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EFFECT OF SHADE TREES IN COCOA AGROFORESTRY SYSTEMS ON COCOA MICROCLIMATE AND PRODUCTIVITY

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EFFECT OF SHADE TREES IN COCOA AGROFORESTRY SYSTEMS ON COCOA MICROCLIMATE AND PRODUCTIVITY

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A Thesis Submitted to the School of Graduate Studies, Kwame Nkrumah University of Science and Technology in partial fulfilment of the requirements for the Degree of

MASTER OF PHILOSOPHY
IN
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DENNIS KYEREH
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DECLARATION

I hereby declare that this work, submitted for the degree of MPhil. (Agroforestry) is the result of my own investigations conducted under supervision and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the thesis.

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DEDICATION

This work is dedicated to the loving memory of my late mother, Mrs. Joyce Serwaa who was such an inspiration. May her soul rest in peace.

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ABSTRACT

The research was conducted to evaluate the effect of shade trees in cocoa systems on the availability of soil moisture, photosynthetically active radiation (PAR), temperature and relative humidity for cocoa in the dry seasons and how these environmental factors influence cocoa productivity. The study was carried out in the Atwima Nwabiagya District (a moist semi-deciduous forest zone) of the Ashanti region of Ghana. Sixteen different shade trees were selected and categorized as low, medium and tall canopy heights. An effect ratio comparing tree sub-canopy effects to the open area effects was adopted and data were analyzed using the R Statistical Package. Soil moisture contents were higher for the medium (0.09) and tall (0.06) canopy height trees but lower for the low canopy heights (-0.07). *Morinda lucida* (0.19), *Spathodea campanulata* (0.16) and *Ficus capensis* (0.13) showed favourable soil moisture effects, however *Citrus sinensis* (-0.26) revealed lower soil moisture levels in the sub-canopy during the dry seasons. Photosynthetic active radiation was significantly higher for the tall (48.5%) and medium (31%) canopy heights but lower for the low canopy heights (10.7%). *Entandrophragma angolense* and *Terminalia superba* had the highest transmitted percentage PAR of 69.2% and 67.1% respectively and the lowest being *Mangifera indica* (3%). The effect of single standing shade trees in cocoa systems to buffer temperature and relative humidity in the dry seasons were not significant. Cocoa aboveground biomass was higher in the sub-canopies of tall (0.07) and medium (0.01) canopy heights but was however significantly lower for low canopy heights (-0.24). Aboveground biomass was highest in the sub-canopy of *Entandrophragma angolense* (0.26) but lowest under *Mangifera indica* (-0.37). The study revealed that potential yields of cocoa were as well higher in the sub-canopies of tall (0.12) and medium (0.06) canopy heights but lower for low (-0.16) canopy height. The pod yields of cocoa were highest under *Ficus capensis* (0.40) and *Ficus exasperata* (0.40) but lowest under *Terminalia ivorensis* (-0.55). Tall and medium canopy height trees in cocoa agroforestry systems potentially ensure higher soil moisture content and PAR availability in the sub-canopy, especially during the dry seasons, which could translate into higher cocoa aboveground biomass and pod yields. The inclusion of low canopy height trees must be done with caution as it may lead to potential yield reduction.

Key words: Soil moisture, photosynthetic active radiation, temperature, relative humidity, aboveground biomass, cocoa yields, canopy height.

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Cocoa (*Theobroma cacao* L.) is an understorey tree and it explains why the crop is traditionally cultivated under the shade of selectively thinned forests in Ghana. The forest shade trees remaining in cocoa systems contribute to carbon sequestration, nutrient recycling, accumulation of soil organic matter, and the conservation of biodiversity (Zapfack *et al*., 2002; Schroth *et al*., 2004). Evapotranspiration which leads to moisture stress are reduced by shade trees during the drier seasons. This is crucial for the establishment and survival of cocoa seedlings in seasonally wet and dry environments (Beer, 1987). Thus, especially in circumstances of low-input agriculture, shade trees confer microclimatic stability to cocoa production (Beer *et al*. 1998; Schroth *et al.*, 2001b; Hartemink, 2005). Usually, multiple species in cocoa agroforestry systems contribute functions not found in monocultures, such as the partitioning of resources, synchrony of resource use, and the capability of each species to capture and cycle nutrients (Schroth *et al*., 2001).

