Goaso**,** Ghana. Survival rates and growth patterns (height, diameter and relative growth rate) were examined in plots composed of monocultures and mixed stands over 60 months. Overall survival for *N. diderrichii* and *P. elata* at stand age 60 months were 35.3% and 59.5% respectively. The overall survival rate, mean height and mean diameter for *N. diderrichii* in mixtures at stand age 60 months were highest in 50% mixture (50%*Nauclea*/50%*Albizia*), followed by 100% mixture (monoculture), and 25% mixture (25%*Nauclea*/25%*Pericopsis*/25%*Terminalia*/25%*Tetrapleura*). Mean relative growth rates in both diameter and height for *N. diderrichii* in mixtures were however highest in 100% mixture, followed by 50% mixture and 25% mixture.

Survival rate for *Pericopsis elata* at 60 months was highest in 100% mixture (monoculture). This was followed by 50% mixture (50%*Pericopsis/*50%*Albizia*), and 25% mixture (25%*Pericopsis*/25%*Nauclea*/25%*Terminali*a/25%*Tetrapleura*). Mean height, mean diameter and mean relative growth rates in *Pericopsis elata* on the other hand were highest in 100% mixture (monoculture), followed by 25% mixture (25%*Pericopsis*/25%*Nauclea*/25%*Terminali*a/25%*Tetrapleura*) and 50% mixture (*50%Pericopsis*/*50%Albizia*) respectively. However, neither survival nor growth was significantly affected by density of *Nauclea diderrichii* and *Pericopsis elata* in mixtures at $p<0.05$.

1.0 INTRODUCTION

1.1 Background

Forests play very critical roles in the social and economic development of humankind. In Ghana, forests provide goods such as timber and other non timber products (e.g. bamboo, chewstick, game) which help most communities to meet the requirements for rural economy. Blay et al., (2008), indicated that the forest supports the livelihood of about 20 million inhabitants particularly in rural communities. 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; Kozlowski, 2000). 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). Moreover, most of the country's forest resources are considered to be degraded (Marfo, 2010). The causes for the continuous forest loss are multidimensional. These include both internal factors such as unsustainable agriculture, conversion to agriculture, wanton logging, wildfires, firewood collection and charcoal production, mining, population pressure, poorly defined land and resource tenure and external factors including market failures, international trade, and the imposition of economic programs such as the Structural Adjustment Program (Appiah et al., 2009; Codjoe and Dzanku, 2009; Teye, 2005; Benhin and Barbier, 2004; Awung, 1998). The concerns about deforestation have mainly focused on the effects on atmospheric gases, climate change and particularly biological diversity (Amisah et al., 2009; Lamb et al., 2005; Benhin and Barbier, 2004; Gupta et al., 2004; Brown and Lugo, 1994; Moran, 1993). Most of the indigenous species like, *Milicia excelsa* and *Milicia regia*, the mahoganies (*Khaya* and *Entandrophragma* species), *Pericopsis elata, Nauclea diderrichii*, and *Triplochiton scleroxylon* which, mainly generate substantial revenues for Ghana's economy, have drastically reduced over the past decades due to some of the factors listed above (Wong, 1989 *in* Benhin and Barbier, 2004).

However, studies have shown that these indigenous species can be restored through plantation development (Kelty, 2006; FAO, 1995). There is a lot of evidence which suggests that plantations can accelerate forests succession of indigenous species on deforested sites through the improvement of biological and physical site conditions (Eckehard et al., 2008; Parrotta, 1992). Studies have indicated that plantations of both indigenous and exotic species can play major roles in restoring the productivity, ecosystem stability, and biological diversity of degraded lands (Lindermayer et al., 2003; Feyera et al., 2002; Montagnini, 2001; Lugo, 1997; Parrotta, 1992).

1.2 Problem statement

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). While monoculture plantations of exotic species have been productive (Cossalter and Pye-Smith, 2003; Odoom, 2002; 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; Lamb, 1998; Montagnini and Porras, 1998).

Indigenous species on the other hand 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). However, inadequate information about indigenous trees biology, ecology, and silvicultural requirements and the high incidences of pests and diseases outbreaks that occur in monocultures especially have mostly led to widespread failure of indigenous tree plantations (Wagner et al., 2008; Feyera et al., 2002; Evans, 1999; Gadgil and Bain, 1999; Butterfield and Fisher, 1994; Hosking, 1983). Plantations of indigenous species usually have large complement of pests and pathogens and thus mostly suffer from pest problems and diseases (Ciesla, 2001; Gadgil and Bain, 1999).

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. Species like *Nauclea diderrichii* (De Wild.) Merr. and *Pericopsis elata* (Harms.) van Meewen are valuable economic trees which are adversely affected by damages from *Orygmophora mediofoveata* Hamps (Lepidoptera: Noctuidae) and *Lamprosema lateritialis* Hampson (Lepidoptera: Pyralidae), respectively when used in plantations (Wagner et al., 2008; Bosu et al., 2004). The shoot-boring caterpillar *Orygmophora mediofoveata* is an important pest which causes high mortality to *Nauclea diderrichii* in heavy multiple attacks (Orwa et al., 2009; Wagner et al., 2008; Bosu et al., 2004). The persistent infestations of *Orygmophora mediofoveata* in plantations have been partly blamed for the lack of large scale plantations of *Nauclea diderrichii* in Ghana (Wagner et al., 2008). *Lamprosema lateritialis* is also considered as the most serious pest of the indigenous timber species *Pericopsis elata* and are endemic to areas where the tree species occur naturally (Wagner et al., 2008; FAO, 2007; Atuahene, 1996). In Ghana, the pest is widespread in the Afram Headwaters and the contiguous Bia Forest reserves where the experimental site is located (Wagner et al., 2008). Since these insects have become very important, any efforts committed to the establishment of large scale plantations of *Nauclea diderrichii* and *Pericopsis elata* in Ghana must of a necessity address the challenges posed by these pests (Bosu et al., 2004; Atuahene, 1996).

Unfortunately, no studies have been done in Ghana to assess alternative pest management options for these insect pests. Moreover there is no information about the effects of low-diversity species mixtures on these pests. Integrated approaches using silvicultural manipulations are frequently recommended for the management of these kinds of pests (Wagner at al., 2008; Waring and O'Hara, 2005; Bosu et al., 2004; Ciesla, 2001). Silvicultural approaches to insect problems are mostly seen as reliable, the cheapest and the least harmful to the ecosystem (Waring and Hara, 2005; Hosking, 1983).

Although there is no consensus about the effects of mixed species on pests (Schuldt et al., 2010; Kaitanienen et al., 2007; Vehviläinen et al., 2007; Riihimäki et al., 2005; Ciesla, 2001; White and Whitham, 2000), the integration of pest management through the use of species mixtures to enhance stand diversity has been encouraged (Wagner et al., 2008; Bosu et al., 2006; Nichols et al., 1999; Montagnini et al., 1995). Kelty (2006), indicated that one major benefit of using species mixtures is their potential to reduce the effects of insects and pests on plantations.

It is widely believed that planting high-risk indigenous species in mixtures with other companion species can lead to a substantial reduction in damages caused to the species (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Bosu et al., 2006; Ciesla, 2001; Montagnini et al., 1995). The potential of mixed tree species to reduce the impacts of pests and diseases can be explained by two complementary mechanisms, i) reduced host plant accessibility and ii) increased populations of natural enemies (Sobek et al., 2009; Vehviläinen et al., 2007; Bosu et al., 2006; Jactel et al., 2006; Kelty, 2006). The use of species mixtures in plantations therefore has the potential to achieve a wide range of economic, ecological, silvicultural and sustainable goals (Erskine et al., 2006; Forrester et al., 2005; Lamb et al., 2005). This study which is part of a broader restoration project was therefore carried out to determine the potential effectiveness of species diversity on the survival and growth of these high-risk indigenous species.

1.3 Research questions

- Can tree species diversity reduce the susceptibility of *Nauclea diderrichii* to *Orygmophora mediofoveata* and *Pericopsis elata* to *Lamprosema lateritialis* respectively?
- Do *Nauclea diderrichii* and *Pericopsis elata* grow better in monocultures or in a mixture with companion species?

1.4 Structure of thesis

The thesis is organised in 7 chapters. Chapter 1 introduces the research topic with a brief background, the justification, research questions and the structure of the write up. Chapter 2 presents the relevant information which formed the background to this study. It first deals with forest resources and their relevance in Ghana, and the challenge with deforestation and its consequences. It further touches on remedial measures to deal with the challenge of deforestation and forest degradation. The chapter then emphasises plantations, their importance and certain environmental challenges associated with plantations. It then tackles the widespread of monoculture and some disadvantages. The chapter continues with mixed-species plantations and their challenges. Furthermore it introduces why the preference for indigenous species and the major problem with their uses in plantations. The chapter closes by emphasising the focal species and integrated pest management strategies. Chapter 3 describes the study area and research approaches. Chapter 4 presents the detailed results of the study. Discussions of the major findings are presented in chapter 5. Chapter 6 concludes the study, whilst chapter 7 provides an abstract of the study in German.

2.0 LITERATURE REVIEW

2.1 Forest resources and their importance in Ghana

The forests in Ghana which are part of the Guinea-Congolean phytogeographical region cover about 24.2 % of the 22,754,000 hectares (ha) total land area of the country (FAO, 2010). These forests and their resources continue to form essential part of the nation's natural heritage. Forest resources of Ghana have been broadly separated into two ecological zones; the Moist tropical or High Forests which covers the south-western third of the country and Savannah woodlands of the north and central parts (Dadebo and Shinohara, 1999; Kotey et al., 1998; Palo and Yirdaw, 1996). The two broad zones characterize the climate, especially rainfall patterns prevalent in the country. The south-western parts of the country where the moist tropical forests are found have high rainfall than the northern portions (Teye, 2005). The High forests zone especially the moist evergreen and moist semi-deciduous portions are the most important for commercial timber species. About 20-25 % of the High forests zone which covers seven main forest types in Ghana has been put under reservation since the late 1920s and '30s. The reserved areas account for 1.77 million ha of forest lands, of which 1.634 million ha is under the management and control of the Forest Services Division (Kotey et al., 1998).

Based on the Forest Protection Strategy developed in 1993, the Forest Services Division categorized these reserved areas into Timber production, Permanent protection, Conversion, Non-inventoried conversion, and Convalescence areas. The timber production areas serve as forests purposely assigned for timber production. The Permanent protection areas were designated forests from which logging activities are prohibited. Apart from hill sanctuaries, the protection areas also include shelter swamp sanctuaries, intact forest sanctuaries, fire protection, special biological protection and provenance areas (Kotey et al., 1998). The Conversion areas are those forests which require planting.

These areas, of which the non-inventoried conversion forests are a part, are well suited for plantation establishments. The Convalescence areas on the other hand are those forests which have reduced stocking but could be rehabilitated within 40 years (Kotey et al., 1998).

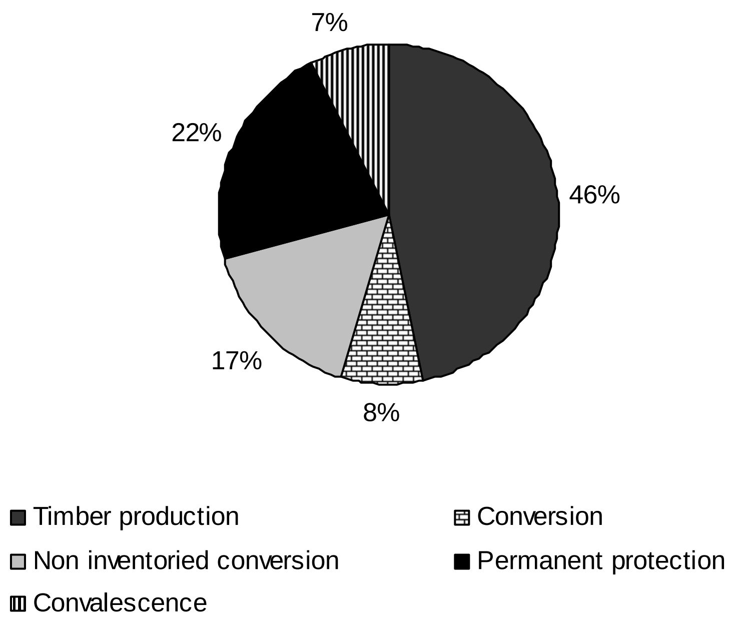


Fig.2.1. Area of Forest Reserves in Ghana. Adapted from: Kotey et al., 1998

These forests are unique due to several reasons – structurally complex, genetically endowed, highly productive and diversified into different subtypes (Roy et al., 2002). Forests play a major role in the socioeconomic development of humankind and are essential sources of harvestable products and a variety of other services (Roy et al., 2002; Kozlowski, 2000; Riswan and Hartanti, 1995). The forests are important sources of timber, raw material for pulp and paper, fuel wood, and energy, and other essential harvestable products like food, medicines, oil and resins. Forests also play vital roles in maintaining the ecological balance and environmental make up of our world (FAO, 2006; Roy et al., 2002).

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). Some developing countries virtually depend on forests and their resources to support socioeconomic and national developments (Dadebo and Shinohara, 1999). Ghana's forests make significant contributions to the national economy. Timber, which is the major market based forest product is currently the fourth largest contributor to Ghana's foreign exchange earnings aside minerals, cocoa and tourism (Marfo, 2010; Siry et al., 2005). The formal timber industry accounts for 11 % of foreign exchange earnings and contributes about 6 % to Gross Domestic Product (GDP) and directly employs about 100, 000 people (Marfo, 2010). Between 2002 and 2007, Ghana earned an average of € 193.048 million annually from the export of wood products such as sawnwood, veneer and plywood (Marfo, 2010). In 2009 alone, Ghana earned an amount of € 128, 226, 984 from the export of 426, 221 m^3 wood products , though there was a decrease of 31.29 % in value and 21.93 % in volume over the same period in 2008 (TIDD, 2010). The forests of Ghana also play important socioeconomic roles in the lives of most communities (Appiah et al., 2009; Blay et al., 2008; Dadebo and Shinohara, 1999). Blay et al., (2008), indicated that forests support the livelihood of about 20 million inhabitants particularly in rural communities for subsistence and traditional uses. Aside timber, the role of forests providing non-timber forest products and other services has been noted and appreciated.

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).

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).

The sector includes about 300,000 hunters who produce between 220,000 to 380,000 tons of bush meat, valued at US $ 210 million to US $ 350 million (ITTO, 2006). Fuel wood and charcoal account for more than 75 % of all energy needs of Ghana and a high percentage of both rural and urban households use them for cooking and water heating purposes. In 2005, fuel wood accounted for 28, 253, 000 m^3 of the total of 29, 458, 000 m^3 of wood products removed from the forests (FAO, 2006). This value was more than the total volume of wood products extracted from the forests in 2000 (FAO, 2006). Falconer (1992) estimated that over 90 % of all households in southern Ghana owned an average of 3.4 baskets. The forest in Ghana has also been recognized as sources of important ecological benefits. These forests are therefore 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

Change is happening at a very fast rate all over the world, with some implications for sustainable human development. The bio-physical environment which contains the basic human life-support systems have always been characterised by change (Gyasi et al., 1995). Though tropical forests have always had a long history of human interferences, and also characterised by change, the rate at which the changes are occurring have raised a lot of concerns (Gupta et al., 2004; Gyasi et al., 1995; Hawthorne and Abu-Juam, 1993; Myers, 1992). The concerns over the rapid disappearance of tropical forests (Myers, 1992), are as a result of the degree of disturbance and the imbalance between disintegration and recovery rates (Hawthorne and Abu-Juam, 1993). Forests in the tropics are particularly under threat from human-induced disturbances (Gupta et al., 2004; Kozlowski, 2000), and approximately 13 million ha of tropical forests are felled, burned or converted to other land uses each year (FAO, 2006).

The forests in Ghana, like other tropical forests is seen to have been very much influenced by human disturbances. There has been a considerable loss of forests in the country in the last 100 years and over, with serious local, national, regional and global implications (Appiah et al., 2009; Foli et al., 2009; Gupta et al., 2004; Palo and Yirdaw, 1996). Siry et al., (2005), argues that forests loss has a far reaching significance which goes beyond loss of forest land but also the decline in the quality of existing forests. Though there are uncertainties about the actual rate of deforestation, the rate of change in Ghana has been rapid and increasing (Appiah et al., 2009; FAO, 2006; Benhin and Barbier, 2004; Sandler, 1993). The present rate of deforestation is among the highest in Africa (FAO, 2010). The average estimated annual rate of deforestation between 1990 and 2000 was 2% (135, 000 ha), which is higher than the average annual rate for both Central and Western Africa which stands at 0.6 % (FAO, 2010; FAO, 2006).

Forest resources in Ghana have reduced from 7 million ha in 1990 to approximately 6 million in 2000 (FAO, 2006). Almost all the forests are depleted and 0.39 million ha of forests reserves are considered as degraded (Marfo, 2010). Over harvesting has led to the downward revision of the national Annual Allowable Cut (AAC) in forest reserves from 1.2 million m^3 in 1990 to 500, 000 m^3 in 2005 (ITTO, 2006). The off-reserve component of the total national AAC (2 million m^3) was set as high as 1.5 million m^3 mainly due to extensive illegal logging and the assumption that with time those areas are likely to be converted to other land uses (Marfo, 2010). However, some have argued that some of the causes of deforestation in the past were legal, purposeful and arguably necessary for development of the country (Grainger, 1993; Hawthorne and Abu-Juam, 1993). The cause of deforestation in Ghana vary and are by no means easy to influence, but they have resulted from a complex interaction of different social, cultural, economic, management and political factors (Teye, 2005; Benhin and Barbier, 2004; Gupta et al., 2004; Capistrano and Kiker, 1995; Grainger, 1993).

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; Grainger, 1993; 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).

2.1.1.1 Proximate or direct causes

The proximate causes are the immediate activities which have direct human influence. These activities are however precipitated by other underlying influences (Teye, 2005; Yiridoe and Nanang, 2001).

2.1.1.2 Unsustainable agriculture

Agricultural production is considered as the main contributor to the economy of Ghana. About 60 % of the economically active population is involved in different agricultural activities, with forests and land as the main production input (Teye, 2005; Benhin and Barbier, 2004; Palo and Yirdaw, 1996).

The sector engages a lot of people because about 57 % of the country's total land area is suitable for agricultural production (Appiah et al., 2009; Benhin and Barbier, 2004). Despite these huge areas which can support agriculture, Kotey et al., (1998) indicated that farming in the southern belt of Ghana which contains the high tropical forests is dominated by bush fallow system. This system otherwise called shifting cultivation involves the clearing of forests, burning the vegetation and growing crops for short periods and subsequently clearing other areas when the soil becomes infertile (Appiah et al., 2009; Palo and Yirdaw, 1996; Riswan and Hartanti, 1995; Myers, 1992).

This practice which was seen as one of the proven sustainable uses of land in the tropics is prevalent in Ghana (Appiah et al., 2009; Palo and Yirdaw, 1996; Grainger, 1993). The traditional practice of shifting cultivation was in itself not destructive to the forest ecosystems (Riswan and Hartanti, 1995), however the challenge is the continued clearing of large tracts of forest areas (Benhin and Barbier, 2004). Most forests areas have been destroyed by farming particularly the practice of shifting cultivation which has been blamed for the loss of several hectares of forests (Appiah et al., 2009; Palo and Yirdaw, 1996; Hawthorne and Abu-Juam, 1993). Shifting cultivation is considered as the main cause of deforestation, accounting for more forest loss than the combined effects of all the other direct factors (Sandler, 1993; Myers, 1992).

This assertion is affirmed by the fact that most nutrients in the tropics are stored in the biomass and therefore clearing the forests leaves the soil infertile. This implies that after two or three harvests, the soil nutrients are depleted leaving the farmer with no other choice than to clear more forest areas. Codjoe and Dzanku (2009) found out that agriculture (driven by shifting cultivation) was a more important cause of deforestation in Ghana than any other factor. It accounts for about 70 % of all deforestation producing several hectares of degraded lands and depleted secondary forests (Yiridoe and Nanang, 2001; Riswan and Hartanti, 1995; IUCN, 1992). Shifting cultivation in Ghana mostly occurs in the off-reserve areas, however increasing portions of reserve areas are being cleared for farming (Palo and Yirdaw, 1996; Hawthorne and Abu-Juam, 1993).

The main concern about shifting cultivation is the fact that it can support low population densities (Grainger, 1993), therefore some argue that farmers involved in these practices are driven by factors such as population pressure, poverty and lack of alternative rural income aside agriculture which shorten the fallow period (Appiah et al., 2009; Palo and Yirdaw, 1996; Grainger, 1993; Myers, 1992).

The persistent migration by settlers to the southern parts of the country has been found to contribute to the high rates of forests degradation (ITTO, 2006). Farmers migrating from other areas of Ghana have inundated the Western Region which contains large tracts of the primary high forests (Kotey et al., 1998). A study conducted by Gyasi et al., (1995) in some districts of the transition zone in the Eastern Region found that farming had replaced nearly all the original natural forests and changed the vegetation to savannah. The major factor impelling the increased farming activities was population pressure from migrants who had settled in these areas.

2.1.1.3 Conversion to agriculture

The continued expansion of agriculture in many parts of the tropics is a major threat to forests, contributing immensely to deforestation (Horne, 1996). In Ghana there has been an increase in both legal and illegal farms in most forest reserves (Hawthorne and Abu-Juam, 1993). Forests continue to be converted to croplands especially in areas where lands for cultivation are becoming scarce. Economic reasons have been cited for the persistent conversion of forests to other land uses in the off- reserve areas (Kotey et al., 1998).

As incomes decline rural communities are forced to clear more forests to sustain their livelihoods (Blom and Cummins, 2009). Forest land clearing has been intensified by the increased emphasis on agricultural production which relies heavily on export commodity crops (Yirdaw, 1996). The quest to diversify the nation's exports with emphasis on non traditional export commodities have led to an increased expansion of cocoa growing areas (Yiridoe and Nanang, 2001). Large portions of the high forests are therefore cleared annually for cocoa production. Benhin and Barbier (2004) used a four-equation model to show that cocoa land expansion is a significant cause of forest loss in Ghana.

However the cultivation of food crops like cassava, plantain and cocoyam by farmers also lead to the clearing of more forest areas. Palo and Yirdaw (1996) stated that so far as the modernisation of the agriculture sector continue to receive little attention the conversion of forests to farmlands is likely to continue.

2.1.1.4 Unsustainable logging

Logging which is one of the main reasons for forest management in Ghana has always been part of the economy of the country (Teye, 2005; Kotey et al., 1998). However, studies have shown that deforestation in Ghana mostly begins with the degradation of well-stocked forests due to unsustainable logging (ITTO, 2006). Though, the country practices selective logging, it is seen as one of the most disturbing factors with significant influence on the forests (Appiah et al., 2009; Palo and Yirdaw, 1996). Logging has been very intense especially in the semi-deciduous zones and has not only led to changes in the composition but also degradation of the forests (Palo and Yirdaw, 1996; Hawthorne and Abu-Juam, 1993).

Though there are many hardwoods, excessive logging in especially the 1970s and 80s almost led to the near extinction of species such as *Pericopsis elata*. 'Salvage felling' which took place during those periods, allowed uncontrolled felling of 'over matured' trees as well as most of the high valued species (Hawthorne and Abu-Juam, 1993). ITTO in 2006 reported that, the 'Scarlet' species which are the most important among the commercial timber species, have been over-harvested at a rate greater than 200 % of the estimated sustainable yield and are under threat of economic extinction. Logging in Ghana has generally been seen as very wasteful (Palo and Yirdaw, 1996). The extraction of timber has been worsened by the high levels of waste which Benhin and Barbier (2004), estimated to be about 50 %. Most of the loggers fail to follow the guidelines provided in the logging plans during harvesting operations leading to damages from felling and extraction (Riswan and Hartanti, 1995; Hawthorne and Abu-Juam, 1993).

This problem is exacerbated by chainsaw milling through illegal loggers who process about 840,000 trees every year (Marfo, 2010). Marfo (2010) also reported that the activities of these illegal loggers generate about 2.5 million m^3 of round wood annually which incidentally exceeds the national AAC of 2 million m^3 designated for the formal timber industry. Apart from the direct effects logging has on the residual stands, it also enhances the spread and intensity of forests fires (Hawthorne and Abu-Juam, 1993). This is due to the fact that excessive logging makes forests more susceptible to fire by causing loading residues which dry up and become more combustible (ITTO, 2006). Ghana has witnessed frequent wildfires since the 1980s especially in the transition zone due to among other things inefficient logging practices. Most of the logging roads which are constructed during logging operations have in away contributed to more deforestation. These roads open up areas which hitherto are inaccessible to farmers and hunters who are usually accused of causing most of the wildfires (Palo and Yirdaw, 1996).

2.1.1.5 Wildfires

Disturbances such as wildfires are a major part of the natural cycle which influence the development, structure and function of forest ecosystems (Attiwell, 1994). Forest fires may either be caused by natural forces or human activities, the latter mostly been the case in Ghana (Teye, 2005; Hawthorne and Abu-Juam, 1993). Apart from the existing weather conditions, factors such as fuel load and degree of combustibility affect the spread and intensity of wildfires (Attiwell, 1994). Since the early 1980s, fires have occurred regularly and caused severe damage to large tracts of forests (ITTO, 2006; Teye, 2005). The damage caused by wildfires has been estimated at about US$24 million every year (ITTO, 2006). Farming, hunting and charcoal production have been identified as the major causes of wildfires, threatening the survival of forests especially drier forest in the country (Teye, 2005; Woldeamanuel, 2005).

Wildfires have been the cause of degradation in especially the Moist semi-deciduous forests zone and the Dry semi-deciduous fire zone in recent years (Teye, 2005; Hawthorne and Abu-Juam, 1993). As noted by Goldammer (1993), these fires eventually rid the forests of common species and favours fire -resistant dry forest and fire-tolerant species. Inefficient logging practices have compounded the problem making the forests more susceptible due to heavy fuel loads from logging residues which become more combustible in drier conditions (ITTO, 2006). Hawthorne and Abu-Juam (1993), cautioned that the continued exploitation of timber and the reluctance of the Forest Services Division to reduce timber yields in the fire prone areas are major challenges in dealing with wildfires in the country. Though recent figures from the Wildfire management project suggest a reduction in the frequency of fires, the spread and intensity are still causing serious effects on the forests.

2.1.1.6 Firewood collection and charcoal production

Firewood collection and charcoal production are in most cases the major products of the forests in Ghana (Palo and Yirdaw, 1996). The use and demand for these products keep increasing (Foli et al., 2009). Firewood and charcoal account for more than 75 % of all energy consumed in the country (FAO, 2006). It is estimated that about 91 % of total round wood produced is used for firewood and charcoal production (Teye, 2005). The use of firewood and charcoal is not only limited to domestic purposes but also used in local breweries, bakeries and fish processing (Yiridoe and Nanang, 2001). The demand for firewood and production of charcoal especially in the transition zone has contributed to the loss of forests in Ghana (Foli et al., 2009; Teye, 2005; Yiridoe and Nanang, 2001). Most of the firewood are collected from the off-reserve areas and fallow lands, however wood in these areas have become scarce therefore leading to increased pressure on the forest reserves (Kotey et al., 1998; IUCN, 1992).

Charcoal production has also impacted both the forest reserves and off-reserve areas (Yiridoe and Nanang, 2001). The entire chain in the production of charcoal from the extraction has negative impacts on the structure of the forests (Webi, 2005). With increasing population, the demand and consumption of firewood and charcoal has increased creating a gap, and this gap will continue to intensify the pressure on forest reserves (Yirdaw, 1996).

2.1.1.7 Mining

Minerals such as gold and diamond are the leading contributors to Ghana's foreign exchange earnings. Gold alone in 2009 rose to 12 % with a production of 2.9 million ounces accruing revenue of $2.8 billion to the economy (Bowers, 2010). Despite the important role these minerals play in the Ghanaian economy, mining has had devastating effects on forests leading to several hectares of forest loss (Codjoe and Dzanku, 2009; Kotey et al., 1998; Riswan and Hartanti, 1995; Hawthorne and Abu-Juam, 1993). Grainger (1993) stated that deforestation occurs when minerals buried under forests are exploited. Open cast mining which is most practiced in Ghana by mining companies have become important cause of deforestation in the country (Grainger, 1993). Surface mining has been detrimental to the forests in Ghana due to the fact that, it is not only the forests biomass which are removed but also the soil (Hawthorne and Abu-Juam, 1993).

Iron ore extraction around Awaso and gold mining in the 1970s and 80s led to the loss of several tracts of forests (Kotey et al., 1998). Hawthorne and Abu-Juam (1993) reported of the threat mining posed to reserves in and around high biodiversity areas like Neung forest reserve in the Wet Evergreen forest zone. Though the National Land Policy of 1999 prevents mining in Permanent Protection areas, government granted leases to some international mining companies to mine in forest reserves such as Ajenua Bepo reserve, Atewa Range, Supuma Shelterbelt reserve, Cape three points and Subri River forest reserve (GNA, 2010).

2.1.1.8 Plantation strategy and taungya farms

Industrial plantations and the use of taungya to expand plantations have contributed to the increasing degradation and deforestation in the country (Blom and Cummins, 2009; Benhin and Barbier, 2004; Dadebo and Shinohara, 1999; Hawthorne and Abu-Juam, 1993). Some forest reserves were converted to industrial plantations like teak as part of attempts to increase the abundance of economically valued species (Hawthorne and Abu-Juam, 1993). Moreover these industrial plantations including non-forestry ones were encouraged by government policies with the intention that the state would benefit from them financially (Blom and Cummins, 2009; Hawthorne and Abu-Juam, 1993).

These large scale plantations caused deforestation as more people migrated to these plantation areas and eventually opened up forests to plant food crops (Yirdaw, 1996). The taungya system which was practiced in the past also promoted the clearing of healthy forests by farmers. The system which was supported with the idea to expand plantations allowed farmers to use reserve areas for farming and plant trees to take over after a certain period (Hawthorne and Abu-Juam, 1993). After the failure of the taungya system a lot of areas like the lower slopes of the Atewa forest reserve have been dominated by the fire prone species like Eupatorium (Hawthorne and Abu-Juam, 1993).

2.1.2 Underlying or indirect causes

In most circumstances, the main root causes of deforestation have been non-forestry related issues which are mostly neglected in the discussions about deforestation (Yiridoe and Nanang, 2001; Myers, 1992).

Most initiatives to address deforestation to a large extend have failed because they focus mainly on the proximate causes (Teye, 2005; Liu et al., 1993 *in* Codjoe and Dzanku, 2009; Myers, 1992). However, these underlying factors interact in a complex relationship to trigger the direct causes of deforestation (Teye, 2005).

2.1.2.1 Population pressure

The population of Ghana has doubled in a few decades and indications are that it will keep growing in the future (Teye, 2005). The annual growth rate of the country's population as at 2004 was 1.8 % (FAO, 2006). Grainger (1993) stated that population growth influences deforestation by two major means, these are; the continual increasing in national population (including both urban and rural areas) and increase in rural population. As the national population increases, pressure for land and other natural resources cannot be avoided hence more forests are converted into different land uses such as agriculture, road building and settlements (Appiah et al., 2009; Blom and Cummins, 2009; Foli et al., 2009; Teye, 2005; Gupta et al., 2004; Yiridoe and Nanang, 2001; Kummer and Turner, 1994). To meet the nutritional needs of the growing population, more closed forests are cleared for agriculture, fuelwood and other general goods and services provided by the forests (Appiah et al., 2007; Teye, 2005; Palo and Yirdaw, 1996). Agricultural production which engages a lot of the population in Ghana has been found to be strongly influenced by population pressure (Benhin and Barbier, 2004; Gyasi et al., 1995; Myers, 1992). Even though there has been a lot of debate about the actual role of rural population growth in deforestation (Foster et al., 2002 *in* Codjoe and Dzanku, 2009), population density in these areas has been found to influence deforestation significantly (Blom and Cummins, 2009; Codjoe and Dzanku, 2009). About 54.2 % of the population in Ghana are living in rural areas and Ghana's population density is 92.5 % persons per every square kilometre, which is about 25 % increase from the 1990 figures (FAO, 2006, Palo and Yirdaw, 1996).

This relatively high rural population especially in the south has resulted mostly due to migration from the north to different parts of the high forest zones in the south (Gyasi et al., 1995). Most forest fringe communities have traditionally extracted forest products to support their livelihoods. However as population pressure increases through migration, the intentions for extraction eventually become profit making (Riswan and Hartanti, 1995). This has put a lot of pressure on the forests especially in the south western parts of the country (Yiridoe and Nanang, 2001; Kotey et al., 1998). Gyasi et al., (1995) found that increased farming activities have led to the clearing of forest areas in the Eastern Region of Ghana. This phenomenon was a result of increased population pressure from mostly migrants. This implies that as population density increase, there is a general expansion and intensification in agriculture especially shifting cultivation (Foster et al., 2002 *in* Codjoe and Dzanku, 2009; Yiridoe and Nanang, 2001; Kotey et al., 1998; Gyasi et al., 1995). This general trend is explained by the fact that almost all rural dwellers depend on subsistence farming and as population increases and demand for forest resources increases, shifting cultivators tend to extend the cultivation period and shorten the fallow periods (Appiah et al., 2009; Kotey et al., 1998; Riswan and Hartanti, 1995; Myers, 1992).

2.1.2.2 Poorly defined land and resource tenure

Challenges resulting from cumbersome land and resources tenurial rights can result in extensive destruction of forest resources (Blom and Cummins, 2009; Codjoe and Dzanku, 2009; Siry et al., 2005; Palo and Yirdaw, 1996; Mendelsohn, 1994). Tenure rights which influence the acquisition, utilization, control and disposal of land or resources from it are very important in deciding how forests are managed, conserved and protected or disregarded (Siry et al. 2005; Capistrano and Kiker, 1995).

The forest land and tenure systems for both reserve and off-reserve areas in Ghana are composed of complex customary and legal agreements for rights and access to forest land and its resources (Marfo, 2010; Dadebo and Shinohara, 1999). The traditional councils and stool chiefs through a system of customary laws are the landholding authorities in the high forest zone. Forest reserves are under communal ownership (landholding communities) which is mostly represented by a chief (Marfo, 2010; Dadebo and Shinohara, 1999; Kotey et al., 1998).

However, the government of Ghana through the Forest Services Division (FSD) has the sole right to manage and control all permanent forest reserves (Kotey et al., 1998; Palo and Yirdaw, 1996). Therefore the commercial use rights of forest commodities in and around the reserves are prohibited, and extraction of non-timber forest products is restricted by a permit system, though the FSD sometimes grant free permits (Dadebo and Shinohara, 1999). The forest reservation process is perceived to have indirectly changed the communal land tenure system and limited the rights of indigenous people and fringe communities to the productive commodities of the forest (Dadebo and Shinohara, 1999). The tenure system for the off-reserves is also distinguished by traditional landholding authorities with absolute title to land on behalf of the people. Though the land together with the timber is owned by landholding communities, the right to the trees are vested in the state for the owners (Kotey et al., 1998; Palo and Yirdaw, 1996). This arrangement makes the state in most situations exercise its right to grant concessions with little or no consultations with the chiefs and local communities. The local communities therefore feel marginalised in the decisions about their resources, which serve as a major disincentive to tree tending (Codjoe and Dzanku, 2009; Dadebo and Shinohara, 1999; Kotey et al., 1998). This poorly arranged property rights in Ghana has mostly led to mismanagement of forest resources and deforestation (Appiah et al., 2009; Palo and Yirdaw, 1996).

2.1.2.3 Poverty and unemployment

The wealth created in most developing countries like Ghana is not spread evenly among the populace (Grainger, 1993). This situation leads to widespread poverty, widening the gap between the rich and poor. The poverty and unemployment situation in Ghana is not very encouraging. Though poverty exists in all the regions of Ghana, it is prevalent in the rural areas (Teye, 2005; Palo and Yirdaw, 1996). Appiah et al., (2009) and Teye (2005) argue that the high rate of poverty and unemployment especially in the rural communities is a contributing factor to deforestation in the country. The high level of rural population, which stands at about 54.2% of the national population have been partly blamed for the high rate of forest loss in Ghana because they mostly depend on forest and its resources for their livelihood (Appiah et al., 2009; FAO, 2006; Palo and Yirdaw, 1996**).** The increased population coupled with reducing income levels increase the pressure on the high forest areas (Palo and Lehto, 1996; Palo and Yirdaw, 1996). As the inability of people to meet their daily economic requirements increase, it also accelerates the expansion of subsistence agriculture, bush meat trade, fuelwood collection and illegal logging through chainsaw milling (Marfo, 2010; Blom and Cummins, 2009; Palo and Yirdaw, 1996). The lack of employment opportunities for the youth especially in rural communities increases unsustainable activities like illegal logging to improve their economic situations (Marfo, 2010). These unsustainable activities mostly lead to deforestation (Shitima, 2005; Palo and Yirdaw, 1996).

2.1.2.4 Weak government policies

Poorly planned or inappropriate government policies can have influence on deforestation and forest degradation (Appiah et al., 2009; Blom and Cummins, 2009; Siry et al., 2005; Teye, 2005; Capistrano and Kiker, 1995; Grainger, 1993; Sandler, 1993).

Policies and legislations which create conducive environment to clear forests for other land uses are major drivers of deforestation (Blom and Cummins, 2009; Siry et al., 2005). Deforestation continues to increase in Ghana because successive government social and economic policies including those from the colonial era have directly or indirectly promoted it (Codjoe and Dzanku, 2009; Dadebo and Shinohara, 1999; Kotey et al., 1998). Policies on agriculture particularly cocoa expansion and pricing, land ownership, mining, and forest resources management have had immense impacts on the way forest resources have been managed, exploited and utilized (Yiridoe and Nanang, 2001; Dadebo and Shinohara, 1999; Kotey et al., 1998). The country's agriculture policy and marketing over the years have been among the main causes of forest land conversion (Teye, 2005; Dadebo and Shinohara, 1999). Successive governments interest in cocoa expansion to areas in the high forest zone have led to reduced forest extent in these areas (Kotey et al., 1998). Though this argument has been advanced, others also are of the view that the increasing cocoa production has been due mainly to increased productivity of already cultivated lands rather than increase in production areas (Yiridoe and Nanang, 2001). Mining policies and activities have also had direct impacts on the forest leading to loss of forests in the country (Kotey et al., 1998; Hawthorne and Abu-Juam, 1993).

Through government policy, the mining industry in a few decades has seen recapitalisation and more liberal legislation and fiscal regimes which have led to the opening up of closed forest areas for mining activities (GNA, 2010; Kotey et al., 1998; Hawthorne and Abu-Juam, 1993). Reforms which included legislation of small-scale mining have made the sector more active and vibrant but with little concern for the impacts on forest resources (Kotey et al., 1998). Logging and export trade in timber have also been a major determining factor of Ghana's policy on forestry (Kotey et al., 1998). Policies on forest resources particularly timber production and utilization have tended to support over-exploitation of economically-valuable species (Dadebo and Shinohara, 1999).

Due to advanced international technologies and changing demands the number of species being logged has increased to include those which were formerly of little economic importance (Kotey et al., 1998). The concession systems used were mostly devised with the intention of maximizing profits, at the expense of forest resource sustainability (Blom and Cummins, 2009).

2.1.2.5 Corruption and weak institutional governance

Corruption on the part of Forest Services Division officials, local leaders and the security agencies particularly police and military has also contributed to forest degradation and deforestation in the country (Marfo, 2010; Blom and Cummins, 2009; Siry et al., 2005; Palo and Lehto, 1996). There is growing perception that corrupt practices exists among officials of the Forestry Services Division and law enforcement agencies (Marfo, 2010). Illegal logging especially through chainsaw milling is prevalent and continues to increase in reserve areas, sometimes with the support of the police and forestry officials (Marfo, 2010; ITTO, 2006; Dadebo and Shinohara, 1999). The ban on illegal chainsaw milling has not been effective in Ghana due to corruption and lack of enforcement by the security agencies. There is the perception that Forestry officials sometimes connive with Timber Utilisation Contract holders to extract more trees than what is indicated through the stock survey.

In addition to corruption, weak institutional governance is also considered as a catalyst for illegal logging which eventually leads to forest degradation and deforestation (Marfo, 2010; Blom and Cummins, 2009; Dadebo and Shinohara, 1999). A study conducted by Marfo (2010) indicated that only 55 % of about 85 % of chainsaw offences reported by forestry officials are prosecuted by the police. The reluctance of the courts to reduce costs for prosecuting chainsaw milling related cases generally serve as a disincentive to forestry officials to monitor the activities of illegal chainsaw operators (Adam et al., 2007).

2.1.3 External factors

External factors such as foreign investments, international trade and market failures cannot be underestimated in the discussions about factors influencing deforestation in Ghana (Teye, 2005; Capistrano and Kiker, 1995).

2.1.3.1 Foreign investments

Foreign investments which provide substantial capital inputs to forest land conversions to more profitable other land form uses can be a major driver of deforestation (Blom and Cummins, 2009). In the early 1980s, Ghana adopted the Structural Adjustment Programs (SAP) from the International Monetary Fund (IMF) and other financial institutions after many sectors of the economy had seen an alternating cycle of boom and scarcity (Codjoe and Dzanku, 2009; Teye, 2005; Benhin and Barbier, 2004; Kotey et al., 1998). The SAP placed much emphasis on increasing exports rather than imports (Codjoe and Dzanku, 2009), devaluation of currencies (Cuddington, 1987 *in* Capistrano and Kiker, 1995), increased private investments from foreign companies (Blom and Cummins, 2009; Teye, 2005; Kotey et al., 1998), and borrowing (Teye, 2005). The macro-economic strategies under the program generally provided strong incentives for short-term profit making instead of long-term sustainability (Codjoe and Dzanku, 2009). Despite some gains such as reduction in inflation and increased Gross Domestic Products (GDP), the program had enormous negative environmental impacts like deforestation (Codjoe and Dzanku, 2009; Teye, 2005).

The SAP have had negative impacts on deforestation both directly and indirectly (Codjoe and Dzanku, 2009; Teye, 2005; Benhin and Barbier, 2004). Under the SAP, improved prices for cocoa production especially and improved credit facilities were incentives to expand cocoa production into forest areas (ISSER, 1992 *in* Benhin and Barbier, 2004).

The SAP also led to the expansion of the timber industry through the purchase of equipments and the promotion of value-added timber processing leading to the depletion of particularly off-reserve timber stock (Kotey et al., 1998). Benhin and Barbier (2004), found that cocoa land expansion and timber production were important causes of deforestation in Ghana. This conclusion was reached after they used a four-equation recursive model which consisted of forest loss, cocoa land, and maize land and timber production equations to assess the impacts of SAP on deforestation.

2.1.3.2 International trade and market failures

Government's economic policies which affect forest resources directly or indirectly sometimes have been influenced by conditions and factors beyond their control (Teye, 2005; Kotey et al., 1998; Capistrano and Kiker, 1995). Trade restrictions by the United States, European countries and other developed countries have affected efforts by successive governments to diversify the country's economy (Teye, 2005). This is situation is a result of the fact that international trade in the past few years have become globalised (Blom and Cummins, 2009). The globalised nature of trade has created a condition where local supply and demand no more dictates the direction of trade and also favours large- scale industrial and export oriented operations (Blom and Cummins, 2009). The effects of this phenomenon have been the expansion of the extraction sectors such as mining and increased demand for timber and other wood products which drive deforestation (Blom and Cummins, 2009; Teye, 2005; Kotey et al., 1998; Capistrano and Kiker, 1995). Moreover the nature of terms of trade even exacerbates the problem which further leads to the increased depletion of forest resources (Codjoe and Dzanku, 2009).

2.1.4 Effects of deforestation

Deforestation as a human impact on forest ecosystems (Riswan and Hartanti, 1995) has many negative effects with severe consequences for Ghana and the world as a whole. The rate of forest loss in the country raises concerns about the capacity of forests to meet the future demands for commodity products and ecological values (Dadebo and Shinohara, 1999). Deforestation and forest degradation have impacts on the economic (Marfo, 2010; Dadebo and Shinohara, 1999; Palo and Yirdaw, 1996), ecological (Amisah et al., 2009; Gyampoh et al., 2007; Teye, 2005; Benhin and Barbier, 2004; Moran, 1993; Sandler, 1993), and socio- cultural (Riswan and Hartanti, 1995) situation of the country. Deforestation is derailing the role that the forest plays in the economic growth and welfare of people in Ghana (Palo and Yirdaw, 1996). According to Marfo (2010) the present rate of destruction to the high forests may cause a serious threat to merchantable trees in the future.

The current estimates suggest that about 2.5 million m^3 of timber is added to the official AAC yearly through particularly illegal logging (Marfo, 2010). Deforestation also has negative impacts on the livelihood of people especially forest fringe communities (Amisah et al., 2009; Benhin and Barbier, 2004; Grainger, 1993). In addition, there are serious social consequences to indigenous communities and their ways of living as a result of deforestation and forest degradation (Riswan and Hartanti, 1995). Moreover deforestation has serious ecological consequences such as loss of biodiversity (Stephens and Wagner, 2007; Benhin and Barbier, 2004), soil degradation (Riswan and Hartanti, 1995; Teye, 2005), loss of productivity (Teye, 2005; Grainger, 1993; Sandler, 1993), disruption of watersheds (Gyampoh et al., 2007), and local climatic changes (Amisah et al., 2009; Gyampoh et al., 2007).

According to Benhin and Barbier (2004) the population of elephants in Ghana has declined due to the continued depletion of the high forest zone. This situation is considered to have a repercussive effect for natural regeneration since the seeds of timber species such as *Tieghemella heckelii* are dispersed by these elephants (Martin, 1991 *in* Benhin and Barbier, 2004). As soils become bare through deforestation they harden with time to form hardpans. This phenomenon reduces the ability for the soil to enhance natural regeneration and the agricultural potential of the soil (Teye, 2005; Benhin and Barbier, 2004). A study by Gyampoh et al., (2007) reported that deforestation and forest degradation have contributed to the low discharges in all water bodies and the complete drying of some streams in the Offin basin in the Ashanti Region of Ghana. Apart all these, the continue loss of forests have also led to changes in climatic conditions in Ghana, with eventual consequences for livelihoods (Amisah et al., 2009; Teye, 2005). Results from Gyampoh et al., (2007) showed a decrease of 22% in mean annual precipitation in response to a 1.3°C rise in temperature between 1961 and 2006 in areas around the Offin basin. Flows in the River Offin have subsequently decreased about 45% (6.9m^3 to 3.8m^3) within that same period (Gyampoh et al., 2007).

2.2 Measures to address forest degradation and deforestation in Ghana

Due to the continued forest loss and degradation in the country, several management options have been taken to rehabilitate degraded areas and to restore some of the over-exploited commercial species. 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 (EP)

Enrichment planting is mostly carried out either for commercial or silvicultural purposes (d' Oliveira, 2000; FAO, 1993). In the case of Ghana, the former was why it was considered. 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 5m within lines that were cut 20m. Though this approach has reportedly been successful in some secondary forests in the Amazon areas (Keefe et al., 2009; d'Oliveira, 2000) 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

Plantation development is another measure which has been adopted to rehabilitate degraded areas and also to restore over-exploited commercial species in Ghana (Foli et al., 2009; Zhang and Owiredu, 2007; Agyeman, 2004; Appiah, 2003; Odoom, 2002). 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, 1999). 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).

2.2.3 Current situation with forest plantation development in Ghana

Despite the failure of the Taungya system, new approaches have been adopted to enhance the development of plantations in the country (Wagner et al., 2008). In the country's bid to restore a considerable proportion of the original forest, Ghana's 1993 Forest and Wildlife Policy gave particular attention to reforestation (Zhang and Owiredu, 2007). According to FAO (2010), the country's area of productive plantation in 2005 was 160,000 ha. This represented just 2.9% of the total forest area. Plantations established have increased from 1,000 ha annually between 1990 and 2000 to 20,000 ha per annum during the period 2000- 2005 (FAO, 2010, Foli et al., 2009). The interest in plantation development has grown within a short period with both public and private sectors playing very active roles. This sudden interest in plantations is due to factors such as the increasing demand for teak poles, increasing degraded areas, reduced stocking of commercially valuable timber species, increasing land denudation through mining activities, tenurial reforms and benefit sharing arrangements (Foli et al., 2009; Blay et al., 2008; Zhang and Owiredu, 2007; Odoom, 2002). The current strategy under the Forest Plantation Development Program involves both the public (Modified taungya system on reserves, Small-farmer Agroforestry Scheme on off-reserves, HIPC Plantation programs, and President Initiative on Forest Plantations) and private (individuals, groups, and companies) sectors (Foli et al., 2009; Wagner et a., 2008; Agyeman, 2004).

These efforts were given a boost by the establishment of the Forest Plantation Development Fund (FPDF), Act 583 in 2000. The Act was established to provide financial assistance for the development of more private commercial forest plantations. Most of these plantations in both the public and private sectors are composed of exotic species with little attention given to indigenous species (Foli et al., 2009). As at 2004, there were about 40,000 ha of plantations which are managed by the Forest Services Division (FSD) for government. 15,000 ha of this figure are commercial timber plantations and about 70% composed of teak (*Tectona grandis*) with the remainder comprising *Gmelina arborea, Cedrela odorata, Terminalia superba, Terminalia ivorensis and Triplochiton scleroxylon* (Foli et al., 2009; Agyeman, 2004; Odoom, 2002). These plantations are capable of supplying about 5 million m^3 of timber annually (Agyeman, 2004).

There were also about 19,000 ha of private plantations in the same period mostly for timber production. These plantations were established by individuals, groups and companies and can supply up to 2 million m^3 of timber and poles per year (Agyeman, 2004; Odoom, 2002). Companies like Bonsu Vonberg Farms Ltd., Subri Industrial Plantation Ltd. (SIPL), Pioneer Tobacco Company Ltd. (PTC) and Ashanti Goldfields Company Ltd. (AGC) have invested substantially in commercial plantations of mostly *Gmelina arborea*, *Eucalyptus* and *Cassia* species (Odoom, 2002). These modest efforts from both the public and private sectors have however been constrained by land acquisition, wildfires, inadequate silvicultural information, access to quality seeds and seedlings, lack of access to credit facilities, high establishment costs, ineffective management and supervision and pest and diseases (Zhang and Owiredu, 2007; Agyeman, 2004; Blay, 2004; Odoom, 2002).

Empirical studies by Zhang and Owiredu (2007) showed plantation establishment to be positively influenced by the amount of land owned and/or cultivated by farmers and farmers access to government extension services. In addition, land market reforms and market incentives also have the potential to improve forest plantation establishment (Zhang and Owiredu, 2007).

2.2.4 Importance of plantations

Due to the near impossibility of the world's natural forests to meet demands placed on them (Bowyer, 2001), plantations have become the obvious option to meet this challenge (Foli et al., 2009; Lugo, 1997). It is estimated that about 4.5 million ha of forest plantations are established each year in the world (Siry et al., 2005). These plantations have been found to function similarly as secondary forest stands under certain conditions (Lugo, 1997). 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; Lamb et al., 2005; Kobayashi, 2004; Lamb, 1998; 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; FAO, 1992), 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). Forest plantations can therefore play a very important role in harmonizing long-term forest restoration and rehabilitation goals with medium-term socioeconomic development objectives (Blay et al., 2008; Parrotta et al., 1997).

2.2.4.1 Production of timber and other wood products

Forests are being influenced by population growth through the rise in demand for wood and other wood products (Bowyer, 2001; Powers, 1999). The rising demand is leading to rapid decreasing forest area per capita (Bowyer, 2001) and degradation of forests (Fenning and Gershenzon, 2002). The wood requirement of the timber industry in Ghana is estimated to be approximately 4 million $m^{3,}$ which exceeds the Annual Allowable Cut from the natural forests (Agyeman, 2004). This deficit has lead to the prediction that Ghana might become an importer of wood in the future (Foli et al., 2009). To meet this shortfall and future demands for timber and other wood products like fuelwood, plantation establishment is the obvious option (Foli et al., 2009; Kelty, 2006; Odoom, 2002; Bowyer, 2001; Lugo, 1997). Forest plantations have the potential to supply the bulk of the nation's wood needs on a long-term basis (Fenning and Gershenzon, 2002; Sedjo, 1999). Plantations that have been established already in Ghana are estimated to have the potential to supply about 7 million m^3 of timber annually (Agyeman, 2004). Because forest plantations are usually more productive than natural forests (Foli et al., 2009; Bowyer, 2001; FAO, 1993), when managed very well they can achieve high growth rates and high wood quality (Kelty, 2006; Siry et al., 2005).

2.2.4.2 Restoration of degraded lands

Forest plantation establishment is considered as one of the potential mechanisms through which large areas of degraded forest lands can be restored (Kelty, 2006; Lamb et al., 2005; Bowyer, 2001; Lamb, 1998). Though Ghana's forests are highly degraded (Marfo, 2010), plantations can be effective in restoring those areas and also provide other socio-economic and environmental benefits (Siry et al., 2005).

This process becomes possible because plantations help to restore productivity and ecosystem stability of these degraded lands (Parrotta, 1992), by increasing biomass and nutrient accumulation, restoring soils, improving microsite conditions and accelerate forest regeneration (Cusack and Montagnini, 2004; Montagnini, 2001; Lugo, 1997; Parrotta, 1992). They also act as nurse trees to shade out grass and other vegetation and provide a forest habitat structure that attracts animal dispersers (Kelty, 2006; Parrotta et al., 1997). Tree plantations are being used to help restore and rehabilitate both degraded reserve and off-reserve areas in Ghana (Blay et al., 2009; Blay et al, 2008; Bosu et al., 2006). Plantations of particularly mixed species have been recommended as an approach to restore most of the over-exploited indigenous species (Bosu et al., 2006; Nichols et al., 1999). Apart from Ghana, tree plantations have also been used as a cost-effective tool to aid the process of restoring degraded forest lands in the Amazonian region (Larsson, 2003; Parrotta and Knowles, 1999), Asia (Kobayashi, 2004; Ashton et al., 1997), Latin America (Piotto et al., 2004; Guariguata et al., 1995) and other parts of Africa (Lemenih, 2004; Yirdaw, 2002).

2.2.4.3 Restoration of biodiversity

Depending on the design and management of reforestation projects (Lamb et al., 2005; Hartley, 2002; Cannell, 1999), plantations established on degraded lands can be important in restoring biological diversity (Rotenberg, 2007; Cossalter and Pye-Smith, 2003; Lindermayer et al., 2003; Bowyer, 2001, Parrotta, 1992). Plantations can enhance biodiversity by either protecting remnants of original vegetation and allowing them to proliferate or creating new ecosystems altogether (Cossalter and Pye-Smith, 2003; Lindermayer et al., 2003). As trees grow and canopy is developed, microsite conditions change and animal dispersers are attracted (Parrotta et al., 1997; Parrotta, 1992). Various studies have shown that plant and animal species richness can be similar or even better in plantations than other forest types (Rotenberg, 2007; Saha, 2001; Van der Merwe et al., 1996).

Rotenberg (2007) observed a positive correlation between increased vegetation complexity and bird species richness when he examined bird use of *Gmelina arborea* plantation in tropical lowlands of Guatemala. He also found bird species richness to be statistically indistinguishable from those in nearby forest fragment. A survey of ground-living spiders by Van der Merwe et al., (1996) in Ngome State Forest, Kwazulu/Natal-South Africa, found no significant difference in mean values of spider diversity between pine plantations and other habitat types like grass, open forest and dense forest. Saha (2001) also reported that *Tectona grandis* plantations had similar woody species richness as compared to a dry semi-deciduous secondary forest in Central India. Plantation forests thus provide habitat and also improve landscape matrix elements by increasing connectivity of natural forest remnants (Brockerhoff et al., 2008). However, managing plantations to promote heterogeneity and stand structure complexity to enhance biodiversity involves trade-offs which may affect timber production (Lindermayer et al., 2003; Cannell, 1999).

2.2.4.4 Tool for poverty alleviation and community participation in reforestation programs

Studies have indicated that reversing tropical forest degradation would require the involvement of local communities in tree domestication together with activities which address livelihoods (Blay et al., 2009; Blay et al., 2008; Kobayashi, 2004; Piotto et al., 2004). Increasing attention is therefore been given to local community-based forest reforestation as an alternative and novel way of addressing conflicting goals of livelihood improvement and sustainable forest management (GNA, 2010; Agyeman, 2004; Piotto et al., 2004). Employment creation for especially rural communities has been one of the major objectives for plantation development in Ghana (Agyeman, 2004; Odoom, 2002). One main component of the second phase of the National Plantation Development Program (NPDP) for the country is to improve the livelihoods of 100 districts across the country by creating over 51,000 jobs (GNA, 2010).

The Modified taungya system been practised in Ghana allows for both the establishment of plantations and introduction of sustainable cropping systems, where seedlings are grown together with crops (Appiah, 2003). Farmers grow annual crops and vegetables such as plantain, cocoyam and tomatoes till the stage of canopy initiation. The operations involved in establishing the plantations like seedling production, site preparation, planting, replanting and weeding also provide short-term employment and income to local communities. The taungya system been used in Indonesia to rehabilitate a degraded mixed dipterocarp forest also has the same approach (Kobayashi, 2004). Local farmers are given the opportunity to grow annual crops among seedlings to improve on their livelihoods (Kobayashi, 2004).

Some restoration projects in the tropics have strong community participation components (Blay et al., 2009; Blay et al., 2008; Kobayashi, 2004; Piotto et al., 2004). The Modified taungya system, HIPC Plantation Program and the Small-farmer Agroforestry Scheme under the Plantation Development Program in Ghana have been designed to involve forest fringe communities in their implementation (Agyeman, 2004). A project carried out by Blay et al.,(2009) to rehabilitate degraded forest sites in some selected forest districts was done with the collaboration of 10 local communities. The initial outcome after four years of project implementation showed that community-based approaches can be used to reverse tropical forest deforestation (Blay et al., 2009). Reforestation programs undertaken in other tropical countries like Costa Rica and Nicaragua also had local community involvement, with farmers especially very much part of the implementation (Piotto et al., 2004).

2.2.4.5 Reducing pressure on natural forests

Though the relationship between natural forests and forest plantations is very complex and there is no consensus on the subject (van Bodegom et al., 2008; Cossalter and Pye-Smith, 2003), under certain circumstances plantations can potentially reduce pressure on natural forests (Stephens and Wagner, 2007; Zhang and Owiredu, 2007; Kelty, 2006; Siry et al., 2005; Odoom, 2001; Sedjo, 1999). Plantations are seen as alternative sources of supply of wood products to natural forests and can therefore be used to reduce the need to exploit the natural forests (Stephens and Wagner, 2007; Odoom, 2001; FAO, 1993). Zhang and Owiredu (2007) stated that plantation establishments were started in Ghana among other things to reduce pressure on the existing natural forest.

In recent times about 90% timber requirements in New Zealand, Chile and Uruguay are satisfied by plantations which have contributed considerably to reducing pressure from the native natural forests (Cossalter and Pye-Smith, 2003). This situation has become possible because tree plantations are typically highly productive as compared to natural forests and they can allow for concentrated wood production on a smaller area (Foli et al., 2009; Siry et al., 2005; Bowyer, 2001). Research in Ghana has demonstrated that some species perform better in plantations than in the natural forest (Foli et al., 2009). Those species showed higher growth rates even under poorly managed conditions and shorter time passage to reach a DBH of 60cm in plantations than under natural forest conditions (Foli et al., 2009). Although productivity in plantations may be higher than natural forests (Kelty, 2006), there is the need to ensure an appropriate balance between production from natural forests and tree plantations and therefore the management of natural forests and plantations are done on a complementary basis (Bowyer, 2001; Odoom, 2001; Grainger, 1993).

2.2.4.6 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).

2.2.4.7 Rehabilitation of damaged sites

There has been an increase in damaged sites which need rehabilitation (Bowyer, 2001; Lugo, 1997). Forest plantations can be an effective tool for arresting site damage and catalysing land rehabilitation (Brown and Lugo, 1994; Parrotta, 1992). Tree plantations for instance have been used for mine spoil rehabilitation (Kelty, 2006; Parrotta and Knowles, 1999), because they have the ability to hasten succession by providing shade, restore soil fertility and ameliorate microclimatic conditions (Parrotta and Knowles, 1999; Brown and Lugo, 1994). Tree plantations can improve soil conditions by increasing the mass and concentration of organic matter and available nutrients (Lugo, 1997).

After evaluating a 13-year old plantation stands on a bauxite-mined site in Trombetas (Pará) Brazil, Parrotta and Knowles (1999) concluded that there was a high probability for long-term restoration success despite the stands relatively poor species richness. Therefore through careful selection of species and management practices based on sound ecological understanding, forest plantations can be a promising tool for wasteland rehabilitation (Parrotta, 1992).

2.2.5 Environmental impacts 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; Zhou et al., 2002, 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 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 (Zhou et al., 2002; 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. They also found 12 different species of granivores and insectivores breeding in the secondary forest but none in the plantation. They later concluded that the uniform age and physiognomy of the plantation trees resulted in less structural complexity and therefore provided fewer habitats for the birds (Kwok and Corlett, 2000). 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)

2.3 Monocultures or monospecific species plantations

Based on their structural complexity or number of species involved, planted forests can either be classified as monoculture (monospecific species) or polycultures (mixed species) plantations (Nichols et al., 2006; Evans, 1999; Wormald, 1992). 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; Erskine et al., 2006). Monocultures which have a long history are mostly the favoured plantation method throughout the tropics including Ghana (Foli et al., 2009; Erskine et al., 2006; Odoom, 2002). Monospecific species plantations are usually composed of exotic single, even-aged species in a compartment (Wormald, 1992) with a homogenous spatial and temporal plant structure (Bragança et al., 1998). They have very simplified structures and reduced number of specialised species.

Though monocultures especially the young ones have simple structures (Lugo, 1997), old plantations have the potential to develop complex structures relatively similar to intact forests (Kanowski et al., 2003). The establishment 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 (Cossalter and Pye-Smith, 2003; Powers, 1999; Sedjo, 1999). 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).

Over 50%-70% of plantations in Ghana are composed of teak monocultures (Foli et al., 2009; Odoom, 2002). Even though these monoculture plantations are promoted as windbreaks, sources of biomass for paper pulp, fibre and fuelwood (Turnbull, 1999), the primary purpose is for the production of commercial timber (Nichols et al., 2006; Cossalter and Pye-Smith, 2003; Powers, 1999; Sedjo, 1999; Turnbull, 1999).

2.3.1 Why monoculture plantations are widespread

Monocultures are the preferred plantation choice because of certain advantages over mixed species plantations (Piotto, 2008). Monoculture plantations are highly productive, relatively simple to manage and usually produce uniform harvest products (Kelty, 2006; Siry et al., 2005; Evans, 1992).

2.3.1.1 High productivity per unit area

In most monoculture plantations, species are specifically selected to match a particular site (Cossalter and Pye-Smith, 2003). This ensures that the species make use of the full potential of the site for optimal growth (Lamb, 1998). Through the phenotypic selection, initial spacing, thinning regimes and rotation length monoculture plantations can be manipulated to produce the desired crops (Hodgman and Munger, 2009; Evans, 1992).

Monocultures can therefore be managed in such a way that all the site resources are concentrated on the growth and production of wood quality on a small area (Piotto, 2008; Kelty, 2006; Binkley et al., 2003). Fast-growing monoculture plantations can produce at least 15m^3 of wood per hectare per year (Cossalter and Pye-Smith, 2003). Due to the potential high productivity, some hold the view that the most appropriate way to successfully grow industrial timber is the use of monoculture plantations (Powers, 1999; Sedjo, 1999).

2.3.1.2 Relatively simple to manage

Monoculture plantations are relatively simple to manage due to their even-aged structure (Hodgman and Munger, 2009; Kelty, 2006; Wormald, 1992). Their structure makes silviculture simple because experience is gained in handling the desired species (Lamb, 1998; Evans, 1992). This also makes operations regularised since planting, tending and thinning are carried out over the whole stand. The knowledge acquired from handling the same species can speed up detection of problems like diseases (Evans, 1992). Moreover in times of pest attack, it may also be easier to treat the stands than in mixtures (Wormald, 1992).

2.3.1.3 Production of uniform end-product

Monoculture plantations usually consist of stands of same species age class selected to suit the needs of the intended use or market (Evans, 1992). With a clear intended purpose, standardized silviculture and harvest operations can be used to produce relatively uniform and homogenous products (Kelty, 2006).

2.3.2 Disadvantages of monoculture plantations

Though monocultures are the predominant plantation types in the world including the tropics (Piotto, 2008; Erskine et al., 2006; Wormald, 1992), 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; Kohli et al. 1996; Butterfield and Malvido, 1992), susceptibility to disturbances (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Riihimäki et al., 2005; Nichols et al., 1999), low resource use efficiency (Dünisch et al., 2003; Cannell, 1999; Evans, 1999; Khanna, 1998) and low level of product diversification (Lamb et al., 2005; Odoom, 2002; Lamb, 1998).

2.3.2.1 Less support for biodiversity

Even though plantation forests have been found to generally provide habitat for species and contribute to conservation of biodiversity (Brockerhoff et al., 2008; Parrotta, 1992), monocultures are considered to rarely support biodiversity (Carnevale and Montagnini, 2002; Kohli et al., 1996; Butterfield and Malvido, 1992). Monoculture plantations are usually composed of single, even-aged species with homogenous spatial and temporal plant structure (Bragança et al., 1998; Wormald, 1992). The structural simplicity and resource homogeneity render the plantations less diverse therefore influencing the abundance and richness of plant and animal diversity they sustain (Erskine et al., 2006; Lamb, 1998).

This phenomenon has been confirmed by some studies which show that pure or monoculture plantations indeed do not support high biodiversity. Carnevale and Montagnini (2002) found highest abundance of regenerating tree individuals in the understorey of mixed plantation composed of *Hieronyma alchoneoides*, *Vochysia ferruginea, Balizia elegans*, and *Genipa americana* with 10,156 individuals/ha than all the monoculture plantations of the same species.

The results also showed highest mean number of species in the mixed plantation (11 species in $32m^2$) followed by monoculture plantations of *Vochysia ferruginea* (8.0 species), *Hieronyma alchoneoides* (7 species), *Balizia elegans* (5 species) and *Genipa Americana* (3 species) (Carnevale and Montagnini, 2002). These results came out after they investigated tree regeneration under mixed and monoculture plantations of native species at La Selva Biological Station in the Atlantic lowlands of Costa Rica (Carnevale and Montagnini, 2002). Another study by Kohli et al., (1996) at the outskirts of Chandigarh India also 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). Results from Butterfield and Malvido (1992) also indicated that mixed tree planting, whether broad-leaf or conifer resulted in higher densities of ground beetle carabids than conifer monocultures. These studies concluded that the low structural variation of the monocultures had contributed to the reduced biodiversity.

However Butler et al., (2008), found no significant difference between the understorey composition of 15-16 years monoculture and mixed plantations of *Jacaranda copaia, Vochysia guatemalensis, Dipteryx panamensis* and *Vochysia ferruginae* in abundance, species richness, and seed-dispersal pattern at La Selva Biological station in Costa Rican Caribbean lowlands. A study on species effects on earthworm density in tropical tree plantations in Hawaii reported higher earthworm densities in monoculture plantations than mixed stands (Zou, 1993). The results showed that mean earthworm densities ranged from $92m^{-2}$ in monoculture *Eucalyptus saligna*, to $281m^{-2}$ in mixtures (25% *Albizia falcatoria* and 75% *Eucalyptus saligna*) and a maximum of $469m^{-2}$ in monoculture *Albizia falcatoria* stands (Zou, 1993).

Despite the assertion that monocultures hardly supports high biodiversity, abundance, richness and species composition in plantations may be species-specific or in the case of mixtures may depend on the type of species combination as well as the intensity of management (Brockerhoff et al., 2008; Butler et al., 2008; Guariguata et al., 1995). Moreover the maximization of timber yield per unit area which usually characterises monocultures is likely to be incompatible with high biodiversity (Cannell, 1999; Wormald, 1992) due to trade-offs between productivity and provision of biodiversity (Lamb et al., 2005; Lindermayer et al., 2003; Lamb, 1998)

2.3.2.2 Susceptibility to disturbances

There is still debate about the susceptibility of forest monoculture plantations to disturbances such as pests and diseases (Schuldt et al., 2010; Kaitanienen et al., 2007; Vehviläinen et al., 2007; Gadgil and Bain, 1999; Folgarait et al., 1995; Wormald, 1992). Gadgil and Bain (1999) indicated that fast-growing intensively managed monoculture plantations have better health due to their general good conditions, proper matching of species to sites and freedom from natural enemies especially in exotics. However many authors have also argued that most monoculture plantations are susceptible to disturbances particularly pests and diseases (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Riihimäki et al., 2005; Bowyer, 2001; McCracken et al. 2000). Monocultures are generally prone to pest attacks because of resource concentration which allows for immediate population expansion as well as the relatively homogenous spatial and temporal structure which increases resource predictability and hence easing pest attacks (Erskine et al., 2006; Bragança et al., 1998). Moreover due to their relatively simplified structure as well as intensive silvicultural practices (Brockerhoff et al., 2008; Lugo, 1992), natural enemies are less abundant in monocultures due to unsuitable climatic conditions (Altien et al., 1993) and the absence of foraging, resting and oviposition sites (Cobbinah et al., 2004; Wormald, 1992).

Nichols et al., (1999) reported that *Milicia excelsa* were colonized much faster by *Phytolama* spp. in monoculture *Milicia* plantation than in mixture with *Terminalia superba* in Ghana. They recommended among other things that silvicultural strategies which promote natural enemies may be helpful in *Milicia excelsa* plantation management (Nichols et al., 1999). McCracken et al., (2000) also found low level presence of pathotype composition of *Melampsora epitea* populations on mixed species of *Salix viminalis* and *dasyclados* and three other varieties of *Salix* than their respective monocultures in Northern Ireland. The damage caused by pine shoot in Uruguay has been the reason for the eventual abandonment of monoculture *Pinus radiata* plantations in the country (Cossalter and Pye-Smith, 2003). Folgarait et al., (1995), however found no difference in infection between monoculture of *Styphnodendron microstachyum* and mixed-species of *Styphnodendron microstacyum* and four other species. Vehviläinen et al., (2007) and Ciesla (2001) therefore cautioned that insect herbivory responses to forest diversity are highly variable and could depend on host tree species and the type of herbivore.

2.3.2.3 Low resources use efficiency

Productivity of tree plantations is described as a function of the supply, capture and efficient use of resources (Richards et al., 2010). Therefore the efficient use of resources such as light, water and nutrients is a very important long-term determinant of plantation productivity (Evans, 1999; Parrotta, 1999; Binkley et al., 1992). Concerns have therefore been raised about the negative impacts of monoculture plantations on sites (Dünisch et al., 2003; Khanna, 1998; 1997). The water use efficiency of monocultures has been found to be low due to the relatively large interception losses (Dünisch et al., 2003; Cannell, 1999). This implies the total loss of water from monoculture plantations is usually high.

Dünisch et al., (2003) found the intra-annual variation of water fluxes to be low in enrichment plantation compared to monocultures, when they compared the water balance, water potential and leaf water potential in a monoculture and enrichment plantation of *Carapa guianensis* on a 'terra firme' site near Manaus, Central Amazon. The long-term sustainability of fast-growing single species plantations is also been questioned due to their effects on soil fertility (Evans, 1999; Khanna, 1998; 1997). The growth rates and short rotation of monocultures can overstress the sites leading to diminish fertility and subsequently poorer yields (Evans, 1999). Losses of N and P from sites through biomass harvest and during site preparation constitute a major threat to nutrient content (Khanna, 1998; Binkley et al., 1992). The repeated harvesting of short rotation *Eucalyptus* for instance depletes site nutrients because of removal of nutrients in the harvested wood and other tree components (Khanna, 1997). A study by Parrotta (1999) showed that the rates of nutrient return for N, P, K, Ca and Mg were higher in mixed stands (50:50) of *Casuarina equisetifolia, Eucalyptus robusta* and *Leucaena leucocephala* than in monoculture stands. Binkley et al., (1992) also reported of greater light capture and high use efficiency in mixed stands of 34%*Eucalyptus*/66%*Albizia* than in monoculture stands of *Eucalyptus* and *Albizia*. Binkley et al., (1992) however stated that resource-use efficiency in plantations differ among species and combination of species.

2.3.2.4 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.

Although management of high valued tropical species includes thinning, there is often no market for the small logs produced (Kelty, 2006; Lamb, 1998). Moreover because monoculture plantations mostly consist of one or few species, in the event of market failure or pest infestation there could be serious challenges. Odoom (2002) reported that the risk of plantation establishment in Ghana has increased due to the low level of diversification.

2.4 Mixed-species plantations

Most plantations in the tropics consists of monocultures (Cossalter and Pye-Smith, 2003; FAO, 1995; Wormald, 1992), however many are advocating in recent times for the expansion of mixed-species plantations (Piotto, 2008; Erskine et al., 2006; Forrester et al., 2006; Kelty, 2006; Nichols et al., 2006; Montagnini et al., 1995). Mixed plantations which cover a very small percentage of the world's plantations (Kelty, 2006) mostly consists of two or more species but usually vary in designs (Vanclay, 2006). Depending on site and silvicultural requirements, mixtures can be arranged as tree by tree, line by line, mixed species of small groups or compartment with different species (Wormald, 1992). Based on the canopy stratification, mixed-species plantations can be classified as either two-layered canopy (consisting of temporary or permanent mixture) or single-layered canopy mainly made of permanent mixtures (Wormald, 1992). Research has shown that when mixed-species plantations are appropriately designed (Kelty, 2006; Vanclay, 2006) they can be an effective management tool to achieve high product diversification (Erskine et al., 2006; Vanclay, 2006; Lamb et al., 2005), improve soil fertility and nutrient cycling (Binkley et al., 2003; Binkley et al., 1992; Wormald, 1992), support biodiversity (Stephens and Wagner, 2007; Carnevale and Montagnini, 2002; Butterfield and Malvido, 1992), rehabilitate degraded areas (McNamara et al., 2006; Lamb, 1998), reduce the risk of pests damage (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Bosu et al., 2006; Riihimäki et al., 2005; Nichols et al., 1999; Montagnini et al., 1995) and greater productivity (Richards et al., 2010; Potvin and Gotelli, 2008; Forrester et al., 2007; Parrotta, 1999; DeBell et al., 1997). Mixed plantations can therefore be used to achieve varied economic, silvicultural, ecological and sustainability goals (Forrester et al., 2005; Lamb et al., 2005).

2.4.1 Productivity in mixed-species plantations

Even though there is a debate about whether mixed-species plantations can achieve greater productivity than monocultures (Piotto, 2008; Firn et al., 2007; Erskine et al., 2006; Vilà et al., 2003; Wormald, 1992), studies show that mixtures can be highly productive (Nadrowski et al., 2010; Potvin and Dutilleul, 2009; Piotto, 2008; Potvin and Gotelli, 2008; Bristow et al., 2006; Forrester et al., 2005; DeBell et al., 1997; Binkley et al., 1992; Kelty, 1989). Results from indigenous trees plantation in Central Panama showed that mixed-species plots had greater tree growth compared to monocultures (Potvin and Dutilleul, 2009). A meta-analysis carried out by Piotto (2008) to compare tree growth in monocultures and mixed plantations found that mixing tree species generally increase plantation growth. Forrester et al., (2007) also reported that mixtures of *Eucalyptus globulus* and *Acacia mearnsii* were twice as productive as *Eucalyptus globulus* monocultures growing on the same site in East Gippsland, Australia.

Another study by DeBell et al., (1997) in a 10-year old plantation in Hamakua coast of the Island of Hawaii showed increased growth of *Eucalyptus saligna* with increasing percentage of *Albizia falcataria* in the stand. Erskine et al., (2006) also reported that four out of five plantation species were more productive in mixtures with other species than in monocultures of respective species, offering on the average 55% increase in mean total basal area. Biomass production and nutrient cycling was found to be greater in mixtures of *Eucalyptus saligna* and *Albizia falcataria* than in monoculture stands of the same species in a 6-year old plantation near Hakalau on the northeast coast of Hawaii (Binkley et al., 1992).

Average biomass of 174 Mg/ha was reported in 34%*Eucalyptus*/66%*Albizia* treatment as against 148Mg/ha in fertilized monoculture *Eucalyptus* and 132Mg/ha in monoculture *Albizia* stand (Binkley et al., 1992). The relatively high productivity reported by these authors was due to the net result of positive and negative interactions among the component species (Jose et al., 2006).

2.4.2 Competition in mixed-species plantations

Competition is one of the most important interactions which can influence productivity and growth in mixed stands of trees (Richards et al., 2010; Piotto, 2008; Forrester, 2004; Callaway et al., 2002). This phenomenon is crucial because in any natural community one species may influence another species directly or indirectly (Hunt et al., 2006; Jose et al., 2006; Cannell et al., 1984). Therefore competition is a very important factor which influences growth and survival of individual plants (Firbank and Watkinson, 1985). 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; Moran, 1997). Competition is mostly for any one or more factors of light, water and nutrients and the closer any two plants are in their responses to limitations in these variables, the more intense the competition between them (Hunt et al., 2006). The distribution of competition in stands is a reflection of the availability of resources for which plants are competing. Competition for light in most cases is asymmetrical because tall plants can shade small plants but not the opposite (Forrester et al., 2006). Competition for below ground resources such as water and nutrients on the other hand is usually symmetric, although in certain situations it can be asymmetrical (Jose et al., 2006). Both intra- and inter-specific competitions exist in mixed plantings and it is nearly impossible to separate the two (Forrester et al., 2006; Firbank and Watkinson, 1985).

However, the effects and responses of the competing variables must be significant to have any relevance (Grace and Tilman, 1990 *in* Hunt et al., 2006).

2.4.3 Intra- and inter-specific competition

Both intra-and inter-specific competition occur in mixed-species plantations therefore leading to relatively more complex interactions (Forrester, 2004). The determination of the net effect of all interactions between plants is the intra- and inter-specific competition (Forrester et al., 2006). Based on yield-density relationship, intra- and inter-specific competition can be described for species in monoculture and mixed plantations (Firbank and Watkinson, 1985). The mean yield per any plant is a function of density in monocultures but where there is no interference within or between species, total yield of each component in a two species mixture is directly proportional to its density (Firbank and Watkinson, 1985).

When intra- and inter-specific competition is the same (or density is too low for interaction), the mean plant size and overall size difference is almost the same in mixed and monoculture plantations (Forrester et al., 2006). In instances where inter-specific competition is higher than intra-specific competition for both species the average size of both species in mixture will be smaller than in monoculture plantations (Forrester, 2004; Powers, 1999). This is so because inter-specific competition is usually attributed to factors like mutual exploitation of limiting resources, direct density effects, production of toxins or a combination of these mechanisms (Tilman, 1987). These mechanisms eventually results in the reduction of survival or growth in species (Jose et al., 2006). However when inter-specific competition is lower than intra-specific competition for both species the average size of both species in a mixture will be greater than in monoculture and the yield of mixtures will also be higher than monocultures (Forrester et al., 2006; Erskine et al., 2006).

Apart from competition, two other interactions or processes which influence growth and productivity of mixed-species plantations are facilitation and complementarity or competitive reduction (Erskine et al., 2006; Kelty, 2006; Forrester et al., 2005; Fridley, 2001; Callaway, 1998).

2.4.4 Facilitation

This is a production mechanism which involves one plant species directly benefiting the growth of another species (Cavieres and Badano, 2009; Kelty, 2006; Forrester, 2004; Callaway et al., 2002; Callaway, 1998), through the beneficial effects on intermediary resources (Fridley, 2001). Facilitation may occur when a neighbouring plant species improve harsh environmental conditions, increase resource availability, introduce beneficial organisms or provide protection from herbivores (Forrester et al., 2005; Callaway, 1998; Callaway and Walker, 1997; Callaway, 1995).

However the main use of the facilitation process in plantations is nutrient enrichment through the combination of nitrogen fixing species and non-nitrogen fixing economic tree species (Forrester et al., 2006; Fridley, 2001; DeBell et al., 1997). The major objective is to improve the nutrition and therefore increase the growth of the non-N-fixing species (Kelty, 2006). This is achieved as nitrogen availability is increased through symbiotic N-fixation (Simard et al., 1997), nutrient cycling (Kelty, 2006; Prescott, 2002; Binkley et al., 1992) and changes in C allocation (Forrester, 2004). The increased in the production of mixtures of *Eucalyptus globulus* and *Acacia mearnsii* in Victoria, Australia was attributed to the possible increase in nitrogen availability due to the presence of *Acacia mearnsii* (Forrester et al., 2007). Binkley et al., (1992) also concluded that the greater nutrient cycling rates of *Albizia falcataria* together with the high nutrient-use efficiency in *Eucalyptus* accounted for the greater productivity in mixed stands.

The presence of *Acacia mearnsii* and *Albizia falcataria* increased the availability of nitrogen to the *Eucalyptus* (Binkley et al., 1992). DeBell et al., (1997), reported that the growth of *Eucalptus saligna* increased as the amount of *Albizia facaltaria* in the stands increased. A study by Khanna (1997) in Southeast Asia on agroforestry systems concluded that *Acacia* fixes nitrogen during the early years of stand establishment and a large proportion is later used by *Eucalyptus* to improve growth and nutrition. These examples show that when positive interactions are dominant, mixed stands may be more productive than monocultures (Forrester et al., 2004). However, Callaway (1998) cautions that although some facilitation relationships may be a result of simple, non-species-specific changes in environmental conditions, many others may be species-specific.

2.4.5 Complementarity

Most research on interactions in mixed-species plantations have focused on facilitative processes rather than complementarity of resource use (Kelty, 2006). However complementarity or competitive reduction is an important mechanism which influences productivity of mixed plantations (Oelman et al., 2010; Erskine et al., 2006; Jose et al., 2006; Menalled et al., 1998). Complementarity occurs when competition from inter-specific neighbours is lower than that from conspecifics (Fridley, 2001). Thus species with complementary characteristics have inter-specific competition that is much lower than intra-specific competition (Cardinale et al., 2007; Kelty, 2006). It mostly occurs in a situation when there is a partitioning of either above or below ground resources which leads to niche separation (Oelmann et al., 2010; Forrester, 2004; Menalled et al. 1998). This principle therefore considers combination of species with different characteristics such as shade tolerance, height growth rate, crown structure, foliar phenology and root depth and phenology (Forrester et al., 2006; Kelty, 2006).

The differences in traits (Oelman et al., 2010; Menalled et al. 1998) may therefore lead to the use of different resources, different amounts of resources types or exploitation of the same resource at different time scales (Fridley, 2001). Thus the component species should be more efficient in accessing and utilising site resources, resulting in total stand biomass production than would occur in monocultures (Erskine et al., 2006; Kelty, 2006). An example of competitive reduction in stand development was demonstrated when a 4-year old plantation of monoculture and mixtures of *Cordia alliodora, Cedrala odorata*, and *Hyeronima alchorneoides* were evaluated for interspecific structural characteristics in the humid Atlantic lowlands of Costa Rica (Menalled et al., 1998). The study found that *Cordia* and *Hyeronima* developed larger mean crown size and breast-height diameters in mixtures than monocultures. The compatibility of the two species was attributed to the formation of a stratified canopy in the mixtures. This resulted in the interception of sufficient light in the upper canopy to allow high productivity of *Cordia* and also enough radiation transmission to the dense, evergreen crowns of *Hyeronima* for rapid growth (Menalled et al., 1998). Kelty, (1989) noted that the establishment of mixed-species plantations with shade-tolerant understorey species may increase yields and reduce competition from understorey vegetation.

2.5 Main challenge with mixed-species plantations

Even though the basic silvicultural requirements for successful mixed-species plantations have been established (Nichols et al., 2006), 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 are therefore more intensive and generally require 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.

2.6 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, 1999; 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).

2.6.1 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 constraint 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 gall-forming 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).

The continual infestations of *Orygmophora mediofoveata* in plantations have been partly blamed for the lack of large scale plantations of *Nauclea diderrichii* in Ghana (Wagner et al., 2008). Apart from the above, *Pericopsis elata* which is one of the most important timber species of the Family Papilionaceae is also affected by caterpillars of pyralid moth which feed gregariously on the leaves leading to growth reduction and death in multiple attacks (Wagner et al., 2008; Atuahene, 1996).

2.7 Description of focal Indigenous species

2.7.1 *Pericopsis elata* (Harms.) van Meewen

Pericopsis elata also called Afrormosia is a species with rare availability in Ghana which belongs to the Family Papilionaceae (Oteng-Amoako, 2006). It is one of the most important commercial species in that family in the timber trade (Atuahene, 1996; Britwum, 1976). Due to its excellent physical properties and durability (TROPIX, 2009), it is considered as an appropriate alternative to teak (Oteng-Amoako, 2006; Atuahene, 1996; Britwum, 1976).

Pericopsis elata is listed in CITES appendix 2 and in the European Union Regulation appendix B because of the high unsustainable exploitation rate (TROPIX, 2009). There has been a decline in the species in Ghana over the years due to lumbering and paucity in natural regeneration (Atuahene, 1996; Britwum, 1976).

2.7.1.1 Morphology

Pericopsis elata is a dominant tree which grows up to a height of about 45m and DBH of 200cm (Oteng-Amoako, 2006). It has a fan-shaped crown and enormous spreading branches. The bole is straight but with low blunt buttresses up to 2.5m high (Oteng-Amoako, 2006; Britwum, 1976). The bark is smooth, light-coloured but flakes off in irregular scales (Britwum, 1976). The leaves are pinnate with a common stalk grooved along the surface and fruits mostly in December (Oteng-Amoako, 2006).

2.7.1.2 Distribution and Ecology

Pericopsisi elata occurs in the mid-west of Ghana between latitude 6° 45′ and 7° 30′N and between 3° and 1° 30′W (Britwum, 1976). The species is sparsely available in Ghana and restricted to the Moist semi-deciduous (North west subtype) and Dry semi-deciduous forests (Oteng-Amoako, 2006; Agyeman et al., 1999; Veenendaal et al., 1996). *Periocpsis* is drought tolerant (Agyeman et al., 1999) but also common in swampy and flat areas (Oteng-Amoako, 2006). It has been described as a non-pioneer light-demander (Veenendaal et al., 1996), thus tolerates overhead shade in the seedling stage but needs full light as it grows (Agyeman et al., 1999).

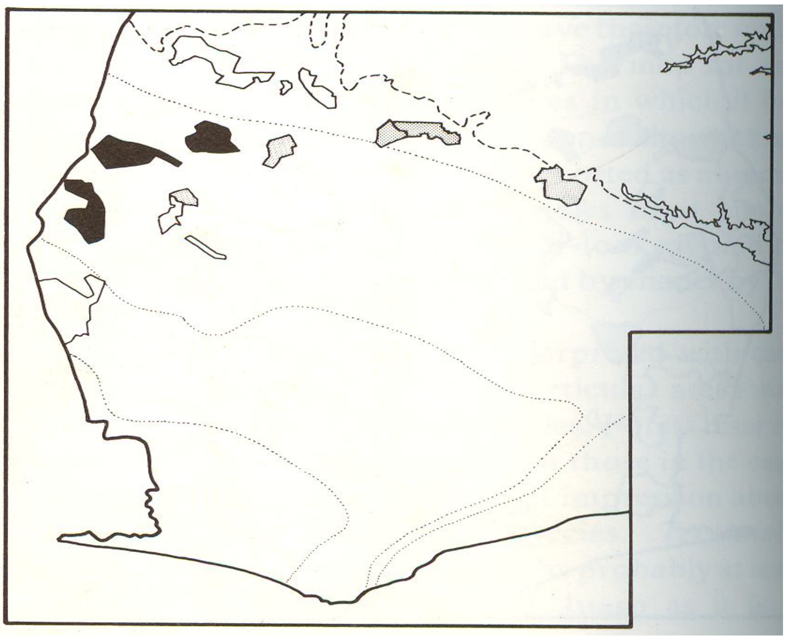


Fig.2.2. Distribution of *Pericopsis elata* in Ghana. Adapted from: Hall and Swaine, 1981

2.7.1.3 Major pest of *Pericopsis elata*

Lamprosema lateritialis Hampson (Lepidoptera: Pyralidae) is the most serious among all the collected pests on *Pericopsis elata* in Ghana (Wagner et al., 2008; FAO, 2007; Atuahene, 1996). It belongs to the Order Lepidoptera and is the only species in the genus *Lamprosema* which attacks forest trees (Wagner et al., 2008). In Ghana it is very common in the Afram Headwaters and the Bia Group of forest reserves and also endemic to areas where *Pericopsis elata* grows naturally (Wagner et al., 2008; Atuahene, 1996).

2.7.1.4 Biology and life history

Lamprosema lateritialis usually occur in communal shelters built from leaves bond together with silk (FAO, 2007). The adult moth is small, yellowish brown with wingspan of approximately 18-21mm (Wagner et al., 2008). The developmental period for this species from the eggs to adult is 34-45 days (Wagner et al., 2008).

There are however 8-9 generations in a year and each female lays eggs in batches between 30-200 eggs on both the upper and lower surfaces of Afrormosia (Wagner et al., 2008; FAO, 2007).

Plate 2.1. Fully developed nest of *Lamprosema lateritialis*. Adapted from: Wagner et al., 2008

2.7.1.5 Damage

The caterpillars feed gregariously on the leaves which are skeletonised and wither (Atuahene, 1996). The insect cause heavy defoliation to the extend that in an average life span of 21 days, it can consume about 140mg dry weight of leaves (Wagner et al., 2008). Their persistent defoliation leads to reduced growth and and even death (FAO, 2007; Atuahene, 1996).

2.7.2 *Nauclea diderrichii* (De Wild.) Merr.

Nauclea diderrichii is a very important commercial species but with spares forest availability in Ghana (Oteng-Amoako, 2006). The species which belongs to the Family Rubiaceae has been exported by most West and Central African countries since the 1960s (Fonweban et al., 1994; FAO, 1993). It is a very durable, high density wood (Orwa et al., 2009; Leakey, 1990) used by many communities as source of food, medicine and means of livelihood (Orwa et al., 2009; Oteng-Amoako, 2006). Apart from furniture and drums, the species is used in Ghana for making mortar (Foli et al., 2009; Orwa et al., 2009). *Nauclea diderrichii* is however classified as vulnerable by the IUCN (Oteng-Amoako, 2006) due among other factors to its current low density in natural forest reserves (Fonweban et al., 1994). Due to this, plantation establishments have been identified as one of the means to ensure its continued availability (FAO, 1993; Leakey, 1990).

2.7.2.1 Morphology

Nauclea diderrichii is an evergreen tree species which grows to about 40m in height and 500cm in diameter (Oteng-Amoako, 2006). It has a cylindrical, slender, straight and branchless bole up to about 27m (Orwa et al., 2009; Oteng-Amoako, 2006). The species also has simple shining leaves with elliptical shape (Orwa et al., 2009) but blunt apex (Leakey, 1990). It has small, green-white-yellow flowers and fruits from May to June and from November to January (Oteng-Amoako, 2006).

2.7.2.2 Distribution and Ecology

Nauclea diderrichii grows very well in areas where annual rainfall ranges from 1600mm to 3000mm (FAO, 1993). It also prefers deep, shallow and well-drained soils and disturbed areas (Oteng-Amoako, 2006; FAO, 1993). In Ghana the species is sparsely distributed in the Wet Evergreen and Moist Semi-deciduous forests (Foli et al., 2009; Oteng-Amoako, 2006; Hall and Swaine, 1981).

Nauclea diderrichii is a pioneer species and a strong light demander (Orwa et al., 2009; Fonweban et al., 1994). It grows very well where adequate overhead light is available and therefore regenerates abundantly in gaps and openings (Oteng-Amoako, 2006).

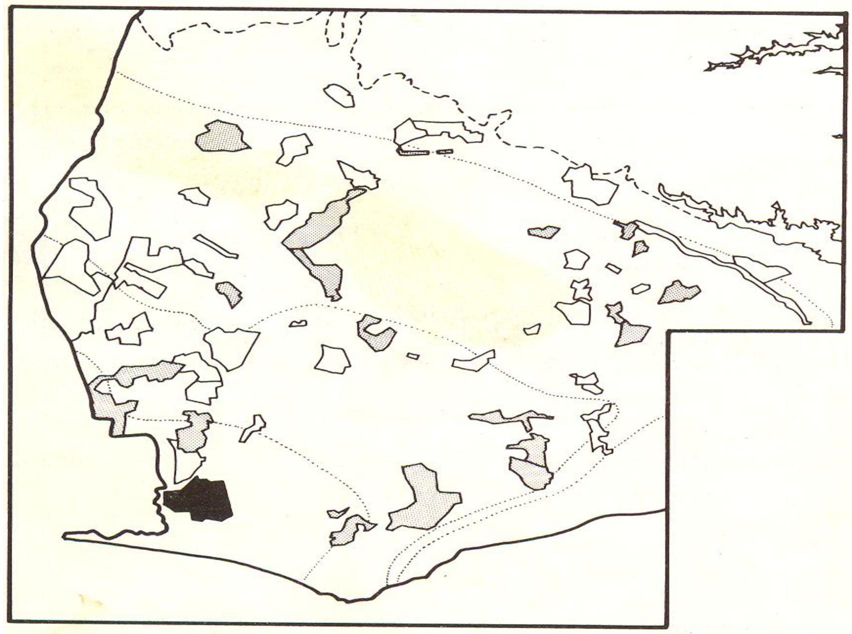


Fig.2.3. Distribution of *Nauclea diderrichii* in Ghana. Adapted from: Hall and Swaine, 1981

2.7.2.3 Major pest of *Nauclea diderrichii*

The shoot-boring caterpillar *Orygmophora mediofoveata* (Lepidoptera: Noctuidae) is an important pest of the high valued species *Nauclea diderrichii* (Orwa et al., 2009; Bosu et al., 2004). The persistent infestations of this insect have been partly blamed for the lack of large scale plantations of *Nauclea diderrichii* in Ghana (Wagner et al. 2008). Attacks by *Orygmophora mediofoveata* in young plantations especially are considered a major threat to plantation establishment in Ghana (Bosu et al., 2004). A survey of pests conducted by Bosu et al., (2004) in the Ashanti Region of Ghana showed high levels of shoot borer infestations in nurseries and plantations of *Nauclea diderrichii*.

2.7.2.4 Biology and life history

The life history of *Orygmophora mediofoveata* is generally unknown especially in the egg and first instar stages (Eidt, 1965 *in* Wagner et al., 2008). The length of a generation is however estimated to be about 3-4 months (Wagner et al., 2008). A matured larva of the last instar is about 1.5mm. Pupation occurs within tunnels made by the caterpillars and lasts about 3 weeks (Wagner et al., 2008).

2.7.2.5 Damage

Caterpillars infest terminal shoots by boring into nodes and especially the apical shoots. They do not girdle the shoots but bore into the pith and produce galleries (Wagner et al., 2008). The stunting of the trees results in the formation of rapid callus tissue over the injured parts which may lead to mortality in case of heavy multiple infestations (Wagner et al., 2008).

2.8 Integrated Pest Management Strategies

Pests such as *Orygmophora mediofoveata, Lamprosema lateritialis* and *Hypsipyla* spp. have become very important and therefore any efforts committed to the establishment of large scale plantations must of a necessity address the challenges they pose (Bosu et al., 2004; Atuahene, 1996). This is because most of these pests have become an integral part of forest ecosystems and they have significant economic, social as well as ecological impacts on the productivity and values of forests (Waters and Stark, 1980). Damages caused by insect herbivory for instance can generally lead to increased mortality (Bosu et al., 2006; Löf et al., 2004), decreased growth (Opuni-Frimpong et al., 2008; Gerhardt, 1998; Atuahene, 1996), lower seed production (Maron, 1998; Crawley, 1989; Rockwood, 1973), and changes in N-cycle in forest ecosystems (Lovett et al., 2002; Kosola et al., 2001).

Due to this several approaches such as chemical, microbial (biotechnology), interference methods, use of natural enemies, host plant resistance and silvicultural techniques have been used for the management of pests in plantations (Bosu et al., 2006; Coyle et al., 2005; Cobbinah et al., 2004; Jäkel and Roth, 2004). Chemical control techniques have had a place in forest pests control for a long time (Waters and Stark, 1980). In Ghana the use of contact insecticides directed at the first instar larvae between the times they hatch and when they enter the shoot has been recommended for the management of *Orygmophora mediofoveata* (Wagner et al., 2008). However the environmental costs associated with the use of chemicals and the effects on non-target species as well as economic and legislative factors are limiting the continued use of chemical applications in pest control (Cobbinah et al., 2004; Muzika and Liebhold, 2000; Hegedus and Khachatourians, 1995).

Many attempts have also been made with varying success, to use natural enemies of major pests to suppress or eliminate pests in plantations (Waters and Stark, 1980). Natural enemies including parasitoids which prey on sawfly, *Nematus salicis-odoratus* were suspected to have collapse the population of sawfly in intensively managed *Populus* plantations in the Pacific Northwest of the United States (Coyle et al., 2005). The use of viral and bacterial agents and other biologically rational approaches have also been recommended in pest management (Wagner et al., 2008; Wylie, 2001). The parasitic nematode, *Beddingia siricidicola* was used against sirex wood wasp outbreak in *Pinus* spp. plantations in Australia (Wylie, 2001). Microbial control of *Lamprosema lateritialis* in *Pericopsis elata* plantations using *Bacillus thuringiensis* showed good results at the Afram Headwaters forest reserve in Ghana (Wagner et al., 2008). Laboratory trials also indicated that the caterpillars of *Lamprosema lateritialis* are susceptible to the fungus *Beauveria* (Wagner et al., 2008). Opuni-Frimpong et al., (2004) also suggested that there is the need to include biotechnology techniques to help reduce the impacts of *Hypsipyla* spp. on mahogany plantations.

The prospects for reducing the impacts of *Hypsipyla* spp. on mahogany plantations have increased after studies showed that *Swietenia macrophylla* and *Cedrela odorata* have partial resistance to attack by *Hypsipyla grandella* in Central America (Watt et al., 2001 *in* Opuni-Frimpong et al., 2008). A study conducted by Attajarusit and Nanta (1998) in Petchabun province in Thailand also reported that resistant varieties of *Leucaena leucocephala* can be used as integrated approach for the management of *leucaena* psyllid.

In addition, integrated approaches using silvicultural manipulations are frequently recommended for the management of pests (Wagner at al., 2008; Waring and O' Hara, 2005; Bosu et al., 2004; Jäkel and Roth, 2004; Ciesla, 2001). Silvicultural methods and management practices can have influence on the probabilities of outbreaks, the extent of damage and reclamation of stands after damage (Waters and Stark, 1980). These approaches to insect problems are mostly seen as reliable, the cheapest and the least harmful to the ecosystem (Waring and O' Hara, 2005; Hosking, 1983).

One major silvicultural management option which is receiving much attention is the integration of pest management through the use of tree species mixtures (Wagner et al., 2008; Bosu et al., 2006; Jactel et al., 2006; Ofori et al., 2004; Nichols et al., 1999). Though there is no consensus about the effects of mixed species on pests (Schuldt et al., 2010; Sobek et al., 2009; Vehviläinen et al., 2007; Ciesla, 2001; Wormald, 1992), the integration of pest management through the use of species mixtures to enhance stand diversity has been encouraged (Wagner et al., 2008; Kelty, 2006; Nichols et al., 1999). This is very critical because studies have shown that tropical tree species are likely to be affected by pests in monocultures (Watt, 1992 *in* Kelty, 2006). Kelty (2006), indicated that one major benefit of using species mixtures is the potential to reduce the effects of insects and pests.

It is widely believed that planting high-risk indigenous species in mixtures other companion species can lead to a substantial reduction in the damage caused to the species (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Bosu et al., 2006; Ciesla, 2001; Montagnini et al., 1995). This argument is supported by Tahvanainen and Root (1972) who stated that in addition to the resistance of individual plant species, plants growing in diverse plant community also experience associational resistance to herbivores by association with other plant species. Thus as plant diversity in ecosystems increase, insect populations remain more stable and herbivory levels decline (Jactel and Brockerhoff, 2007).

Research carried out in Ghana by Nichols et al., (1999) and Bosu et al., (2006) showed that mixed-species plantations of *Milicia excelsa* with other companion species under various silvicultural regimes could be used to substantially reduce the level of gall-forming psyllid *Phytolyma lata*. Nichols et al., (1999) found significant reduction in the number of Psyllid galls two months after planting in mixtures of *Milicia excelsa* and *Terminalia superba* than in monoculture *Milicia.* In the same plantation, Bosu et al., (2006) also reported after 8-years that planting *Milicia excelsa* in mixture (50:50) with *Terminalia superba* was effective in reducing damage from gall forming Psyllid. They further stated that the shade from *Terminalia superba* may have helped reduce galls on *Milicia excelsa* (Bosu et al., 2006). Mixtures are also recommended as a strategy in the integrated pest management of the *Hypsipyla* shoot borer in mahogany plantations (Wagner et al., 2008). Ofori et al., (2004) reported that planting of *Khaya ivorensis* and *Khaya anthotheca* in association with *Azadirachta indica* and *Albizia lebbeck* gave a positive response in the control of shoot borer, *Hypsipyla robusta.* By increasing species diversity in plantations, they can assist in preventing attacks on high risk trees by either creating a barrier or providing food and refuge for the natural enemies of foraging insects (Wormald, 1992).

Two complementary mechanisms which may help explain the potential of species mixtures to reduce the risk of pest damages are i) reduced host plant accessibility and ii) increased populations of natural enemies (Sobek et al., 2009; Watt, 1992 *in* Kelty, 2006; Tahvanainen and Root, 1972; Risch, 1981)

2.8.1 Reduced host plant accessibility

One major factor which influences the population of pests is the availability of suitable plant host (Wormald, 1992). Thus pests are more likely to find and stay in areas where their host plants are abundant (Vehviläinen et al., 2007) because of the higher probability of host plant location, longer tenure time, higher feeding rates and greater reproductive success (Letourneau, 1987). This implies that the level of herbivory may increase as the amount of individuals of the same host plant increases (Sobek et al., 2009). Due to this monocultures may potentially be at risk because the infestation of a pest can affect all or most of the trees which are mostly from the same genetic source (Kelty, 2006). Increasing the species diversity of a plantation can also affect the behaviour of the insect pest to the host plant (Risch, 1981). By breaking the homogeneity, mixtures may influence the ability of the pest to find the host plant and therefore prevent attack (Kelty, 2006; Wormald, 1992). This is because as the relative resource concentration is reduced, it will be somehow difficult for the pest to locate the host plant (Risch, 1981). Risch (1981) also noted that species diversity can influence the probability of a pest staying in a habitat and the reproductive behaviour of the pest.

2.8.2 Increased populations of natural enemies

Though mechanisms and strategies natural enemies of pests use to find their host are varied and complex (Wormald, 1992), natural enemies are important regulators of insect pests (Riihimäki et al., 2005; Risch, 1981). It is therefore important that management strategies which will encourage the increase in populations of these natural enemies are pursued in forest ecosystems. Arguments have been made to the effect that natural enemies are generally less abundant in monocultures due to unfavourable conditions and abundance of foraging and oviposition sites (Watt, 1992 *in* Kelty, 2006; Riihimäki et al., 2005; Risch, 1981). Increasing tree species diversity in plantations is seen as creating a complex environment which eventually increases the potential abundance and effectiveness of natural enemies of pests (Riihimäki et al., 2005; Risch, 1981). This is because a diverse environment can lead to increased ground cover, greater temporal and spatial distribution of food sources and increased herbivore richness (Risch, 1981). Thus as species diversity increase there is also the likelihood of increased activity of parasites, predators and parasitoids (Letourneau, 1987).

Mixed-species plantations can therefore supply more favourable conditions for predators and other natural enemies and reduce the probability of fluctuations in their populations. Riihimäki et al., (2005) tested the natural enemies hypothesis in two separate sites in Western Finland and found that the survival probability for autumnal moth (*Epirrita autumnata*) was lower in birch-pine stands than in single stands of birch and pine in 2002, but later in 2003 survival probability was lowest in the mixed stands only in the first week. They therefore concluded that herbivore survival and predation may be influenced by both tree composition and species diversity (Riihimäki et al., 2005). Vehviläinen et al., (2007) also suggests that since response of pest to forest diversity is highly complex, and may depend on factors such as the host tree, the type of herbivore involved and other stand characteristics.

3.0 MATERIALS AND METHODS

3.1 Study Area

The five year old plantation is situated in the Bia Tano Forest Reserve near Goaso in the Brong Ahafo Region of Ghana. The site is under the Goaso Forest District and lies within the Moist Semi-deciduous Forest Zone (Hall and Swaine, 1981). The trials for this study which were established in June 2005 are composed of five experimental plots with mixtures of different species. The species used were *Nauclea diderrichii* (De Wild.) Merr., *Pericopsis elata* (Harms) van Meewen, *Albizia adianthifolia* (Schum.) W. F. Wright, *Terminalia superba* (Engl. & Diels), and *Tetrepleura tetraptera* (Schum. & Thonn.) Taub. (Table 3.1). The experimental plots were established on a site which is heavily degraded due to extensive logging activities (Aduse-Poku et al., 2003).

3.1.1 Geology and Soil

The Goaso forest district is located in gently sloping landscape underlain by Pre-Cambrian rocks (Adu, 1992 *in* Awadzi et al., 2004), predominantly phyllites, grey wackes, schist and gneisses of the Birrimian and Tarkwaian systems (Hall and Swaine, 1976). These rocks contain a lot of minerals and therefore there are some suggestions that the forest area has large quantities of mineral resources (Ardayfio-Schandorf et al., 2007). The soils in the area are dominated by forest ochrosols (Brammer, 1962 *in* Owusu-Bennoah et al., 2000) or Acrisols (ISSS/WRB, 2006) or Bekwai/ Nzima-Oda association of the Ghanaian soil classification system (Owusu-Bennoah et al., 2000) which is the common soil type in the semi-deciduous forests zone. These soils are weathered and dominated by low activity kaolinitic clays and sesquixides of iron and aluminium. The upper slopes are mostly red, strongly leached and well-drained. The middle horizons turn into brown and are moderately well drained (Owusu-Bennoah et al., 2000). The soils are very productive and therefore support the cultivation of large scale plantations and food crops such as cocoa, oil palm and maize (Adu, 1992 *in* Owusu-Bennoah et al., 2000).

This is partly due to the fact that the nutrients are concentrated on the top 0-20cm where organic matter has been built up for several years through the decomposition of plant biomass. Though the soils are fertile, direct exposure to rainfall and wind leads to erosion which eventually affects the soil fertility.

3.1.2 Climate

The site lies between Latitude 07°58.5'N and Longitude 02°01.3'W, with 26.3m mean altitude. The area receives an annual rainfall of between 1500mm-1750mm and mean monthly minimum and maximum temperatures varying between 26°C and 29°C respectively. There are two rainfall seasons – the major season occurs from April to July with a short dry season in August. The minor season begins in September and ends in October with a long dry season between December and March (A. D. A, 2002).

3.1.3 Vegetation

The vegetation in the Bia Tano Forest Reserve is a Moist semi-deciduous forest type. The reserve is one of the six contiguous Bia forests in the Goaso Forest District. It falls within the *Celtis-Triplochiton* association (Taylor, 1960 *in* Lawson et al., 1970) and has uneven tree canopy with emergent trees of more than 60 m in height. These emergent trees are interspersed in the plantation. The vegetation under the plantation is mainly dominated by *Chromolaena odorata*, herbaceous species like *Aspilia africana, Solanum erianthum, Perquitina nigriscens*, and *Talinum triangularis* (Plate 5.2). In addition the understorey is also composed of different species of grasses like elephant grass and other woody creepers.

3.2 Establishment of plots

The 1ha plantation (125m x 80m) was established in June 2005. There are 20 plots, each measuring 10m x 10m with 36 trees per plot and a plant spacing of 2m x 2m. There was also a spacing of 3m between adjacent plots. This was necessary to avoid possible edge effects (Foggo et al., 2001). Seedlings which did not survive after the initial planting were replaced three months later in September 2005. The initial height and diameter measurements were taken 6 months after planting, but with the exception of 2006 and 2009, measurements were subsequently carried out every year. Measurements were not taken in those years due to logistical constraints. Additional data were taken on the 1st and 2nd of June, 2010. The plots were maintained by weeding *Chromolaena odorata* and other competing vegetation from the time of establishment until the end of 2007 as and when needed. No other silvicultural manipulations were carried out.

3.3 Experimental design

There were five treatments made up of three mixed-species of between two and four species combinations and two monocultures of *Nauclea diderrichii* and *Pericopsis elata* (Table 3.2). The three companion species were *Albizia adianthifolia, Terminalia superba* and *Tetrepleura tetraptera* (Table 3.1). The plots were arranged in a Randomized Complete Block Design with four replicates for each treatment (Fig. 3.1). The blocks were laid in a horizontal manner along the contours of the gently sloping landscape. Block 1 was placed at the highest contour followed by Blocks 2, 3, and 4 in that order. Thus, Block 4 was placed in the lowest contour, and was closest to a nearby stream. The tree species in treatment A, B, C, and D were planted in rows whilst those in treatment E were planted at random (Lamb, 1998) (Table 3.2). The experiment followed the substitutive or replacement series design, in which the mixed plots were planted at the same density as monocultures (Vanclay, 2006; Snaydon, 1991).

3.4 Selected trees species

The species selected for the trial (Table 3.1) were based on their potential economic values, relevance for plantation development in Ghana, conservation concerns and other non wood benefits they provide (Foli et al., 2009; Benhin and Barbier, 2004). *Terminalia superba* and *Nauclea diderrichii* are part of the priority species recommended for plantation development in Ghana mostly because of their economic importance as well as conservation concerns (Foli et al., 2009; Oteng-Amoako, 2006; Agyeman, 2004; Bosu et al., 2004). *Albizia adianthifolia* and *Tetrapleura tetraptera* are fast-growing nitrogen fixers which can play very important facilitation roles (Diabete et al., 2005; Högberg and Piearce, 1986). The uses of these fast-growing species have several advantages which exceeds the practice of inorganic fertilizer application (Orwa et al., 2009; Swaine et al., 2005). These species can help to maintain and improve soil fertility through nitrogen fixation, thus reducing the requirement for expensive inorganic fertilizers (Ibeawuchi, 2007). *Albizia adianthifolia* has been found to have great tolerance to seasonal drought and can survive in stressful environments (Swaine et al., 2007). The species also produces gum resin and could be used as shade.

Tetrepleura tetraptera also known as Prekese on the other hand has several uses which can be beneficial to local communities (Sonibare and Gbile, 2008). The infusion of the fruit of *T. Tetrapleura* is mostly used locally for the treatment and control of human ailments including inflammatory conditions, hypertension, diabetes mellitus and schistomiasis (Sonibare and Gbile, 2008; Ojewole and Adewunmi, 2004; Ngassoum et al., 2001). The presence of *T. tetraptera* has been found to be the most limiting factor for the snail carrying shistosoma (Adewunmi et al., 1990). The ripened and dried fruit is widely used in Ghana as spice in flavoring local soups (Abbiw, 1990). *Tetrapleura tetraptera* has also been found to have the ability to form nitrogen-fixing nodules in symbiosis with rhizobia (Ibeawuchi, 2007; Diabete et al., 2005).

These fast-growing species are therefore recommended for reforestation and rehabilitation of degraded lands because of their potential for fodder, fuelwood, ornamentals and as sources of food, medicine and timber (Orwa et al., 2009; Swaine et al., 2007). *Pericopsis elata* is also a very important economic species which is listed by the IUCN as facing biological extinction (Benhin and Barbier, 2004).

Table 3.1: Selected trees species for planting in degraded areas

Scientific name	Local name	Remarks
Nauclea diderrichii (ND)	Kusia/ Opepe	Heavily attacked by the *Nauclea* shoot borer, *Orygmophora mediofoveata.* Selected as control to assess effects of mixtures.
Pericopsis elata (PE)	Kokrodua	Attacked by *Lamprosema lateritialis* and also heavily logged. Used as control to ascertain the effects of mixtures on susceptibility to insect attack.
Terminalia superba (TS)	Ofram	Fast growing: serves as control for evaluating the effect of non-nitrogen fixing companion tree on the survival and growth of high risk species. It also makes timber of excellent quality and can be used for both indoor and outdoor joinery and plywood.
Albizia adianthifolia(AA) and Tetrapleura tetraptera(TT)	Albizia and Prekese	Fast growing: nitrogen fixing companion trees- to test the effect of nitrogen fixing companion species on the survival and growth of high risk species. They also have the potential to provide non wood products and other ecosystem services.

Table 3.2: Experimental treatments for restoration plantings

Treatment name	Remarks
A = 100% ND	Only *Nauclea diderrichii*
B = 100% PE	Only *Pericopsis elata*
C = 50% ND : 50% AA	To test effect of *Albizia adianthifolia* on survival and growth of *Nauclea diderrichii*
D = 50% PE : 50% AA	To test the effect of *Albizia adianthifolia* on survival and growth of *Pericopsis elata*
E = 25% ND : 25% PE : 25 TS% : 25% TT	High diversity: test effect of diversity on growth and survival of *Nauclea diderrichii* and *Pericopsis elata*

B	A	C	D	E
C	D	E	A	B
A	B	C	D	E
D	E	A	B	C

Fig.3.1. Layout of experimental plots at Bia Tano Forest Reserve near Goaso in the Brong Ahafo Region of Ghana

3.5 Data collection and analyses

3.5.1 Assessing reduction in susceptibility of *Nauclea diderrichii* and *Pericopsis elata* to *Orygmophora mediofoveata* and *Lamprosema lateritialis* respectively

Yearly survival of all the species were carried out by counting the number of individual plants in each plot. The total number of plants per species was calculated and subsequently the percentage survival for *Pericopsis elata* and *Nauclea diderrichii* in each treatment was also determined.

The percentage survival was calculated as

$$\text{Survival \%} = \frac{\text{Number of seedlings survived}}{\text{Total number of seedlings planted}} \times 100\%$$

A two-way analysis of variance (ANOVA) was further performed on the percentage survival of *Pericopsis elata* and *Nauclea diderrichii* with host density (percent of *Pericopsis* and *Nauclea* in the mixtures) or block as main effects at α= 5% level of significance. A separate one-way ANOVA was conducted to compare differences between groups also at α= 5%.

3.5.2 Growth dynamics in monocultures and mixed stands

Growth assessments of all selected species were done by measuring either the diameter at 10cm from the soil level or at 130cm breast height (DBH) when the trees had grown taller than 140cm and also the heights. The mean relative growth rates (RGR) for height and diameter of *Pericopsis elata* and *Nauclea diderrichii* were calculated as

$$RGR = \frac{1}{w} \times \frac{\Delta w}{\Delta t} = \frac{\ln w_2 - \ln w_1}{t_2 - t_1}$$

where w_1 and w_2 are the growth at the beginning and end of period of interest respectively, and t_1 and t_2 are the sampling period in months. The mean RGR was necessary because RGR as a measure of growth efficiency is considered as one of the most sensitive measures of competitive ability (Guan et al., 2008).

A two-way Analysis of Variance (ANOVA) of the means was additionally carried out to determine the growth differences with host density (percent of *Pericopsis* and *Nauclea* in the mixtures) or block as main effects also at α=5%. One-way ANOVA was done to compare differences between means (data collected prior to stand age 60 months for both survival and growth analyses were provided by Dr. Paul P. Bosu - Forestry Research Institute of Ghana). The analyses of the data were done using the Microsoft Office Excel 2003 computer spreadsheet software (Microsoft Corporation, 2003).

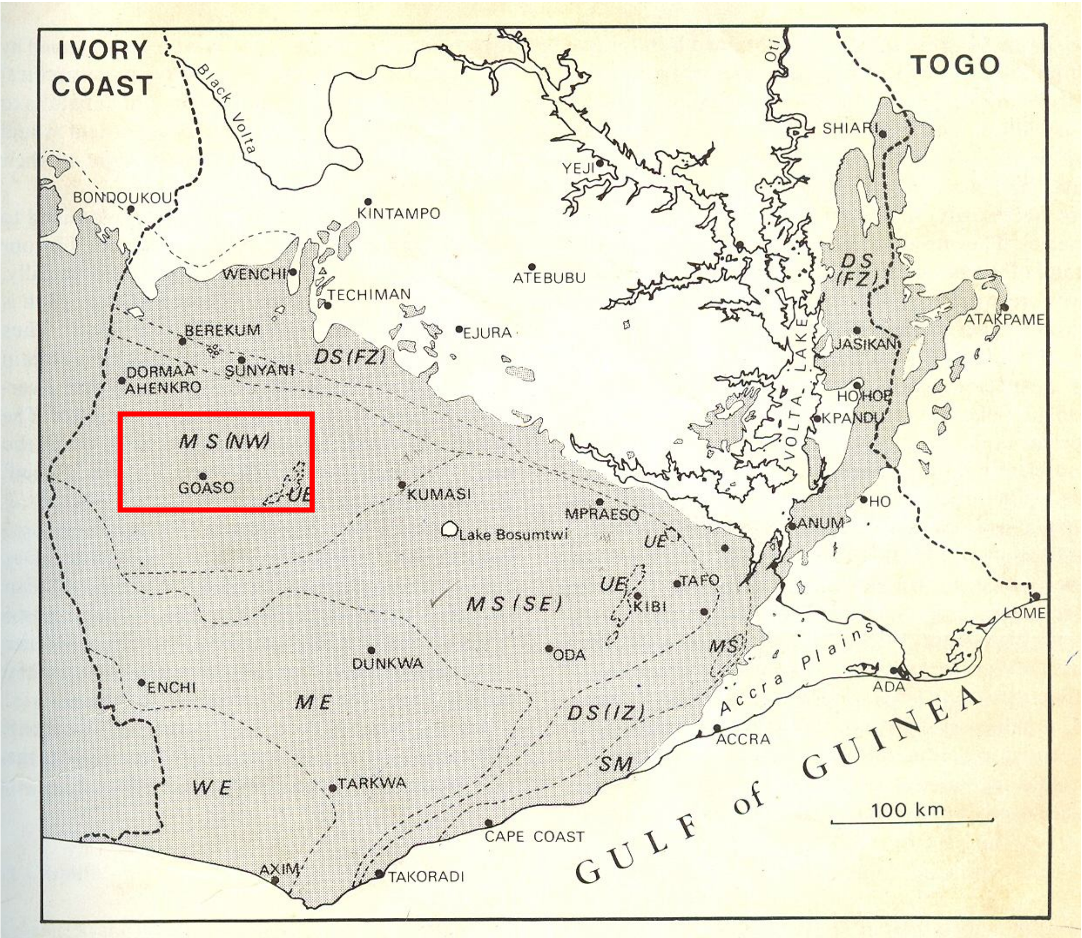


Fig.3.2. Distribution of forest types in southern Ghana. Red rectangle is the study area in the Moist Semi-deciduous forest zone. Adapted from Hall and Swaine, 1981

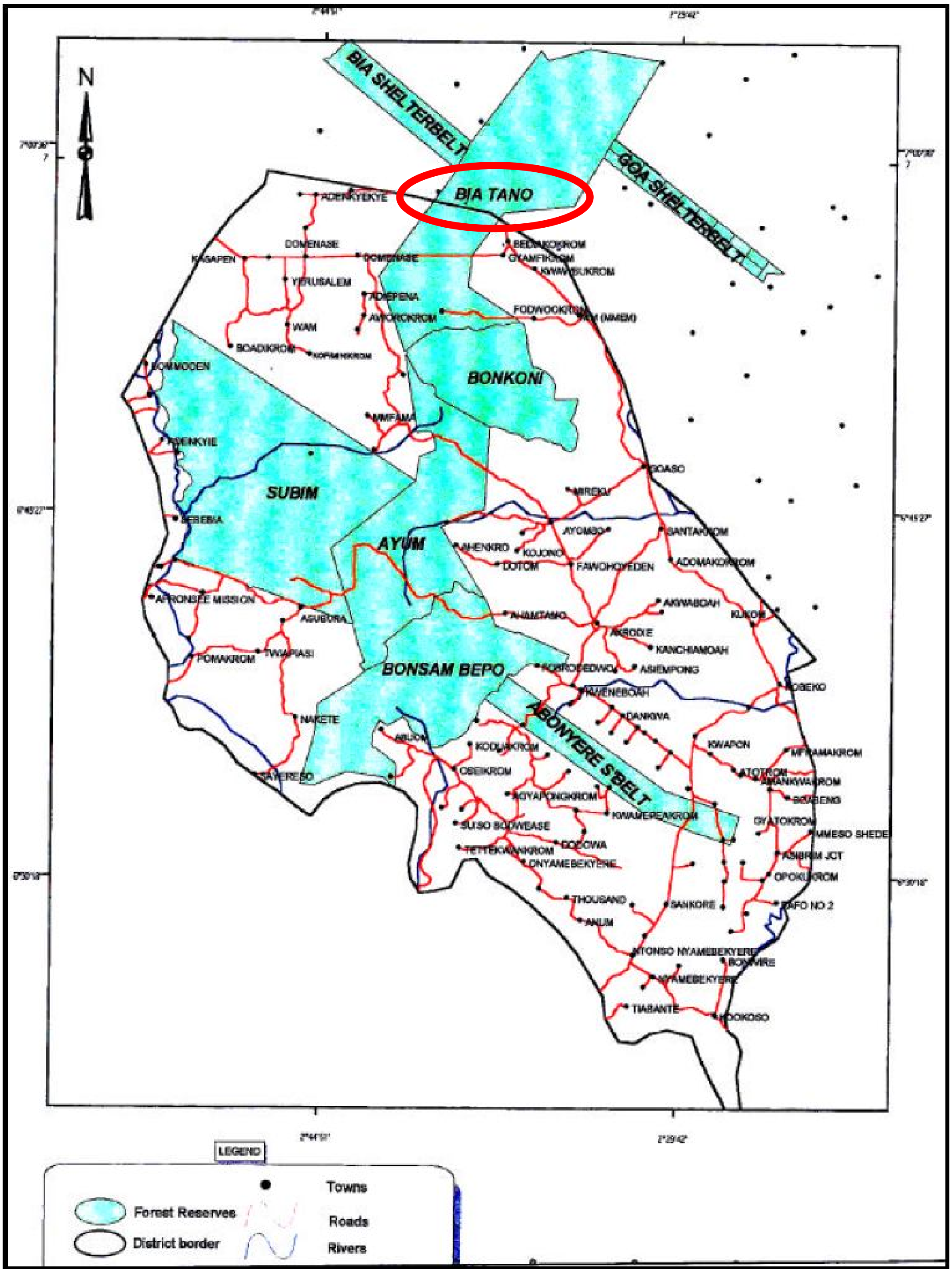


Fig.3.3. Goaso Forest District. Red circle indicates the study area

4.0 RESULTS

4.1 Survival for all species

The overall mortality at stand age 60 months was species-specific, varying greatly among species. After 60 months, 317 out of a total of 720 seedlings planted remained (Table 4.1), a survival rate of approximately 44%. At 60 months, survival ranged from 16% for *Albizia adianthifolia*, 35.3% for *Nauclea diderrichii*, 59.5% for *Pericopsis elata* and 77.8% for both *Terminalia superba* and *Tetrapleura tetraptera* (Table 4.1). Therefore mortality was highest in *Albizia adianthifolia*, followed by *Nauclea diderrichii*, *Pericopsis elata* and both *Terminalia superba* and *Tetrapleura tetraptera* respectively. The survival rate for *Albizia adianthifolia* was extremely low, and with a mortality rate of 56%, survival for the entire plantation in 60 months was considerably low.

Table 4.1. Number of seedlings planted, number which survived and the percentage survivals for all species after 60 months.

Species	No. of seedlings planted	No. survived	% Survival
Pericopsis elata	252	150	59.5
Nauclea diderrichii	252	89	35.3
Albizia adianthifolia	144	23	16.0
Terminalia superba	36	28	77.8
Tetrapleura tetraptera	36	28	77.8
Total	**720**	**317**	**44**

4.2 Survival for focal species

4.2.1 *Pericopsis elata*

The general survival rate for *Pericopsis elata* at stand age 60 months was above average. Of the 252 seedlings planted, 150(59.5%) remained after 60 months of plantation establishment (Table 4.2). At stand age 6 months, the survival rate was very impressive at 97.6%. However, the survival rate declined drastically to 65.1% after 24 months (Table 4.2), a mortality rate of about 32.5% within 18 months.

The survival rate subsequently reduced to 63.1% after 36 months. Considering the high mortality after 24 months, mortality was considerably low for this period. There was a further decline in survival rate to 59.5% at age 60 months (Table 4.2), a mortality rate of 3.6% in 24 months.

Table 4.2. Number of survived seedlings and percentage survival *of Pericopsis elata* at different stand ages in months.

Stand Age(Months)	No. of seedlings survived	% Survival
6	246	97.6
24	164	65.1
36	159	63.1
60	150	59.5

4.2.1.1 *Survival of Pericopsis elata in mixtures*

At 60 months approximately, 150 *Pericopsis elata* seedlings remained for all the treatments combined (Table 4.2). However, 87 out of the 144 *Pericopsis* seedlings (60.4%) in all the four 100% mixture (monoculture) plots had remained (Fig. 4.1). 43 out of 72 seedlings (58.3%) in the 50% mixture, and 20 out of 36 seedlings (55.6%) in the 25% mixture plots survived (Fig. 4.1). However, the differences in survival rates were not statistically significant at $p<0.05$ (F=0.03, df=2, p=0.970) after 60 months (Table 4.4). Therefore the density of *Pericopsis elata* in a plot and block did not influence the survival rates after 60 months. At age 6 months, the survival rate for *Pericopsis elata* was 77.1% for the four 100% mixture plots, and 80.6% for both 50% and 25% mixtures (Fig. 4.3). This indicates that mortality was higher in the 100% mixture, than in 50% and 25% mixtures after 6 months. These differences were not significantly affected by density of *Pericopsis elata* in plots (Table 4.4). There was however a significantly higher block effect on survival at $p<0.05$ (F=13.8, df=3, p=0.004) at age 6 months.

The differences tested with one-way ANOVA showed that survival rates were not significantly different for Blocks 1 and 2, and Blocks 2 and 3 but differences between survival rates for Blocks 2 and 4, Blocks 1 and 4 and Blocks 3 and 4 were highly significant. There was a little decline in survival for 100% mixture from 77.1% to 68.1% after 24 months, a mortality rate of about 9%. The survival rate for 50% mixture however declined heavily by 22.2% to 58.3% after 24 months, and the 25% mixture also reduced to 66.7% within the same period (Fig. 4.3). The 100% mixture (monoculture) further declined to 67.4%, and the 25% mixture also reduced to 61.1% after 36 months of stand establishment. The survival rate for 50% mixture however stabilised after 24 months (Fig. 4.3). This shows that the treatment did not experience any mortality after 24 months. There was however a further decline to 60.4% and 55.6% in survival for the 100% and 25% mixtures respectively after 60 months of stand establishment. Despite the differences in survival rates, density and block had no significant influence on survival after 24 and 36 months (Appendix I). Survival was therefore better in the 100% mixture (monoculture) followed by 50% and 25% mixtures respectively at age 60 months.

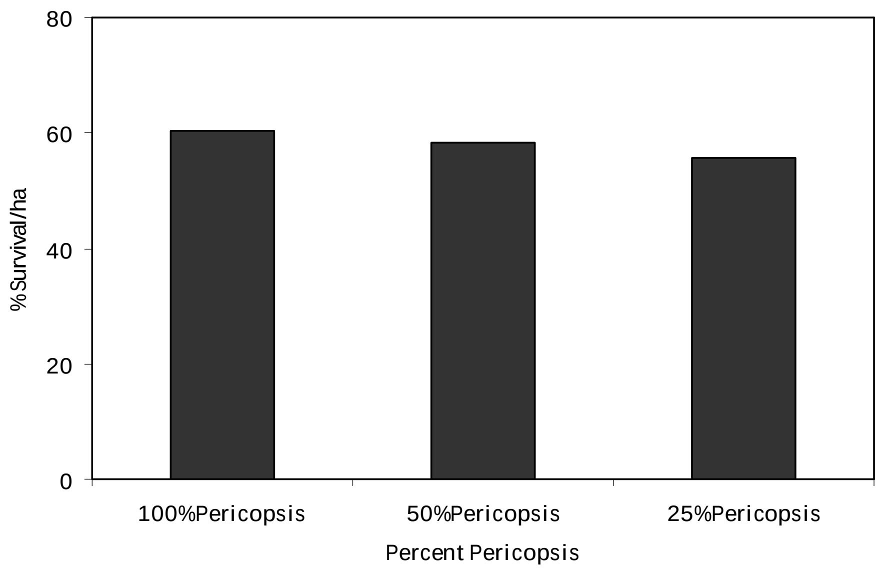


Fig.4.1. Percentage survival for *Pericopsis elata* in mixtures at 60 months after plantation establishment

4.2.2 *Nauclea diderrichii*

At 60 months, mortality rate in *Nauclea diderrichii* was very high. The survival rate for the species was below average (Table 4.1). Of the 252 seedlings planted, 89 remained in all the plots after 60 months, accounting for a survival rate of 35.3% (Table 4.3). There was a considerable reduction in survival with time, just as observed in *Pericopsis elata* (Table 4.2). At stand age 6 months, the rate of survival was surprisingly high at 64.3% (Table 4.3). There was a huge increase in mortality in the 18 months which followed, and at age 24 months the survival rate had reduced to 38.9% (Table 4.3). This trend was also observed in *Pericopsis elata* within the same period (Table 4.2). There was a further decline in survival from 38.9% to 35.7% after 36 months (Table 4.3). Mortality was however almost negligible from that period to age 60 months.

Table 4.3. Number of survived seedlings and percentage survival of *Nauclea diderrichii* at different stand ages in months

Stand Age (Months)	No. of seedlings survived	% Survival
6	162	64.3
24	98	38.9
36	90	35.7
60	89	35.3

4.2.2.1 *Survival of Nauclea diderrichii in mixtures*

A total of 89 seedlings remained at 60 months for all the treatments (Table 4.3). Of the 144 seedlings planted in 100% mixture(monoculture) plots, 51 had remained (35.4%). 27 out of 72 seedlings (37.5%) in all the four 50% mixture plots , and 11 out of 36 seedlings (30.6%) in the 25% mixture plots survived (Fig. 4.2).

At age 60 months, the differences in the survival rate among the monoculture and mixed plots were not significant at $p<0.05$ ($F=1.44$, $df=2$, $p=0.309$), but there was a significantly higher difference due to block effect ($F=13.4$, $df=3$, $p=0.005$) (Table 4.4). Comparing the different blocks showed that survival rates were not significantly different for Blocks 2 and 4 and Blocks 1 and 2 but differences existed for Blocks 2 and 3, Blocks 3 and 4, Blocks 1 and 3. In the case of *Nauclea diderrichii* the rate of survival was highest in 50% mixture, followed by 100% and 25% mixtures respectively at age 60 months.

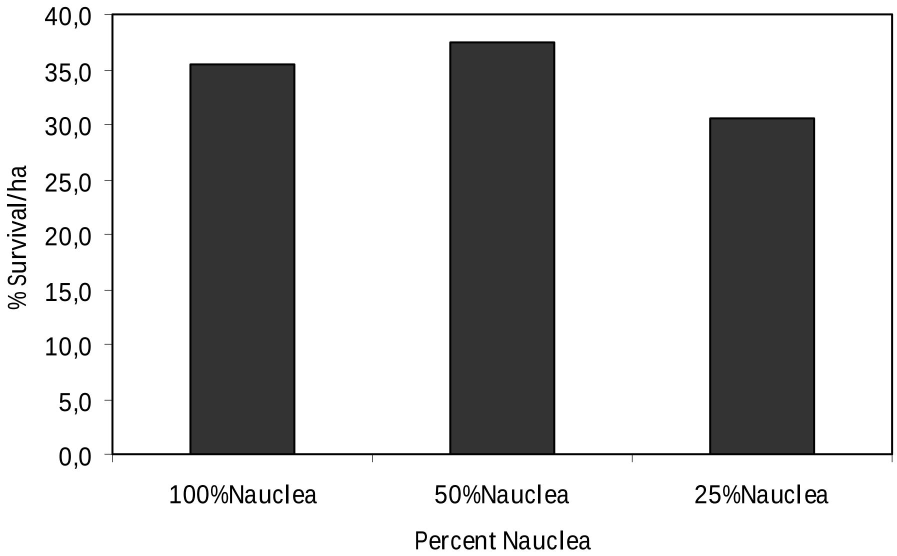
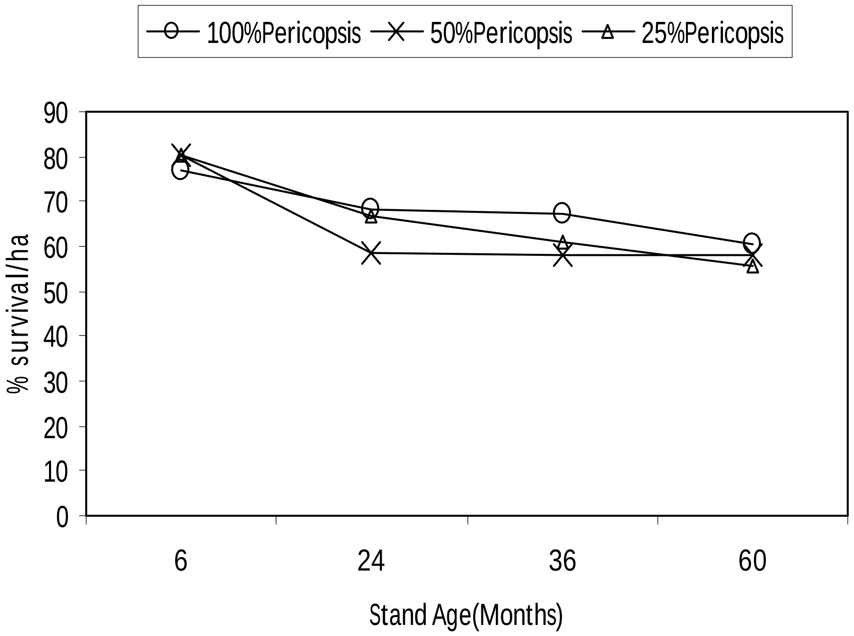


Fig.4.2. Percentage survival for *Nauclea diderrichii* in mixtures at 60 months after plantation establishment

At stand age 6 months, the survival rate of 100% mixture (monoculture) was better than the other two treatments. The survival rate was 70.8% for the four 100% mixture plots, 63.9% and 38.9% for 50% and 25% mixtures respectively (Fig. 4.3). *Nauclea* seedlings mortality in the 25% mixture for first six months was very high (Fig. 4.3). The survival rate for the three mixtures were significantly affected by both density ($F=5.85$, $df=2$, $p=0.039$) and block ($F=7.93$, $df=3$, $p=0.016$) (Table 4.4). Although survival was significantly influenced by *Nauclea diderrichii* density, this observation was not expected.

At age 24 months, there was a considerable decline in the survival rate for 100% mixture from 70.8% to 39.6%, a mortality rate of about 31.3%. Survival was also reduced substantially to 37.5% in 24 months for the 50% mixture. The survival rate for the 25% mixture however stabilised within the same period. The trend for the 25% mixture was unusual since no mortality was recorded after 24 months (Fig. 4.3). Surprisingly there was an increase in the survival rate of the 100% mixture at age 36 months from 39.6% to 41%. It was possible to have a situation like that because at age 6 months incidence of dieback was observed on the *Nauclea diderrichii* seedlings (Bosu, 2005), and therefore some of the seedlings may have been assumed to be dead. Since dieback does not always kill seedlings, there is the chance for recovery (Nadolny, 1995). Within the same period, the 25% mixture declined to 30.6%. This survival rate continued to age 60 months. There was however a further decline in the survival rate of 100% mixture to 35.4% at age 60 months. The survival rates for monoculture and mixed plots at stand age 24 and 36 months were not significantly influenced by both density and block (Appendix I).

a)



b)

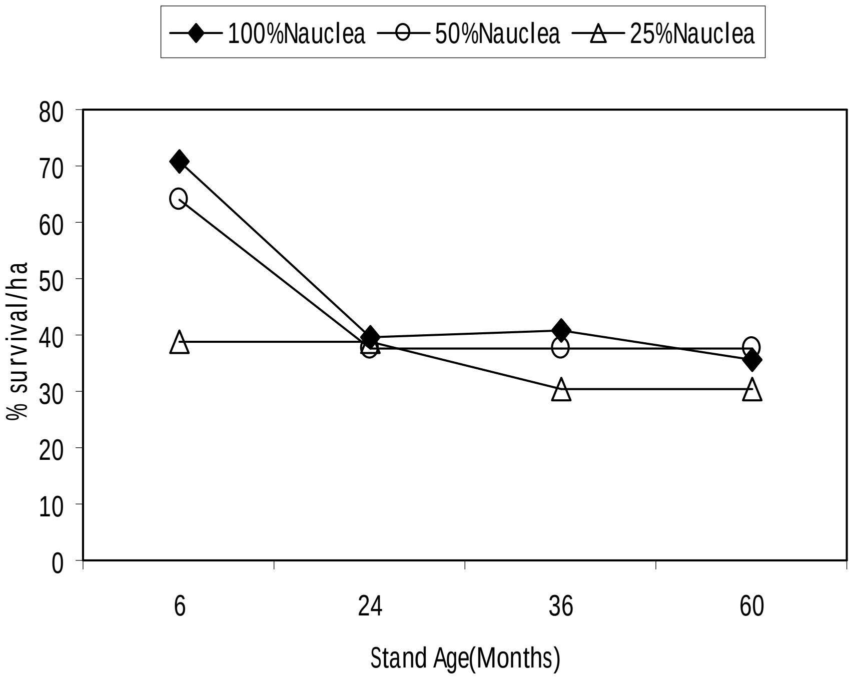


Fig.4.3. Percentage survival for a) *Pericopsis elata* and b) *Nauclea diderrichii* in mixtures at different stand ages

Table 4.4. Two-way ANOVA survival rate in a) *Pericopsis elata* and b) *Nauclea diderrichii* at stand age 6 and 60 months. Source of variation for a given row with asterisks is significantly different at p<0.05

a)

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	0.135	2	0.876	5.143	0.031	2	0.97	5.143
Block	13.8*	3	0.004	4.757	1.457	3	0.317	4.757

b)

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	5.853*	2	0.039	5.143	1,436	2	0.309	5.143
Block	7.933*	3	0.16	4.757	13.4*	3	0.005	4.757

4.3 Growth

4.3.1 Patterns of growth in all species

Measurements in the plantation at 60 months of age established differences in species in terms of diameter and height growth. The mean heights and mean diameters across all species were highest in *Terminalia superba* (Table 4.5). At age 60 months, mean height growth for *Terminalia superba* was 7.7m, followed by *Nauclea diderrichii*, *Tetrapleura tetraptera* and *Albizia adianthifolia* respectively (Table 4.5). *Pericopsis elata* showed the least mean height of 3.1m after 60 months (Table 4.5). The pattern of growth in mean diameter was however different for *Nauclea diderrichii* and *Tetrapleura tetraptera*. Mean diameter was higher in *Tetrapleura tetraptera* than *Nauclea diderrichii*, although the situation was opposite in mean height (Table 4.5). Mean diameter was highest in *Terminalia superba*, followed by *Tetrapleura tetraptera* and *Albizia adianthifolia* (Table 4.5). *Pericopsis elata* again had the least mean diameter after 60 months of plantation establishment (Table 4.5).

Table 4.5. Mean diameters and mean heights of all species after 60 months of plantation establishment with standard errors in parenthesis.

Species	Mean Diameter/cm	Mean Height/m
Pericopsis elata	3.90 (0.107)	3.1 (0.066)
Nauclea diderrichii	9.55 (0.329)	6.8 (0.169)
Albizia adianthifolia	6.35 (0.92)	5.0 (0.448)
Terminalia superba	12.57 (1.00)	7.7 (0.544)
Tetrapleura tetraptera	9.79 (0.684)	5.9 (0.360)

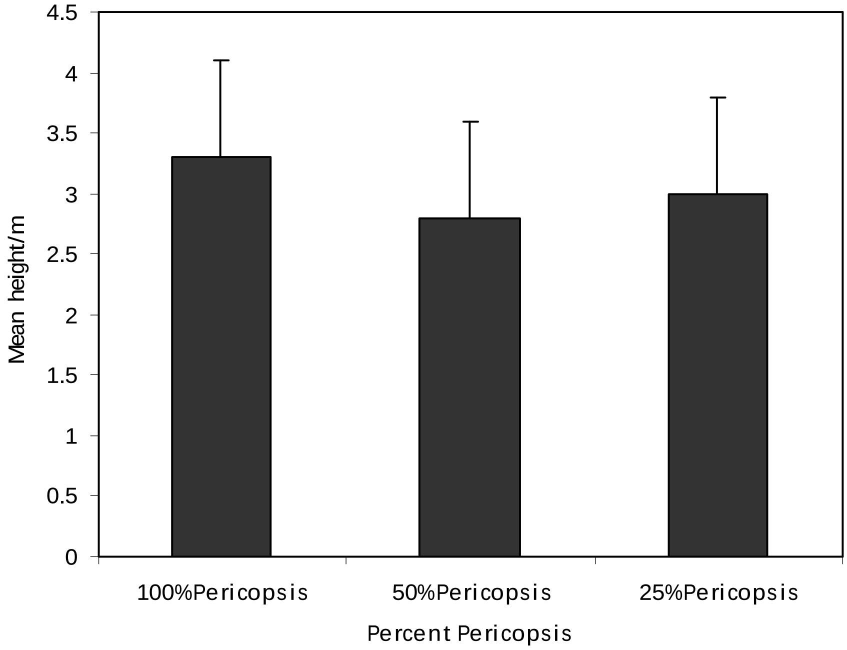
4.3.2 Patterns of growth in *Pericopsis elata* mixtures

4.3.2.1 Height

At stand age 60 months, the mean height of *Pericopsis elata* was higher in the 100% mixture (monoculture), than 25% and 50% mixtures respectively (Fig. 4.4). The mean height of 100% mixture was 3.3m and that for 25% and 50% mixtures were 3m and 2.8m (Fig. 4.4). However the differences in mean heights were not statistically affected by both density (F=0.72, df=2, p=0.524) and block (F=0.829, df=3, p=0.524) at stand age 60 months (Table 4.6). Mean height was better in 100% mixture than 25% and 50% mixtures at age 6 months respectively (Fig. 4.5), even though there was no significant difference in density (F=0.803, df=2, p=0.491) and block (F=0.528, df=3, p=0.679) (Table 4.6). Growth in height was greatest in the 25% mixture after 36 months, followed by 100% mixture and the least recorded by 50% mixture. At age 60 months, the differences in height started showing (Fig. 4.5), with mean height of 3.26m for 100% mixture, 3.03m and 2.76m for 25% mixture and 50% mixture respectively.

4.3.2.2 Diameter

60 months after planting, pattern of growth in diameter was similar to height. Trees in the 100% mixture (monoculture) had the highest mean diameter of 4.07cm, followed by 25% mixture and 50% mixture (Fig. 4.4). The mean diameter of 50% mixture was the least at 3.67cm after 60 months (Fig. 4.4). There was also no significance difference among the mixtures in terms of density (F=0.81, df=2, p=0.488) and block (F=0.667, df=3, p=0.602) (Table 4.6). At age 6 months, mean diameter of *Pericopsis elata* was higher in 100% mixture, than 25% and 50% mixtures, but this trend changed until age 60 months (Fig. 4.5). The mean diameter for 100% mixture (monoculture) was 1.13cm, followed by 25% mixture and 50% mixture with mean diameters of 1.07cm and 1.02cm respectively (Fig. 4.5). Both density and block did not significantly affect diameter growth at age 6 months (Table 4.6).



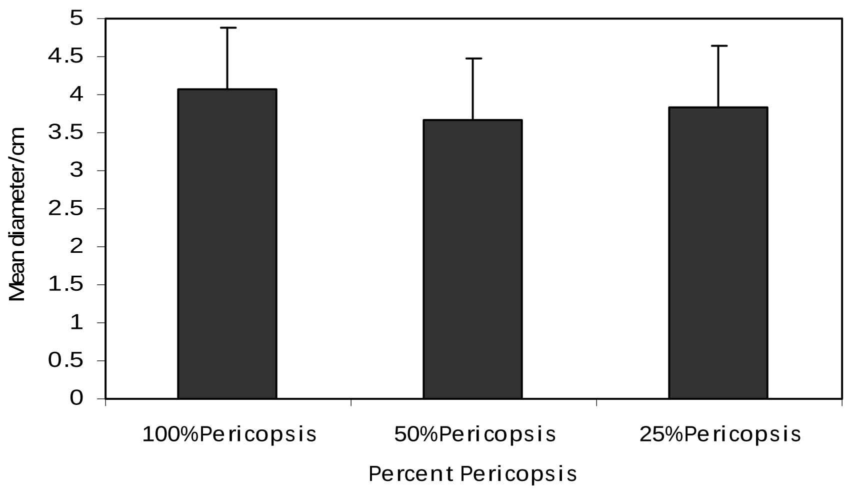
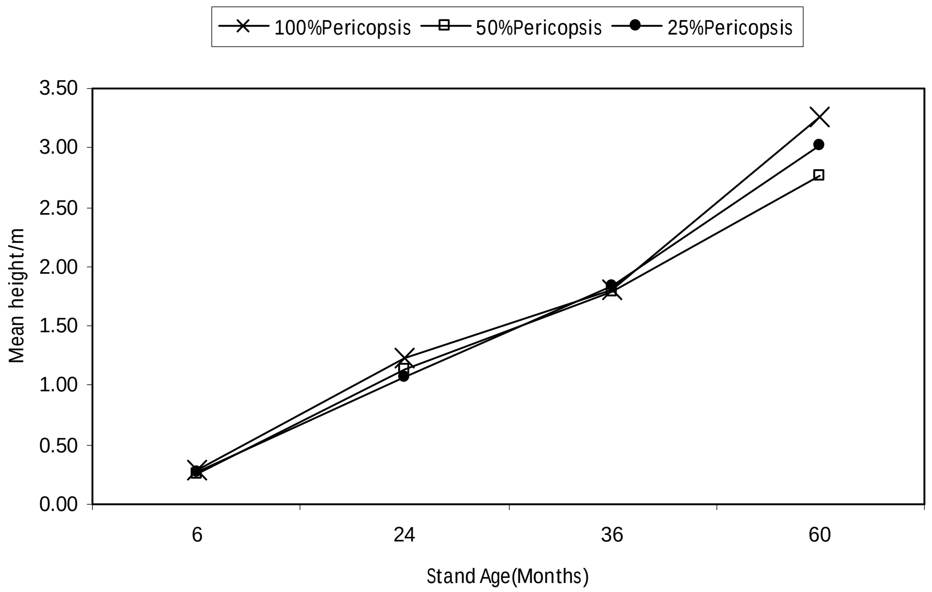


Fig.4.4. Mean height and mean diameter of *Pericopsis elata* in mixtures after 60 months (bars indicate standard error of means)

Although the same trend continued for 100% mixture(1.95cm), the mean diameter of 50% mixture(1.79cm) at age 24 months was however higher than 25% mixture (1.78cm). Incidentally at age 36 months the mean diameter for 25% mixture increased more than the other mixtures (Fig. 4.5). It was followed by 100% mixture and 50% mixture respectively.

There was a further increase in the mean diameter for 25% mixture but was not better than 100% mixture and 50% mixture at age 60 months. Therefore comparing the three mixtures, 100% mixture (monoculture) attained a greater mean diameter than 25% and 50% mixtures (Fig. 4.5).



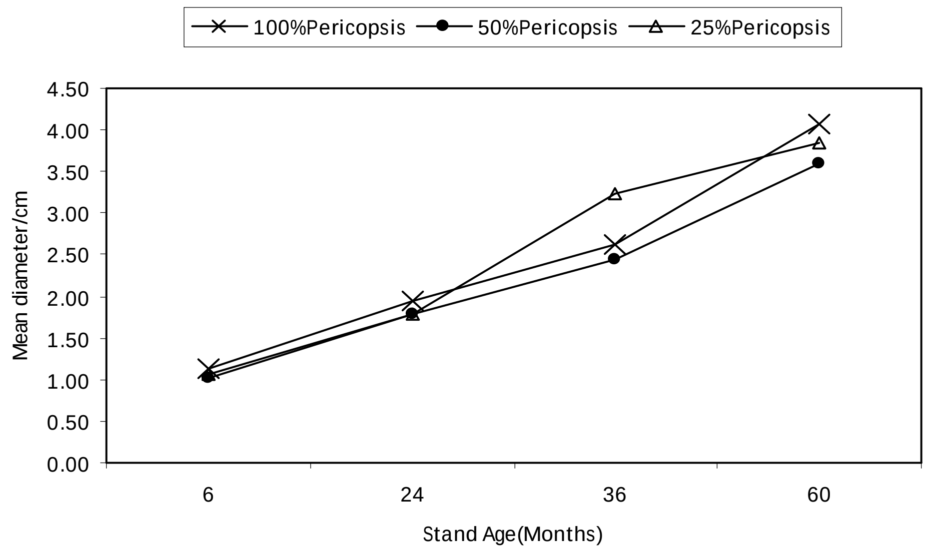


Fig.4.5. Mean heights and mean diameters distribution in mixtures of *Pericopsis elata* from age 6 to 60 months

Table 4.6. Two-way ANOVA for mean height and mean diameter of *Pericopsis elata* in mixtures 6 and 60 months after plantation establishment

a) Mean height

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	0.803	2	0.491	5.143	0.72	2	0.524309	5.143
Block	0.528	3	0.679	4.757	0.829	3	0.524372	4.757

b) Mean diameter

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	1.205	2	0.363	5.143	0.81	2	0.488	5.143
Block	2.121	3	0.199	4.757	0.667	3	0.602	4.757

4.3.2.3 Relative Growth Rate (RGR)

RGR is a good measure to assess inter-tree competition for above and below ground resources (Guan et al., 2008; Cannell et al., 1984). At stand age 60 months mean RGR in height (RHGR) was greatest in 100% mixture (monoculture), than 25% and 50% mixtures respectively. Mean RHGR was 1.2, 1.1 and 1.0 for 100% mixture, 25% mixture and 50% mixture respectively (Table 4.8). Mean RGR in diameter (RDGR) was also highest in 100% mixture (monoculture), followed by 25% and 50% mixtures (Table 4.8). This indicates that inter-tree competition may have been strongest in 50% mixture since it had the least RDRG (Cannell et al., 1984). Density and block however had no significant effect on mean RGR in height and diameter after 60 months (Appendix III).

4.3.3 Patterns of growth in *Nauclea diderrichii* mixtures

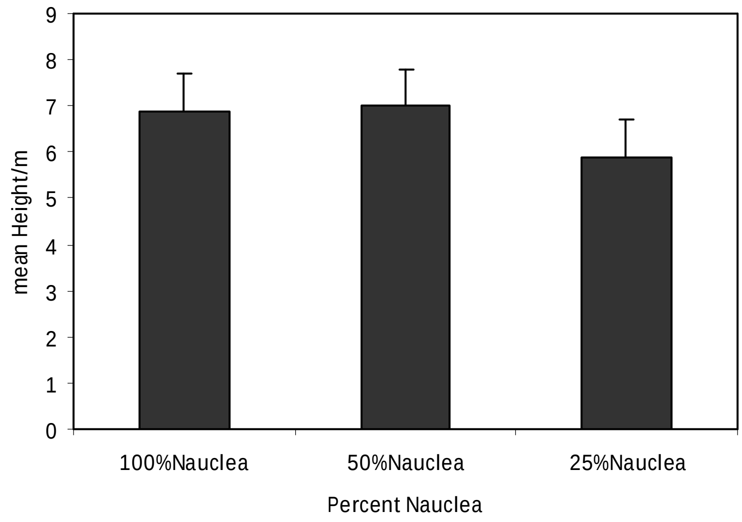
4.3.3.1 Height

Mean height was greatest in 50% mixture, followed by 100% (monoculture) and 25% mixtures respectively at stand age 60 months (Fig. 4.6). 50% mixture at age 60 months recorded a mean height of 7.0m, while mean heights for 100% mixture and 25% mixture were 6.9m and 5.9m (Fig. 4.6). Mean heights were not significantly affected by density (F=0.044, df=2, p=0.957) and block (F=1.067, df=3, p=0.43) (Table 4.7). Mean heights for mixtures were significantly affected by block (F=5.624, df=3, p=0.035) at stand age 6 months but not density (F=0.563, df=2, p=0.597) (Table 4.7). Further analysis showed that mean heights at age 6 months were significantly different for blocks 2 and 3 and blocks 2 and 4 (Appendix II). At stand age 6 months, 25% mixture had a better mean height at 0.45m (Fig. 4.7), than 100% mixture(0.41m) and 25% mixture (0.36m), despite the fact that its survival rate at the same period was very low (Fig. 4.3). However at stand age 24 months, mean height of 25% mixture was surpassed by 100% and 50% mixtures respectively. At stand age 36 months, mean heights of 100% and 50% mixtures were the same at 2.76m, while that of 25% mixture was 2.61m (Fig. 4.7). Mean heights for mixtures at stand age 24 and 36 months were not statistically affected by density or block. After 36 months, mean heights were almost at par for 100% and 50% mixtures until age 60 months when slight differences began to show (Fig. 4.7).

4.3.3.2 Diameter

The growth trend for mean diameter of *Nauclea diderrichii* in mixtures followed the same pattern as height at stand age 60 months (Fig. 4.6). At stand age 60 months, mean diameter was highest in 50% mixture, followed by 100% (monoculture) and 25% mixtures. Mean diameters for 50%, 100% and 25% mixtures in 60 months were 10.10cm, 9.39cm and 8.60cm respectively (Fig. 4.6).

There was no significant difference due to density (*F*=0.329, *df*=2, *p*=0.732) and block (*F*=0.635, *df*=3, *p*=0.619) at age 60 months (Table 4.7). Unlike height growth, mean diameter for the mixtures was not significantly influenced by density (*F*=0.469, *df*=2, *p*=0.647) and block (*F*=1.714, *df*=3, *p*=0.263) at stand age 6 months (Table 4.7). Mean diameter also followed similar trend like height growth at age 6 months (Fig. 4.7). At stand age 6 months, 25% mixture had the highest mean diameter of 1.57cm, followed by 100% mixture (monoculture) at 1.46cm and 1.23cm for 50% mixture (Fig. 4.7). The trend however changed at stand age 24 months, where mean diameter was slightly higher for 100% mixture than that of 25% mixture and 50% mixture. At stand age 36 months, mean diameter was still highest in 100% mixture, compared to 25% and 50% mixtures respectively. Although there were slight differences in mean diameters at age 36 months, the observed differences were not influenced by density and block effects. The differences in mean diameter however started showing at age 60 months (Fig. 4.7), though not statistically significant (Table 4.7).



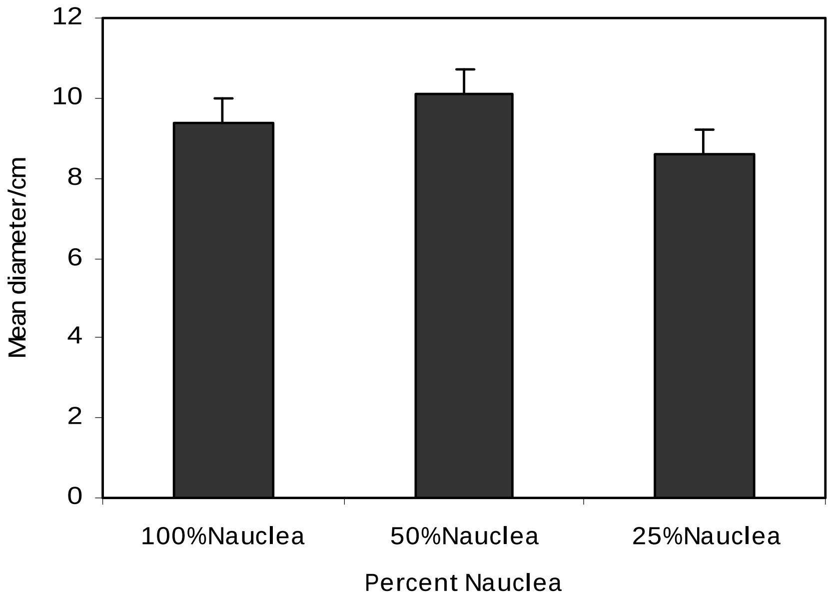
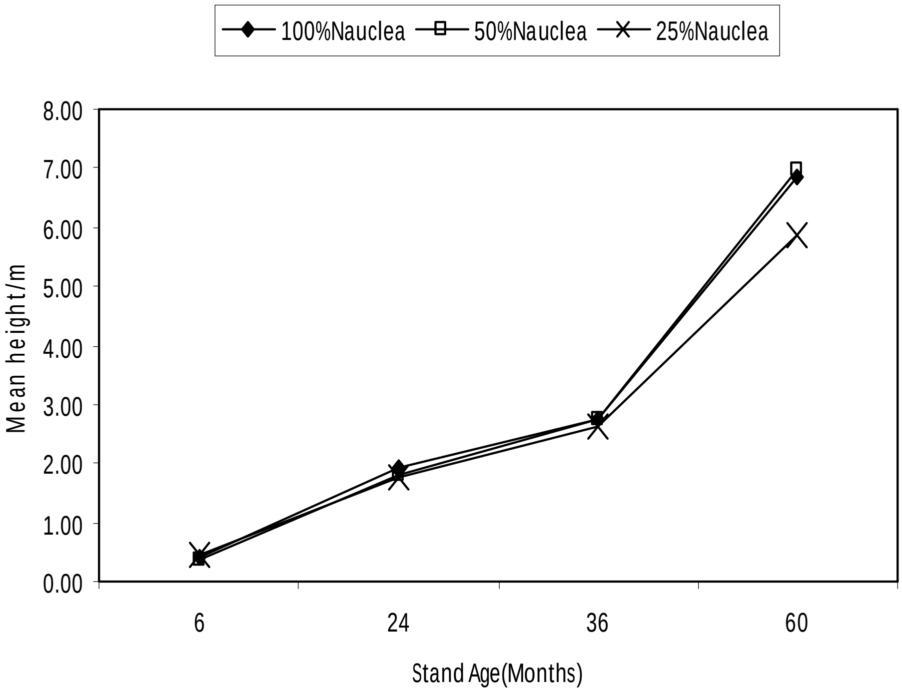


Fig.4.6. Mean height and mean diameter of *Nauclea diderrichii* in mixtures after 60 months (bars indicate standard error of means).



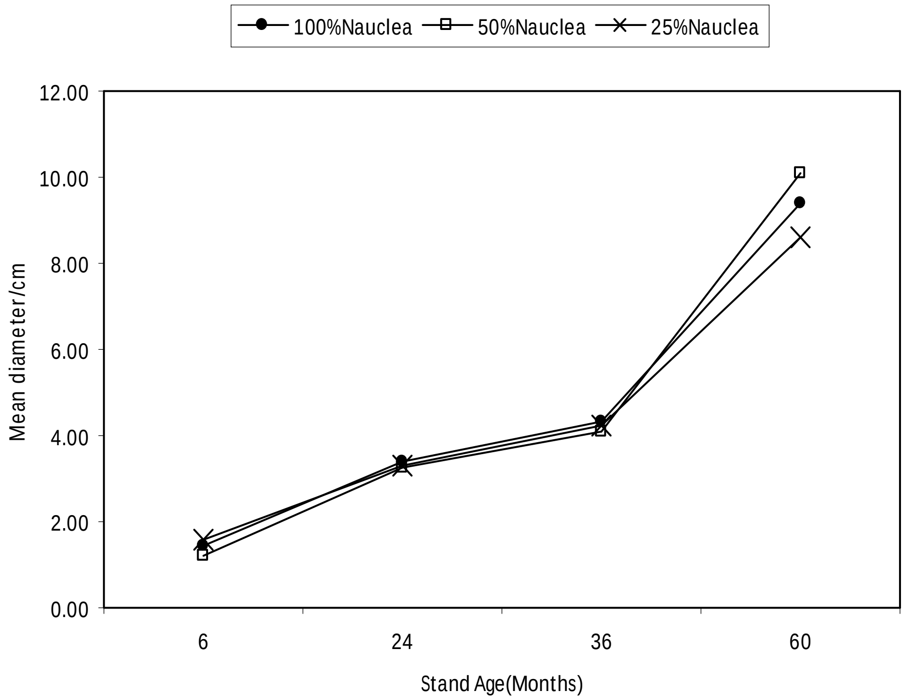


Fig.4.7. Mean heights and mean diameters distributions in mixtures of *Nauclea diderrichii* from age 6 to 60 months

Table 4.7. Two-way ANOVA for mean height and mean diameter of *Nauclea diderrichii* mixtures 6 and 60 months after plantation establishment. Mean for a given row with asterisks is significantly different at p<0.05

a) Mean height

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	0.563	2	0.597	5.143	0.044	2	0.957	5.143
Block	5.624*	3	0.035	4.757	1.067	3	0.43	4.757

b) Mean diameter

	6 months				60 months			
Source	*F*	*df*	*P-value*	*F-crit*	*F*	*df*	*P-value*	*F-crit*
Density	0.469	2	0.647	5.143	0.329	2	0.732	5.143
Block	1.714	3	0.263	4.757	0.635	3	0.619	4.757

4.3.3.3 Relative Growth Rate (RGR)

Mean RGR in height (RHGR) for *Nauclea diderrichii* was highest in 100% mixture (monoculture), followed by 50% mixture and 25% mixture (Table 4.8). Mean RHGR was 2.0, 1.9, and 1.7 for 100% mixture (monoculture), 50% mixture and 25% mixture respectively (Table 4.8). Mean RGR (RDGR) in diameter also showed similar pattern. Mean RDGR for 100% mixture was 2.25, followed by 2.23 for 50% mixture and 2.07 for 25% mixture (Table 4.8). The highest value in RGR for 100% mixture indicates a possible reduced inter-tree competition in the monoculture. At stand age 60 months, there was no significant difference among RGR in height and diameter for mixtures (Appendix III).

Table 4.8. Mean Relative Growth Rates (RGR) in height and diameter for a) *Pericopsis elata* and b) *Nauclea diderrichii* in mixtures after 60 months

a)

Mixture	Mean RHGR/m m^{-1} m^{-1}	Mean RDGR/cm cm^{-1} m^{-1}
100% *Pericopsis*	1.2	1.39
50% *Pericopsis*	1.0	1.21
25% *Pericopsis*	1.1	1.27

b)

Mixture	Mean RHGH/m m^{-1} m^{-1}	Mean RDGR/cm cm^{-1} m^{-1}
100% *Nauclea*	2.0	2.25
50% *Nauclea*	1.9	2.23
25% *Nauclea*	1.7	2.07

5.0 DISCUSSION

5.1 Mortality

Both biotic and abiotic factors as well as certain processes can act either on their own or interact in a complex manner to have a confound effect on survival and growth of plant species (Furuta and Aloo, 2009; Lin et al., 2004; Meiners and Handel, 2000; Callaway and Walker, 1997; Maron, 1997). Pest damages from insect herbivory (Sobek et al., 2009; Wagner et al., 2008; Bosu et al., 2006; Nichols et al., 1999; Atuahene, 1996; Montagnini et al., 1995), competition (Maron, 1997; Duncan, 1991; Cannell et al., 1984), and environmental heterogeneity (Healy et al., 2008; Potvin and Gotelli, 2008; Swaine, 1996; Chapin et al., 1987) have longed been recognised as factors which can have both additive and non-additive impacts on tree seedling mortality and growth.

5.1.1 Pest damage

Nauclea diderrichii and *Pericopsis elata* are high valued indigenous species which are attacked by *Orygmophora mediofoveata* and *Lamprosema lateritialis* respectively when grown in plantations (Wagner et al., 2008; Bosu et al., 2004; Atuahene, 1996). Damages caused by insect herbivory can generally lead to increased mortality (Bosu et al., 2006; Löf et al., 2004), decreased growth (Opuni-Frimpong et al., 2008; Gerhardt, 1998; Atuahene, 1996), lower seed production (Maron, 1998; Crawley, 1989; Rockwood, 1973), and changes in N-cycle in forest ecosystems (Lovett et al., 2002; Kosola et al., 2001). The general recommendation is that planting these high risk indigenous species in mixtures with companion species can lead to a substantial reduction in stand damage from insect pests (Wagner et al., 2008; Bosu et al., 2006; Kelty, 2006; Ofori et al., 2004; Nichols et al., 1999). The first part of this study was therefore conducted to assess whether tree species diversity can reduce susceptibility of *Nauclea diderrichii* and *Pericopsis elata* to their respective primary pests.

The results obtained in this present study for the two species over the whole experimental period generally showed that the effects of tree species diversity on *Orygmophora mediofoveata* and *Lamprosema lateritialis* seem to vary temporary (Vehviläinen et al., 2007; Koricheva et al., 2006). The overall survival rate of 35.3% for *Nauclea diderrichii* over 60 months of stand establishment was very low (Table 4.1), considering the fact that a survival rate of 84% was recorded in a 5-year old plantation in Omo forest reserve in Nigeria (Onykwelu et al., 2003). *Nauclea diderrichii* seedlings and young plantations are noted for attacks from the shoot borer, *Orygmophora mediofoveata* (Orwa et al., 2009; Wagner et al., 2008; Oteng-Amoako, 2006; Bosu et al., 2004). There is therefore every indication that the high mortality in *Nauclea diderrichii* was partly due to attacks from its primary pest. Bosu (2005) working in the same plantation observed various stages of dieback in *Nauclea diderrichii* seedlings in the stand 5 months after plantation establishment, although the shoot borer had not totally colonized the whole stand. Additionally, defoliation caused by the variegated grasshopper, *Zonocerus variegatus* was also observed (Bosu, 2005). Insect damage is one of the more easily recognised factors of dieback (Landsberg and Wylie, 1988), and even though seedlings can recover from it (Nadolny, 1995), multiple attacks can lead to high mortality (Wagner et al., 2008; Landsberg and Wylie, 1988).

The high mortality observed in *Nauclea diderrichii* at stand age 60 months could therefore be partly attributed to the onset of dieback in the seedlings. This was obvious because some of the trees eventually developed multiple stems (Plate 5.1), which is a responds from the species to apical shoot damage (Orwa et al., 2009; Leakey, 1990). Bosu et al., (2004) reported of heavy attack by *Orygmophora mediofoveata* on *Nauclea diderrichii* seedlings at a nursery in Fumesua near Kumasi, Ghana. Infestation levels greater than 50% of seedlings and about 40% mortality was observed (Bosu et al., 2004).

In the same study, significant levels of shoot borer attacks were also recorded in young *Nauclea diderrichii* plantations at Pra-Anum and Afram Headwaters forest reserves in the Ashanti Region of Ghana (Bosu et al., 2004). In the early 1960s infestation levels of 30%-80% were recorded in many taungya plantations in Nigeria (Wagner et al., 2008).

Plate 5.1. 60-month old *Nauclea diderrichii* tree which developed double stems in response to attack on apical shoots from stem borer, *Orygmophora mediofoveata*

Overall, survival for *Nauclea diderrichii* in mixtures at stand age 60 months was highest in 50% mixture (50%*Nauclea*/50%*Albizia*) (Fig. 4.2). Of the 144 seedlings planted in 100% mixture (monoculture) plots, 51 remained (35.4%). 27 out of 72 seedlings (37.5%) in all four 50% mixture and 11 out of 36 seedlings (30.6%) in the 25% mixture (25%*Nauclea*/25%*Pericopsis*/25%*Terminalia*/25%*Tetrapleura*) plots survived (Fig. 4.2). These results agree with some studies which showed decreases in insect herbivory on tree species in mixtures than in monocultures (Jactel and Brockerhoff, 2007; Kaitaniemi et al., 2007; Bosu et al., 2006; Jactel et al., 2006; Riihimäki et al., 2005; Ofori et al., 2004; Jactel et al., 2002; Nichols et al., 1999; Su et al., 1996). Nichols et al., (1999) found significant reduction in the number of Psyllid galls two months after planting in mixtures of *Milicia excelsa* and *Terminalia superba* than in monoculture *Milicia excelsa* stands. In the same plantation, Bosu et al., (2006) also reported after 8-years that planting *Milicia excelsa* in mixture (50:50) with *Terminalia superba* was effective in reducing damage from gall forming Psyllid. They further stated that the shade from *Terminalia superba* may have helped reduce galls formation on *Milicia excelsa* (Bosu et al., 2006). Results from Ofori et al., (2004) also showed that planting of *Khaya ivorensis* and *Khaya anthotheca* in association with *Azadirachta indica* and *Albizia lebbeck* gave a positive response in the control of shoot borer, *Hypsipyla robusta.*

The possible reasons for the present results include the fact that mixed stands are generally associated with high amount of natural enemies and the different species can provide alternative shelter and foraging sites for these natural enemies (Kaitaniemi et al., 2007; Riihimäki et al., 2005; Jäkel and Roth, 2004). Wagner et al., (2008) citing Eidt (1965) indicated that three species of endoparasites have been identified on *Orygmophora mediofoveata*. Moreover association with non-host species can also provide physical or chemical barrier to host location by foraging or dispersing herbivores (Jactel and Brokerhoff, 2007).

Even though 50% mixture (50%*Nauclea*/50%*Albizia*) recorded the highest survival, there was no significant difference among the mixtures. This observation agrees with other studies on insect herbivory in monoculture and mixed-species plantations (Potvin and Gotelli, 2008; Bosu et al., 2006; Vehviläinen et al., 2006). Bosu et al., (2006) reported a high survival for *Milicia excelsa* in mixtures than in monoculture but indicated that mortality was not significantly influenced by density of *Milicia* in plots. Results from Vehviläinen et al., (2006) also showed no significant difference in herbivore between Silver birch and paired mixtures with Scots pine and Norway spruce at the end of the vegetation period. It is however in contrast to some other studies which reported significant herbivory reduction between monocultures and mixtures (Sobek et al., 2009; Jactel and Brokerhoff, 2007; Kaitanienen et al., 2007; Jactel et al., 2006; Jactel et al., 2002). Kaitanienen et al., (2007) found that a significantly lower proportion of sawfly larvae and eggs survived on pines grown in mixtures with birch as compared with monoculture stands in western Finland. A meta-analysis of world-wide data of 119 studies showed a significant reduction of herbivory in more diverse forests than monocultures (Jactel and Brokerhoff, 2007). Although the overall survival was highest in 50% mixture at age 60 months, the results for stand age 6 months on the contrary showed a higher survival rate for 100% mixture (monoculture), than 50% mixture and 25% mixture (Fig. 4.3). However there was a heavy increase in mortality after that period. These contrasting results for different stand ages indicate that total insect herbivore damage is not constant over time (Koricheva et al., 2006; Vehviläinen et al., 2006). Moreover despite the relatively decreased mortality in the 50% mixture, the 25% mixture consisting of (25%*Nauclea*/25%*Pericopsis*/25%*Terminalia*/25%*Tetrapleura*) had the least survival rate after 60 months (Fig. 4.3). This shows the importance of considering species diversity threshold in insect herbivory-diversity relationship and possible influence of other factors which can potentially act to influence the benefits of mixed species in reducing pest damages in *Nauclea diderrichii* and *Pericopsis elata* (Healy et al., 2008; Jactel et al., 2002; Maron, 1997).

Overall survival rate for *Pericopsis elata* at stand age 60 months was 59.5%. The above average survival rate is consistent with suggestion from Atuahene (1996) that attack by defoliating moth, *Lamprosema lateritialis* may not necessarily cause significant tree mortality in *Pericopsis elata*. However repeated damage from defoliators including *Lamprosema lateritialis* can kill trees outright or make them more susceptible to other mortality factors (Wagner et al., 2008; Griffiths et al., 2004; Atuahene, 1996). Though the data suggests extremely high survival rate at age 6 months (Table 4.2), Bosu (2005) reported of complete colonisation of all *Pericopsis elata* seedlings in the stands by *Lamprosema lateritialis* after 5 months of plantation establishment. According to Jackson and Bach (1999), damages from insect herbivore are prevalent when leaves are young and can affect survivorship. Results from Atuahene (1996) showed about 31% mortality in *Pericopsis elata* seedlings at the Mesewam nursery near Kumasi, Ghana. He attributed the cause directly to repeated defoliation by leave tying *Lamprosema lateritialis* over a period of one-year (Atuahene, 1996). The first assessment of survival in December, 2006 coincided with the minor peak period of *Lamprosema lateritialis* population (Wagner et al., 2008). During the peak season caterpillars move together and feed gregariously on leaves and shoots causing damages which could lead to death especially with time (Wagner et al., 2008; FAO, 2007; Gerhardt, 1998).

In general results for *Pericopsis elata* in mixtures at stand age 6 months and 60 months gave a conflicting response to the effect of diversity on *Lamprosema lateritialis* (Fig. 4.1&4.3). Overall survival rate for *Pericopsis elata* at stand age 6 months was highest in 25% mixture and 50% mixture (50%*Pericopsis*/50%*Albizia*), than 100% mixture (monoculture) (Fig. 4.3). This was in contrast to the results obtained for *Nauclea diderrichii* at the same stand age (Fig. 4.3).

The results confirm observations from other studies which showed increased level of insect herbivory in monocultures as compared to species mixtures (Sobek et al., 2009; Jactel and Brokerhoff, 2007; Bosu et al., 2006; Jactel et al., 2006). Jactel et al., (2006) found that *Matsucoccus feytaudi* was consistently higher in monoculture maritime Pines than in mixed maritime and Corsican pine stands. Results from Sobek et al., (2009) also indicated that there was a decline in damage caused by leaf chewing herbivores in mixed beech stands as compared to monoculture beech stands. These results came out after they examined levels of herbivory suffered by beech and maple saplings across a tree species diversity gradient in Germany (Sobek et al., 2009).

The possible explanation for the high mortality in *Pericopsis elata* monoculture stands is that the concentration of *Pericopsis elata* seedlings within the same area may have increased the susceptibility of the stands to *Lamprosema lateritialis* attacks (Vehviläinen et al., 2007; Tahvanainen and Root, 1972). One major factor which influences population of pests is the abundance of suitable host (Wormald, 1992). Thus insect pest is more likely to find and stay in areas where their host plant is abundant (Vehviläinen et al., 2007; Kelty, 2006) because of the higher probability of host plant location, longer tenure time, higher feeding rates and greater reproduction success (Letourneau, 1987). The feeding behaviour of *Lamprosema lateritialis* larvae may have been favoured by the closeness of *Pericopsis elata* seedlings to each other in the monoculture stands (Atuahene, 1996). The larvae of *Lamprosema lateritialis* mostly move together and after causing damage to leaves of one seedling, immediately move to the nearest suitable fresh, mature leaves where the process of feeding is repeated (Wagner et al., 2008).

It is however unlikely that increased natural enemies in the high diversity treatments (50% mixture and 25% mixture) contributed to the relatively low mortality rates. This is because although several larval and pupal parasites such as *Neoplectops nudinerva* and *Braunsia erythraea* have been identified in Ghana to attack *Lamprosema lateritialis* larvae, the level of parasitisation in the field has been very low (Wagner et al., 2008). The results for *Pericopsis elata* in mixtures at stand age 60 months was however different (Fig. 4.3). The overall results showed that 100% mixture (monoculture) rather had the highest survival rate followed by 50% mixture and 25% mixture respectively (Fig. 4.1). This result also agrees with some studies which indicated high herbivory induced mortality in highly diverse stands as compared to monocultures (Schuldt et al., 2010; Vehviläinen et al., 2007; White and Whitham, 2000; Folgarait et al., 1995; Montagnini et al., 1995). A meta-analysis of uniformly collected data on insect herbivory and damage on Silver birch, Black alder and Sessile oak in boreal and temperate forest zones, indicated that insect herbivory on oak and alder was significantly higher in mixtures than in the monocultures of respective species (Vehviläinen et al., 2007). Schuldt et al., (2010) also reported of increased herbivory on saplings and shrubs with increased species richness in forest stands.

The data obtained at different stand ages however did not show any significant difference in survival among the different *Pericopsis elata* mixtures (Table 4.4). This agrees with results from other studies which did not show any significant difference in insect herbivory response in monocultures and stands of different species mixtures (Vehviläinen et al., 2007; Bosu et al., 2006; Koricheva et al., 2006; Cappuccino et al., 1998; Folgarait et al., 1995; Montagnini et al., 1995). A study by Montagnini et al., (1995) in the humid lowlands of Costa Rica did not find any significant difference in pest damage in nine of the twelve species between monoculture and mixed-species plots.

A striking similarity between the results obtained for both *Nauclea diderrichii* and *Pericopsis elata* was the different responses of the species to their primary pests at different stand ages and the fact that just like in the case of *Nauclea diderrichii,* the 25% *Pericopsis elata* mixture also had the least survival rate at age 60 months (Fig. 4.1). As observed earlier this indicates that insect herbivory-diversity relationship in *Nauclea diderrichii* and *Pericopsis elata* may not be consistent but may vary temporally (Koricheva et al., 2006), and that certain factors can possibly act together with insect herbivory to mask the impacts of species diversity on their primary insect pests (Healy et al., 2008; Meiners and Handel, 2000).

5.1.2 Competition

Apart from herbivory, competition is another factor considered as important source of mortality in seedlings (Furuta and Aloo, 2009; Boyden et al., 2005; Meiners and Handel, 2000; Moran, 1997; Firbank and Watkinson, 1985; Cannell et al., 1984). Interactions take place as component species attempt to capture both above and below ground resources required for growth (Jose et al., 2006). Both intra- and inter-specific competition can therefore affect growth and survival when allowed to operate (Myster and McCarthy, 1989). The results from the study indicate that the overall survival rates for *Nauclea diderrichii* and *Pericopsis elata* at stand age 60 months were least in the 25% mixture (Fig. 4.1&4.2). With a planting distance of 2m x 2m, there is the likelihood that competition in the stands may have contributed to mortality rates in both species. Plant density which is mostly influenced by initial planting distance is capable of affecting survival of plants by altering the balance between competition and herbivory (Furuta and Aloo, 2009; Potvin and Gotelli, 2008). Therefore the tendency and intensity of intra-specific and inter-specific interaction increase as plant density increases (Kropff, 1994 *in* Jose et al., 2006). Consequently high mortality in seedlings can be expected when competition become intense (Whitesell, 1974).

In monoculture and mixed plantations of *Nauclea diderrichii*, a planting distance of not less than 3.5m x 3.5m has been used (Onyekwelu et al., 2003; FAO, 1993). The overall survival rate for *Nauclea diderrichii* might have been influenced by inter-specific competition from companion species in the mixed species plots as well as intra-specific competition between *Nauclea diderrichii* seedlings in the 100% mixture (monoculture). Inter-specific competition in the high diversity treatments may have also contributed to mortality in *Pericopsis elata*. Parker and Salzman (1985) however noted that the effects of competition on survivorship may depend greatly on whether plants were experiencing herbivore attacks. This is because even though severe insect herbivory can cause mortality (Löf et al., 2004) the principal effect of pest damage is the reduction in the competitive abilities of plants (Müller-Schärer, 1991; Crawley, 1989). Competition and herbivory can therefore interact in non-obvious ways to affect seedling survival (Furuta and Aloo, 2009; Meiners and Handel, 2000; Menalled et al., 1998; Parker and Salzman, 1985).

The results obtained agree with other studies which demonstrated interaction between pest damage and competition in plants (Furuta and Aloo, 2009; Meiners and Handel, 2000; Parker and Salzman, 1985; Müller-Schärer, 1991). Furuta and Aloo (2009) recorded mortality of about 85% in heavily infested *Abies sachalinensis*. They attributed the high mortality to combined effects of aphid infestation and competition (Furuta and Aloo, 2009). Another study in New Mexico, US showed a very high mortality in *Gutierrezia microcephala* plants due to interaction between defoliation from *Hesperotettix viridis* and competition (Parker and Salzman, 1985). Meiners and Handel (2000) also found a significant interaction between herbivory in *Acer rubrum* and *Quercus palustris* and competition. The highest mortality in both species occurred when competition and intensity of herbivory were very high (Meiners and Handel, 2000). *Nauclea diderrichii* is known to respond strongly to the effects of both above and belowground competition (Toledo-Aceves and Swaine, 2008).

With the exception of *Pericopsis elata* (Agyeman et al., 1999), all the other species used in the experiment are pioneers (De Ridder et al., 2010; Oteng-Amoako, 2006; Onyekwelu et al., 2003; Kyere et al., 1999; Swaine and Whitmore, 1988; Swaine and Hall, 1983) and can only establish in sufficient light (Oteng-Amoako, 2006). Hence, despite the fact that *Nauclea diderrichii* seedlings could recover from dieback (Nadolny, 1995), the deep shade created by companion species which were not affected by the pest might have suppressed the seedlings, thereby decreasing the quantum of photosynthetic active radiation needed for growth (Lewis and Tanner, 2000; Menalled et al., 1998). This decrease in light can cause the seedlings to become etiolated and eventually die (Bosu et al., 2006; Kelty, 2006; Meiners and Handel, 2000). A study by Menalled et al., (1998) showed that even though *Cedrala odorata* seedlings in monoculture recovered from dieback due to *Hypsipyla grandella* attacks, those in the mixtures were suppressed by the competition from surrounding trees.

In addition to inter-specific competition, intra-specific competition between *Nauclea diderrichii* seedlings which suffered from dieback and ones not colonized in the monoculture plots could have also contributed to the high mortality. According to Weiner and Thomas (1986) asymmetric competition for light is very intense in even aged monospecific stands. The same situation might have also happened to influence survival of *Pericopsis elata*. The defoliation suffered by *Pericopsis elata* seedlings may have reduced the competitive ability (Fenner, 1987). *Pericopsis elata* is described as Non-Pioneer Light Demander (Swaine, 1996; Hawthorne, 1995 *in* Oteng-Amoako, 2006) indicating that although it can tolerate shade in the early stages (Veenendaal et al., 1996), it needs full overhead light as it grows (Agyeman et al., 1999). Although the survival rates for 25% and 50% mixtures were highest at age 6 months (Fig. 4.3), the data shows a drastic increase in mortality in both treatments after 6 months (Fig. 4.3). The seedlings at that stage might have been suppressed by companion species which were not affected by the leave tying caterpillar.

The results from this study thus confirm suggestions that the impact of specialist pest may be severe in mixtures because of inter-specific competition from surrounding trees (Kelty, 2006).

In contrast the very impressive survival rate for *Terminalia superba* was not surprising since the species can successfully be established in monoculture and mixed plantations (Bosu et al., 2006; Wormald, 1992). The high survival rate for *Terminalia superba* and *Tetrapleura tetraptera* in this study therefore may have been influenced among other factors by their very strong competitiveness for above and belowground resources respectively (De Ridder et al., 2010; Oteng-Amoako, 2006; Akinnifesi et al., 1999; FAO, 1993).

Considering the effects that companion species used in this study had on the rate of survival of *Nauclea diderrichii* and *Pericopsis elata*, response of insect herbivore to tree species diversity in these species may strongly depend on among other factors species composition or stand characteristics (Sobek et al., 2009; Potvin and Gotelli, 2008; Vehviläinen et al., 2007). The potential confounding effects that the ecological characteristics of species in mixed plantations can have on herbivory damage has in recent times highlighted the importance of species composition in mixed stands (Sobek et al., 2009; Vehviläinen et al, 2008; Jactel and Brokerhoff, 2007; Vehviläinen et al., 2007; Koricheva et al., 2006).

Many authors argue that as much as stand diversification may be important in impacting herbivory in certain circumstances (Jactel and Brokerhoff, 2007; Kaitaniemi et al., 2007), species composition is equally important (Nadrowski et al., 2010; Vehviläinen et al., 2007; Koricheva et al., 2006; Riihimäki et al., 2005) or may even override the effects of stand diversity (Sobek et al., 2009; Vehviläinen et al, 2008).

5.1.3 Site factors and environmental heterogeneity

Different mechanisms underlying seedling mortality may interact to determine the net effect of biodiversity (Potvin and Gotelli, 2008). Site factors such as climate and soil as well as variation in topography, soil properties and drainage of a site can either amplify or diminish effects of species diversity on insect herbivore incidence and damage (Nadrowski et al., 2010; Healy et al., 2008; Bragança et al., 1998; FAO, 1993). Diversity effects on herbivory may therefore depend on its interaction with the local environmental conditions (Hooper et al., 2005). Because variations in site characteristics and abiotic conditions are important in determining individual plant's performance (Cannell et al., 1984), the influence of these factors on mortality may be considered more important than local biodiversity levels (Potvin and Gotelli, 2008). The results from this study and field observations showed that survival rates could have been affected by the general site conditions and variability in site characteristics such as soil conditions, topography and drainage. Climatic conditions and edaphic factors may have contributed to the extremely poor survival rates of especially *Albizia adianthifolia* and *Nauclea diderrichii* (Table 4.1).

In contrast the same conditions might have favoured the other species resulting in their above average survival rates (Table 4.1). This was probably the case because the distribution of many forest trees in Ghana shows very strong association with climatic and soil conditions (Swaine, 1996; Hall and Swaine, 1981; Hall and Swaine, 1976). Even though *Nauclea diderrichii* is a dominant tree in the moist semi-deciduous forest zone (Hall and Swaine, 1981; Hall and Swaine, 1976) it has a sparse distribution and is rarely found outside its natural range (Onyekwelu et al., 2003). Moreover it has a slight preference for well-drained shallow soils (Oteng-Amoako, 2006; FAO, 1993). *Albizia adianthifolia* also has a wide distribution throughout the rainfall forest areas in Ghana (Swaine et al., 2007) but more abundant in seasonally dry forests (Swaine et al., 2005) and absent from only the wettest sites (Swaine et al., 2005).

It normally grows poorly outside its natural range (DI, 2002) and is commonly associated with dry, infertile soils (Swaine, 1996). These characteristics probably played prominent roles in affecting the survival rate of *Albizia adianthifolia* because the soils in the forest zone where the experimental site is located have been described as quite fertile and the site also has relatively high rainfall (Adu, 1992 *in* Owusu-Bennoah, 2000). According to Wormald (1992) planting species in conditions which are different from those of its natural range can cause problems. These factors may have contributed to the low survival rates recorded in *Albizia adianthifolia* and *Nauclea diderrichii* (Table 4.1). The other species may have however benefited from the site conditions.

Pericopsis elata is sparsely available in Ghana (Oteng-Amoako, 2006), mostly restricted to the western corridors particularly in the Brong Ahafo Region (Swaine, 1996). It is drought tolerant (Swaine, 1996), and also common in swampy areas but has no preference for fertile or infertile soils (Oteng-Amoako, 2006). The Bia-group of contiguous forests where the experimental site is located is a natural range for *Pericopsis elata* (Atuahene, 1996). This explains to a large extent the relatively low mortality it recorded after 60 months (Table 4.1) despite its susceptibility to the leave tying *Lamprosema lateritialis*. According to Cossalter and Pye-Smith (2003) one benefit of matching species to its site is that it increases the potential to reduce pest attack. Apart from its above ground competitive abilities (Orwa et al., 2009), *Terminalia superba* has abundant occurrence in Ghana (Hall and Swaine, 1981). It also has no preference for wet or dry soils (Oteng-Amoako, 2006), and can occasionally withstand flooding (Orwa et al., 2009). These characteristic together with its competitive ability for light might have contributed to its high survival rates (Table 4.1). The overall high survival rate of *Tetrapleura tetraptera* at stand age 60 months may be due to its tolerance to a wide range of climatic and soil conditions (Oteng-Amoak, 2006).

It has a widespread distribution except in drier forests (Orwa et al., 2009). Its major advantage is that it has extensive distribution of fine roots (Akinnefesi et al., 1999) and can also tolerate acidic soils (Abbiw, 1990). Apart from the general site factors, variations in soil properties, topography and drainage within experimental plots can also confound the effects of species diversity on herbivory (Nadrowski et al., 2010; Healy et al., 2008). Experimental plots within a site may vary in several physical factors and this heterogeneity can influence biodiversity effects (Potvin and Gotelli, 2008). A redundancy analysis carried out by Healy et al., (2008) on data from a plantation in Central Panama revealed that environmental heterogeneity explained about 50% of variation in subplot tree mortality where as diversity accounted for only 23%-30% of the variation. Results from this experiment at stand age 6 months indicated that survival rates in mixtures for both *Pericopsis elata* and *Nauclea diderrichii* were significantly affected by block (Table 4.4). Moreover at age 60 months, survival rates for different densities of *Nauclea diderrichii* were also influenced significantly by block (Table 4.4). Even though prior to the experiment soil analysis was not carried out for plots containing different diversity levels, field observation showed a possible variability in the soil properties and other microsite conditions. The site had a gently sloping topography and some plots in the Block 4 were laid at the lowest portion of the gentle slope closest to a nearby stream. A casual look at the data revealed a relatively high mortality in plots located in the Block 4 compared to other blocks. All the *Albizia adianthifolia* seedlings planted in Block 4 died after 60 months (data not shown). The flat terrain and the presence of the stream could have altered the drainage and soil physical and chemical properties. There was also the possibility that plots closest to the stream could get waterlogged during the long rainfall season, since the area generally experiences high amounts of rainfall (Hall and Swaine, 1981). The general changes in soil conditions and other factors may have affected the survival rates particularly in *Albizia adianthifolia* and *Nauclea diderrichii* which have preference for well drained soils (Swaine, 1996; FAO, 1993).

5.2 Growth

The many ecological benefits provided by mixed-species plantations are not questionable (Piotto, 2008; Lamb et al., 2005; Kaye et al., 2000; Montagnini and Porras, 1998), but the fact that they can achieve greater growth and productivity has been queried (Firn et al., 2007; Vilà et al., 2003; Wormald, 1992). Several studies have however shown that mixtures can be highly productive compared to monoculture plantations (Nadrowski et al., 2010; Potvin and Dutilleul, 2009; Potvin and Gotelli, 2008; Bristow et al., 2006; Erskine et al., 2006; Forrester et al., 2005; DeBell et al., 1997; Binkley et al., 1992). The second part of this study was therefore conducted to answer the question *'Do Nauclea diderrichii and Pericopsis elata grow better in monocultures or in mixtures with companion species?* As in the case of mortality, plant growth is influenced by several biotic and abiotic factors which either act alone or together to affect plants (Meiners and Handel, 2000; Gerhardt, 1998).

5.2.1 Pest damage

Damages caused by insect herbivores can generally lead to a reduction in plant production (Opuni-Frimpong et al., 2008; Atuahene, 1996). The growth rates recorded in *Nauclea diderrichii* and *Pericopsis elata* at stand age 60 months were likely affected by damages from their respective primary pests (Wagner et al., 2008). Overall mean height and mean diameter for *Nauclea diderrichii* at 60 months were 6.8m and 9.55cm respectively (Table 4.5). Even though it was quite good considering the high mortality recorded, growth in height especially may have been affected by attacks from *Orygmophora mediofoveata.* The mean height and mean diameter were lower than those recorded in Nigeria and Cameroon within the same period (Onykwelu, 2007; Fonweban et al., 1994). Onyekwelu (2007) reported a mean height of 9.0m in Omo forest reserve, Nigeria. At a spacing of 2.5m x 2.5m, results from Fonweban et al., (1994) also showed a mean diameter of 12.12cm in 5-years and a third-year mean height of 7.01m in Southern Bakundu, Cameroon.

Pericopsis elata also recorded a mean height and mean diameter of 3.1m and 3.90cm respectively (Table 4.5). Atuahene (1996) noted that defoliation by *Lamprosema lateritialis* could affect productivity by reducing diameter growth in *Pericopsis elata.*

5.2.2 Facilitation

Overall mean height and mean diameter for *Nauclea diderrichii* in mixtures at stand age 60 months were highest in 50% mixture (50%*Nauclea*/50%*Albizia*), followed by 100% mixture (monoculture) and 25% mixture (Fig. 4.6). This result corroborate the findings of other studies which also found 50:50 mixtures more productive than other combinations (Bosu et al., 2006; Bristow et al., 2006; Forrester et al., 2004; Binkley et al., 2003; Bauhus et al., 2000; Khanna, 1997). Bosu et al., (2006) reported that highest mean height of *Milicia excelsa* at stand age 8-9 years was attained in 50%*Milicia*/50%*Terminalia*. A study by Bauhus et al., (2000) also showed stem volume and tree height to be highest in 50%*Eucalytus*/50%*Acacia* mixtures. They also found that fine-root nitrogen concentrations of *Eucalyptus globulus* were highest in the 50:50 mixtures (Bauhus et al., 2000). Similarly, Bristow et al., (2006), also reported of largest diameters in 50:50 (50%*Eucalyptus*/50%*Acacia*), even though they were cautious due to changes in original design by cyclones. These observations reinforce the suggestion that future mixed-species trials could be more efficient if only monocultures and 50:50 mixtures are used (Forrester et al., 2005). The increase in growth especially mean diameter recorded in 50% mixture (50%*Nauclea*/50%*Albizia*) was probably due to the presence of *Albizia adianthifolia* (Cavieres and Badano, 2009; Piotto, 2008; Diabete et al., 2005). *Albizia adianthifolia* is known to nodulate (Diabete et al., 2005; Högberg and Piearce, 1986), and can also fix atmospheric nitrogen (Swaine et al., 2005). The presence of *Albizia adianthifolia* may have led to high rates of photosynthesis and greater efficient use of resources such as nutrients and water (Richards et al., 2010; Fridley, 2001; Binkley et al., 1992).

According to Binkley and Gardina (1997) net primary production could be greater in mixtures if one species could obtain more of a limiting resource. The increased available nitrogen might have been made possible either through symbiotic N-fixation (Kelty, 2006; Simard et al., 1997; Binkley et al., 1992) or increased nutrient cycling due to fast decomposition of plant litter from *Albizia* (Richards et al., 2010; Prescott, 2002). The total available nitrogen in the plant-soil system is increased as atmospheric nitrogen is fixed (Khanna, 1998), and nutrient cycling is accelerated (Prescott, 2002). Many studies have reported of increased productivity in non-N fixing economic species due to the presence of nitrogen fixing leguminous species (Nichols and Carpenter, 2006; Forrester et al., 2004; Binkley et al., 2003; Bauhus et al., 2000; DeBell et al., 1997; Khanna, 1997). A study by Nichols and Carpenter (2006) in southern Costa Rica showed that *Terminalia amazonia* grew significantly better when mixed with the legume tree, *Inga edulis*. Forrester et al., (2004) also reported of increased above ground biomass in *Eucalyptus globulus* which was attributed to the presence of *Acacia mearnsii*. An interesting observation in this current study however was the fact that increased availability of nitrogen from *Albizia adianthifolia* was only manifested in the growth of *Nauclea diderrichii* in 50% mixture at stand age 60 months (Fig. 4.6). Mean diameters and mean heights in mixtures were least in 50% mixture from 6 months to 36 months (Fig. 4.7). The change in growth pattern confirms the assertion that net effect of biodiversity on productivity may increase with time (Cardinale et al., 2007) and that rates of nitrogen fixation can also increase with increase in age (Richards et al., 2010). Despite the highest growth in 50% mixture, differences in mean heights and diameters among the mixtures were not statistically significant (Table 4.7). Although there were no significant differences at stand age 60 months, the trend can change with time (Fig. 4.7). Mean while contrary to the facilitation role *Albizia adianthifolia* might have played, the inclusion of *Tetrapleura tetraptera* in the high diversity treatment seem not to have affected the growth of *Nauclea diderrichii* (Fig. 4.6).

Similar to survival rates for *Pericopsis elata*, mean height and mean diameter at age 60 months were highest in 100% mixture (monoculture). However contrary to survival rates, mean heights and mean diameters were higher in 25% mixture (25%*Pericopsis*/25%*Nauclea*/25%*Terminali*a/25%*Tetrapleura*) than 50% mixture (*50%Pericopsis*/*50%Albizia*) (Fig. 4.4). The result is in conformity with other studies which reported greater growth and productivity in some tree species planted in monocultures compared to mixtures (Oelmann et al, 2010; Erskine et al., 2006; Petit and Montagnini, 2006; Redondo-Brenes and Montagnini, 2006; Piotto et al., 2004; Stanley and Montagnini, 1999). Results from Petit and Montagnini (2006) showed that *Calophyllum brasiliense*, *Virola koschnyi* and *Hyeronima alchorneoides* significantly grew better in monocultures than in mixed plantations. The same study also found greater productivity in *Dipteryx panamensis*, *Genipa americana* and *Balizia elegans* when grown in monocultures compared to mixtures (Petit and Montagnini, 2006). Erskine et al., (2006) also reported that *Araucaria cunnighamii* planted in the humid tropics of Australia performed poorly in mixtures with average basal area and stand basal area 16% and 10% lower respectively, than in monoculture stands. Another study conducted by Piotto et al., (2004) in the dry tropics of Costa Rica demonstrated that *Tectona grandis* planted as monoculture was the most productive compared to all species and the mixture of species. Similarly Oelmann et al., (2010) also found *Hura crepitans* to have produced less biomass in mixtures than in monocultures. Piotto (2008) noted that mixed plantations can either have a positive or negative effect on growth of tree species.

The results however contrast several other studies which recorded better growth in mixtures than monoculture stands (Potvin and Dutilleul, 2009; Piotto, 2008; Forrester et al., 2007; DeBell et al., 1997; Binkley et al., 1992). A meta-analysis carried out by Piotto (2008) to compare tree growth in monocultures and mixed plantations indicated that mixing tree species generally increase plantation growth.

Forrester et al., (2007) also reported that mixtures of *Eucalyptus globulus* and *Acacia mearnsii* were twice as productive as *Eucalyptus globulus* monocultures growing on the same site in East Gippsland, Australia. Despite the fact that there was no statistically significant difference among the mixtures (Table 4.4), the results may suggest that other factors probably had greater effect on growth of *Pericopsis elata* than species diversity and the inclusion of nitrogen fixing species (Forrester et al., 2006; Wormald, 1992). Unlike *Nauclea diderrichii*, it seems the presence of *Albizia adianthifolia* in 50% mixture did not enhance growth in *Pericopsis elata* (Fig. 4.4). This observation is in line with Callaway (1998) who indicated that because facilitation may be species specific, some species can have either negative or neutral effects on others. According to Wormald (1992) the beneficial effects of mixtures with nitrogen fixing trees are not always very obvious. Studies have shown that facilitative interactions do not always produce greater growth in mixtures compared to monocultures (Parrotta, 1999). Parrotta (1999) found that the admixture with either *Casuarina equisitifolia* or *Leucaena leucocephala* after 8.5-years had little or no effects on the growth and productivity of *Eucalyptus robusta*.

The present study however showed a very surprising result at stand age 36 months (Fig. 4.5). Mean heights and mean diameters for *Pericopsis elata* in mixtures were highest in 25% mixture (containing *P. elata, N. diderrichii, T. superba and T. tetraptera*) as compared to 100% mixture and 50% mixture (Fig. 4.5). This probably was due to the presence of *Tetrapleura tetraptera* in the high diversity treatment (Table 3.1) which is able to form nitrogen fixing nodules with rhizobia (Ibeawuchi, 2007; Diabete et al., 2005). Högberg and Piearce (1986) also reported ectomycorrhizal association in the genus *Pericopsis* from some sites in Zambia. Though somehow surprising, Swaine et al., (2005) indicated that as plants grow larger, their demand for nitrogen in most cases increases and therefore effect of nitrogen fixers on growth can be expected.

Since *Tetrapleura tetraptera* is known to have a very extensive fine-root system in the upper soil horizon (Akinnifesi et al., 1999), it is possible that the transfer of nitrogen could have resulted from below ground root and nodules turnover (Khanna, 1998; Wormald, 1992). According to Wormald (1992) nitrogen fixation can function as direct transfer from root nodules to the soil. However this facilitative process seems to have short lived and lasted close to only 24 months (Fig. 4.5). At stand age 60 months growth in *Pericopsis elata* in the 25% mixture fell behind 100% mixture (monoculture) (Fig. 4.5). This confirms suggestions that nitrogen fixation can vary with age (Richards et al., 2010; Forrester et al., 2006) and the effects of one species on the other can change with time (Wormald, 1992). Rates of nitrogen fixation may increase to a peak and then decline as nitrogen availability increases and nutrient cycling within stand provides sufficient nitrogen required by plants (Richards et al., 2010). Moreover different nitrogen fixing tree species have varied potentials to form symbiosis with rhizobia (Diabete et al., 2005) and the amount of nitrogen fixed can also be influenced by soil, plant and fungus factors (Danso et al., 1992).

5.2.3 Competition

For improved growth and productivity in mixed-species plantations, it is important that species interactions reduce competition and rather increase availability of limiting resources for growth (Piotto, 2008; Forrester et al., 2006; Kelty, 2006: Nichols and Carpenter, 2006). This implies that intense competition can prevent absolute increases in productivity in mixtures (Richards et al., 2010; Callaway, et al., 2002; Hooper, 1998). The fact that mean height and mean diameter for *Nauclea diderrichii* at age 60 months were highest in 50% mixture (50%*Nauclea*/50%*Albizia*) shows that inter-specific competition was less severe as compared to intra-specific competition in 100% mixture (monoculture) and inter-specific competition in the 25% mixture (Piotto, 2008). However, the result for *Pericopsis elata* showed greater growth in 100% mixture (monoculture), compared to the other mixtures.

This indicates intense inter-specific competition in the mixed stands (Erskine et al., 2006; Forrester et al., 2006). Forrester et al., (2004) stated that when inter-specific competition is greater, mixed stands will be less productive than monocultures. Mean relative growth rates in diameter and height for *Nauclea diderrichii* in mixtures were highest in 100% mixture (monoculture), followed by 50% mixture and 25% mixture respectively (Table 4.8). According to Guan et al., (2008) the distribution of RGR is a good measure to assess inter-tree competition for both below and above ground resources. When RGR is low it is an indication of intense competition between plants (Cannell et al., 1984). This implies that inter-specific competition between species in the 25% mixture was very intense and that was why *Nauclea diderrichii* recorded least growth and survival in that treatment (Fig. 4.2&4.6). According to Cannell et al., (1984) trees with many taller neighbours mostly have lower RHGRs than trees with few taller neighbours. RGR in diameter and height for *Pericopsis elata* were highest in 100% (monoculture), followed by 25% mixture with 50% mixture recording the least (Table 4.8). This demonstrates the intense inter-specific competition which may have existed between *Pericopsis elata* and *Albizia adianthifolia* while intra-specific competition in the monoculture stands was reduced. The high RGR in monoculture stands shows that *Pericopsis elata* grew efficiently even when resources were limited (Guan et al., 2008).

The results obtained for both focal species may not be too surprising due to the ecological characteristics of species in the plantation. Binkley (1997) stated that overall growth in stands depends on constant supplies of resources, which may be affected by the species selected. Moreover competition between neighbours intensifies as their morphological and physiological similarities increase (Hunt et al., 2006), which may eventually reduce growth and productivity (Boyden et al., 2008).

Since all the species in the plantation are light demanding at some stage (De Ridder et al., 2010; Oteng-Amoako, 2006; FAO, 1993), inter-specific competition between focal species and companion species in the mixed-species plots for particularly light and other resources may have reduced growth (Potvin and Dutilleul, 2009; Petit and Montagnini, 2006). Complementarity or competitive reduction therefore had no place in the stand (Forrester et al., 2004; Menalled et al., 1998).

Results from Hunt et al., (1999) demonstrated that early-age competition from *Acacia dealbata* on *Eucalyptus nitens* substantially reduced volume by almost 25% by age 8-years. It was however surprising that *Nauclea diderrichii* in 50% mixture which had a lower mean RHRG and mean RDGR compared to 100% mixture (Table 4.8) eventually attained the highest growth rate in terms of height and diameter (Fig. 4.6). This further reveals the facilitative role *Albizia* might have played in enhancing growth in *Nauclea diderrichii* in mixtures. This demonstrates the tendency for facilitation and competition to occur concurrently in a stand (Callaway and Walker, 1997; Callaway et al., 2002), and unless facilitative processes dominate, monocultures will be more productive than mixtures (Forrester et al., 2006). Based on RGR distributions the intense competition could have also added to the lack of significant contribution by the *Albizia adianthifolia* to growth of *Nauclea diderrichii*. When competition from non-nitrogen fixing species is strong enough to reduce growth of nitrogen fixing species, it may also reduce rates of nitrogen fixation (Richards et al., 2010; Forrester et al., 2007). It is therefore possible that *Nauclea diderrichii* which overtopped *Albizia adianthifolia* could have reduced its ability to fix high levels of nitrogen. On the contrary *Albizia adianthifolia* under stressed could have also used already fixed nitrogen to maintain its own survival. A study by Laclau et al., (2008) in Brazil reported that suppressed *Acacia mangium* in mixed stands could not influence biomass production and partitioning within *Eucalyptus grandis*.

Since competition can influence the outcome of facilitative processes (Potvin and Duttilleul, 2009; Callaway, 1995), productivity of *Nauclea diderrichii* and *Pericopsis elata* in mixtures may not be primarily determined by the number of species but may probably be dependent more on the species composition (Nadrowski et al., 2010; Oelmann et al., 2010; Healy et al., 2008; Firn et al., 2007; Wormald, 1992). It is however important to point out that in this present study the selection of species was not so much based on their complementary characteristics but on species potential economic values, relevance for plantation development in Ghana, as well as conservation concerns and other non-wood benefits they provide (Foli et al., 2009; Benhin and Barbier, 2004). These criteria were necessary to achieve the broader objectives of the restoration project underway in Ghana.

5.2.4 Site factors and environmental heterogeneity

Site conditions such as climate and soil characteristics are important determinants of growth and productivity in forests (Forrester et al., 2005; Baker et al., 2003; Vilà et al., 2003; Binkley, 1983). The influence of these factors therefore makes it difficult to predict sites that can lead to increased growth and productivity in mixed-species plantations (Forrester et al., 2005; Kelty, 1989). As stated earlier although no soil analysis was carried out, the general climatic and edaphic factors of the site could have influenced the growth patterns in *Nauclea diderrichii* and *Pericopsis elata* and thereby confounding the effects of diversity on growth (Boyden et al., 2005; Vilà et al., 2003; Fridley, 2002).

A study conducted by Vilà et al., (2003) in Catalonia, Spain found regional forest productivity to be driven by climatic and soil factors. Overall mean height and diameter for *Pericopsis elata* at age 60 months were highest in 100% mixture (monoculture), compared to 25% mixture and 50% mixture (Fig. 4.4).

This probably is an indication that perhaps planting *Pericopsis elata* in its natural ecological range (Atuahene, 1996) in the long term may have outweighed species diversity effect and inclusion of nitrogen fixing species (Forrester et al., 2006; Wormald, 1992). According to Forrester et al., (2006) and Wormald, (1992) matching species to site is very critical to the success of mixed-species plantations. Lack of significant influence of *Albizia adianthifolia* and *Tetrapleura tetraptera* on growth of neither *Nauclea diderrichii* nor *Pericopsis elata* may have been partly due to prevailing soil factors (Boyden et al., 2005; Forrester et al., 2005; Swaine et al., 2005). Wormald (1992) noted that for nitrogen fixing species to make a positive contribution to stand growth, the site conditions must be suitable. The amounts and rates of nitrogen fixation by nitrogen fixing species depends very much on soil and any other factor which affects plant growth (Ibeawuchi, 2007; Forrester et al., 2006; Binkley et al., 2003; Danso et al., 1992). The relatively high levels of nitrogen in soils found in the moist-semi deciduous forest zone of Ghana (Baker et al., 2003; Hall and Swaine, 1981) despite some variations may have partly accounted for lack of significant effect of particularly *Albizia* on growth of focal species. Nitrogen fixing plants can be very efficient especially when there is not only a deficiency in soil nitrogen, but other nutrients especially phosphates (Binkley et al., 2003; Danso et al., 1992; Wormald, 1992). According to Ibeawuchi (2007) nodulation failures may occur because of high soil mineral nitrogen. Results from Swaine et al., (2005) showed that the capacity for *Albizia adianthifolia* to form nodules was strong when soil nitrogen was in low supply. The same study also reported that the importance of *Albizia adianthifolia* is greatest in dry forest zones (Swaine et al., 2005). Similarly a study by Binkley (1983) in Mt Benson near Nanaimo, BC, Canada and Skykomish in western Washington, US gave contrasting results based on site index and soil fertility. He found the presence of Alder in Mt. Benson, which was nitrogen deficient and had low site index, increased average Douglas-fir diameter.

On the contrary, the presence of Alder on the highly productive Skykomish site decreased average diameter, basal area and basal area growth of Douglas-fir. He therefore concluded that mixing Red Alder and Douglas-fir seemed to have great potential in increasing Douglas-fir productivity on infertile, N-deficient sites (Binkley, 1983)

Aside the general site conditions, heterogeneity in soil, and topography of a site can also influence growth and productivity of plantations (Nadrowski et al., 2010; Boyden et al., 2008; Healy et al., 2008). Topography and soil nutrient supply are important factors which can alter tree interactions in forest stands (Boyden et al., 2008; Nichols et al., 2001). Boyden et al., (2008) noted that gradients in soil resource supplies on a site can shift the balance in competitive processes in mixed-species stands. Results from this study at age 6 months showed a significant influence of block on *Nauclea diderrichii* mean height (Table 4.7). Further analysis revealed significant mean height differences in Blocks 2 and 3, and Blocks 2 and 4 (Appendix II). This result is in line with a study by Nichols et al., (2001). In their study conducted on a degraded pasture in Southwestern Costa Rica, Nichols et al., (2001) reported a significant effect of block on height growth of *Terminalia amazonia*. They attributed the effect to topography of the site (Nichols et al., 2001). In this study blocks were laid horizontally along contours of a gentle sloping landscape. Block 1 was placed on the highest contour, followed by the other blocks, with Block 4 at the foot of the slope. In a study by Baker et al., (2003) in a moist-semi deciduous forest in Ghana, they found that topographic position had a significant effect on the soil water regime at lower positions in the topography. They also indicated that the total C, total N, and exchangeable K concentrations significantly declined down slope, implying that soil fertility declined down the catena (Baker et al., 2003). The differences in the topography in the study site may have therefore partly accounted for differences in height as well as overall growth pattern in the stand.

6.0 CONCLUSION

Despite the possible limitations in the study especially regarding the plot sizes, the study can serve as basis for offering suggestions on possible silvicultural requirements for *Nauclea diderrichii* and *Pericopsis elata* plantations. One very important outcome from this study is the fact that *Pericopsis elata* can be planted either in monoculture or in mixture with other species. It also confirms earlier observations that *Nauclea diderrichii* can perform in both monoculture and mixed stands. However for *Nauclea diderrichii* and *Pericopsis elata* to fully benefit from mixtures, it is important to combine them with shade tolerant species to increase positive interactions and reduce competitive processes. Planting both species in their natural ecological range can increase the possibility of enhancing survival rates and also increasing growth. The study generally agrees with Bosu et al., (2006), that if trees grow through the critical period of pest damages, they may be able to grow to large sizes with time. It is however apparent from the study that the possibility of species diversity in either reducing herbivory or increasing growth in *Pericopsis elata* and *Nauclea diderrichii* cannot be decoupled from other factors such as species composition, initial spacing, site conditions (climate and soil) and the general environmental variability of the site. Even though tree species diversity could not significantly reduce pest damage and increase growth in *Nauclea diderrichii* and *Pericopsis elata*, the main developmental objective of increasing biodiversity as well as providing ecological goods and services are being achieved. For instance *Tetrapleura tetraptera* in mixed plots started fruiting after 48 months of plantation establishment. It is therefore important to encourage mixed-species plantations of *Nauclea diderrichii* and *Pericopsis elata* to help achieve different economic, ecological, silvicultural and sustainable objectives.

7.0 GERMAN ABSTRACT (Zusammenfassung)

Die hohe Anfälligkeit gegenüber Schädlingen und Krankheitserregern und die verursachten Schäden stellen eine der größten Herausforderungen bei der Verwendung einheimischer Arten wie *Nauclea diderrichii* und *Pericopsis elata* in Plantagen dar. *Nauclea diderrichii* (De Wild.) und *Pericopsis elata* (Harms.) werden durch *Orygmophora mediofoveata* Hamps (Lepidoptera: Noctuidae) und *Lamprosema lateritialis* Hampson (Lepidoptera: Pyralidae) geschädigt zum Beispiel wenn sie in Plantagen eingesetzt werden. Allerdings liegen in Ghana keine Informationen über alternative Optionen zur Bekämpfung dieser Schädlinge vor. Eine viel beachtete Empfehlung ist das anpflanzen der betroffenen Arten in Mischungen mit anderen Arten, welche den Druck der Schädlinge reduzieren sollen. Diese Studie, Teil eines groß angelegten Wiederherstellungsprogramms in Ghana, wurde durchgeführt, um herauszufinden, ob Baumartendiversität die Empfindlichkeit von *N. diderrichii* und *P. elata* gegenüber ihren primären Schädlingen verringert und um die Wuchsleistung dieser Arten in Monokulturen und Mischungen herauszufinden. *N. diderrichii*, *P. elata* und begleitende Arten (*Albizia adianthifolia, Terminalia superba* und *Tetrapleura tetraptera*) wurden in verschiedenen Mischungen gepflanzt (0:100, 50:50, und 25:25:25:25%) in einen wiedereinbauentwurf in der Bia Tano Forest Reserve, in der Nähe Goaso, Ghana. Überlebensraten und Wachstumsmuster (Höhe, Durchmesser und relative Wachstumsrate) wurden in Parzellen von Monokulturen und Mischbestände aus über 60 Monate untersucht. Die Gesamt-Überlebensrate für *Nauclea diderrichii* und *Pericopsis elata* im Alter von 60. Monaten waren 35.3% und 59.5%. Die globale Überlebensrate die mittlere Höhe und der Durchmesser von *N. diderrichii* in Mischungen im Alter von 60 Monate waren am höchsten in 50%Gemisch (50% *Nauclea*/50%*Albizia*), gefolgt von 100% Gemisch (Monokultur) gefolgt, und 25% Gemisch (25%*Nauclea*/25%*Pericopsis*/25%*Terminalia*/25%*Tetrapleura)*.

Mittlere relative Wachstumsrate für *Nauclea diderrichii* in Mischungen waren am höchsten in 100% Gemisch, im Vergleich zu 50% Gemisch und 25% Gemisch. Überlebensrate für *Pericopsis elata* im Alter von 60 Monaten war am höchsten im 100% Gemisch, gefolgt von 50% Gemisch (50%*Pericopsis*/50%*Albizia*) und 25% Gemisch (25%*Pericopsis*/25%*Nauclea*/25%*Terminalia*/25%*Tetrapleura*). Andererseits waren mittlere Höhe, mittlerer Durchmesser und mittleren relativen Wachstumsraten in *Pericopsis elata* am höchsten in 100% Gemisch (Monokultur), gefolgt von 25% Gemisch (25%*Pericopsis*/25%*Nauclea*/25%*Terminalia*/25% *Tetrapleura*) und 50% Gemisch (50%*Pericopsis*/50%*Albizia*). Allerdings war weder das Überleben noch das Wachstum maßgeblich durch die Dichte von *Nauclea diderrichii* und *Pericopsis elata* in Gemischen bei $p < 0.05$ betroffen.

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Plate 5.2. Understorey of a mixed plot

Plate 5.3. Mixed plot containing *Terminalia superba, Nauclea diderrichii*, *Pericopsis elata,* and *Tetrapleura tetraptera*

Plate 5.4. 60 month old *Terminalia superba*

Plate 5.5. Using the height stick during measurements

Plate 5.6. A butterfly spotted in the plantation

APPENDIX 1

Two-way ANOVA for survival rates in a) *Pericopsis elata* b) *Nauclea diderrichii* at stand age 24 and 36 months

a) 24 months

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	221.193	2	110.5967078	0.25245	0.7847538	5.14325
Block	4539.61	3	1513.203018	3.45401	0.0917376	4.75706
Error	2628.6	6	438.1001372			
Total	7389.4	11				

ii) 36 months

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	279.064	2	139.531893	0.15372	0.8607852	5.14325
Block	2121.27	3	707.090192	0.77898	0.5472466	4.75706
Error	5446.24	6	907.707476			
Total	7846.58	11				

b) 24 months

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	9.0020576	2	4.50103	0.0472	0.95426	5.1433
Block	135.67387	3	45.2246	0.4742	0.71159	4.7571
Error	572.27366	6	95.3789			
Total	716.94959	11				

ii) 36 months

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	255.91564	2	127.958	0.5502	0.60338	5.1433
Block	778.67798	3	259.559	1.1161	0.4137	4.7571
Error	1395.3189	6	232.553			
Total	2429.9126	11				

APPENDIX II

One-way ANOVA for Block effect on *Nauclea diderrichii* mean height in mixtures at stand age 6 months

Blocks 2& 3

Source of Variation	SS	df	MS	F	P-value	F crit
Block	0.020394559	1	0.02039	17.1948	0.0143	7.70865
Error	0.004744367	4	0.00119			
Total	0.025138926	5				

Blocks 2 and 4

Source of Variation	SS	df	MS	F	P-value	F crit
Block	0.168202245	1	0.1682	12.6104	0.02377	7.70865
Error	0.053353667	4	0.01334			
Total	0.221555912	5				

APPENDIX III

Two-way ANOVA for RGR in mean heights and mean diameters for a) *Pericopsis elata* and b) *Nauclea diderrichii*

a) *Pericopsis elata*

RHGR

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	0.05891	2	0.02945	2.60689	0.15317845	5.14325
Block	0.0914	3	0.03047	2.69638	0.13913294	4.75706
Error	0.06779	6	0.0113			
Total	0.2181	11				

RDGR

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	0.07102	2	0.03551	1.53699	0.28910837	5.14325
Block	0.13849	3	0.04616	1.99794	0.21585247	4.75706
Error	0.13863	6	0.0231			
Total	0.34814	11				

b) Nauclea diderrichii

RHGR

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	0.1941	2	0.09705	1.97637	0.2190919	5.14325
Block	0.33493	3	0.11164	2.27354	0.1802129	4.75706
Error	0.29463	6	0.04911			
Total	0.82367	11				

RDGR

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Density	0.07667	2	0.03834	1.30923	0.33741433	5.14325
Block	0.18069	3	0.06023	2.05696	0.20749561	4.75706
Error	0.17568	6	0.02928			
Total	0.43304	11				