Even though the favourable effects of trees in cocoa systems are widely stated (Beer, 1987; Mialet-Serra *et al.*, 2001; Siebert, 2002), information on the magnitude of these effects and how they ultimately translate into effects on yield in Ghana is scarce. More precisely, it is not yet evident to what extent shade trees influence different microclimatic factors in cocoa systems and whether the magnitude of effects depend on the type of shade tree, thus which specific tree traits favour or hamper cocoa growth and yields (Somarriba and Beer, 2011; Tscharntke *et al.*, 2011).

Benefits might differ between tree species and not all benefits might be equally important for cocoa growth and production.

Blaser *et al.* (2013) observed that trees with elevated canopies might reduce physiological stress in cocoa by intercepting sunlight at midday, while allowing enough light to penetrate to the understory during mornings and late afternoons therefore providing an improved microclimate for cocoa. With low canopy species, on the other hand, the canopy is directly spread above the cocoa trees and hence, most light will not reach the cocoa trees in the sub-canopy independent of the angle of the sun or time of the day (Beer, 1987). Such dynamics have been found to have strong effects in natural systems (Blaser *et al.,* 2013) but the potential negative implications of low canopy trees have not been investigated in cocoa agroforestry. Cocoa is highly sensitive to water and light or photosynthetic active radiation (PAR) availability (Zuidema *et al.*, 2005). According to Hartemink (2005), the effects of shade trees on the sub-canopy microclimate might have beneficial effects on cocoa biomass and yields.

1.2 Problem Statement

Shade trees, which provide shade for the cocoa in the sub-canopy, are fundamental components of cocoa agroforestry systems as these trees influence microclimatic stability (Hartemink, 2005). Shade trees have been shown to have the tendency to buffer relative humidity, soil moisture and temperature extremes in cocoa systems (Lin *et al.*, 2008; Verchot *et al.*, 2007) and may thus protect cocoa trees from water stress during drier periods of the season. However, the microclimatic effects of shade trees on cocoa crops is often discussed controversially (Somarriba and Beer, 2011; Tscharntke *et al.*, 2011) as it is not yet evident in which aspects and which specific shade trees favour or hamper cocoa growth and yields.

1.3 Justification

Cocoa yields are highly sensitive to water and light availability (Zuidema *et al.*, 2005; Carr and Lockwood, 2011) and hence information on the potential for shade trees to be used in cocoa systems to regulate cocoa environmental factors such as light, temperature, relative humidity and soil moisture dynamics is required to help ensure sustainable cocoa production. Species-specific studies support the importance of shade trees in cocoa systems for improved microclimate (Isaac *et al.*, 2007) but comparisons of more species are required to give adequate tree trait based recommendations.

This study will provide specific information on the magnitude to which tree traits influence different microclimatic factors in cocoa systems and the extent to which these effects favour or hamper cocoa growth and potential yields.

1.4 Aim of Study

The aim of this study was to evaluate the effect of shade trees on microclimate in cocoa agroforestry systems and how the microclimate influence aboveground biomass and potential pod yields of cocoa.

1.5 Specific Objectives

1. To evaluate the effect of shade trees on volumetric soil moisture content for cocoa.
2. To evaluate the effect of shade trees on photosynthetic active radiation availability for cocoa.
3. To assess the effect of shade trees on temperature and relative humidity in a cocoa agroforestry system.
4. To determine the effect of shade trees on aboveground biomass of cocoa trees.
5. To determine the effect of shade trees on potential pod yields of cocoa.

1.6 Hypotheses

- Tall and medium canopy height trees with deep roots in cocoa systems will ensure higher soil moisture content and photosynthetic active radiation availability in the sub-canopy.

- The canopy height of shade trees will significantly influence aboveground biomass and potential pod yields of cocoa.

- Leafing phenology of different shade tree species will influence microclimate in cocoa agroforestry differently.

CHAPTER TWO

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LITERATURE REVIEW

2.1 COCOA

2.1.1 Origin, History, and Dissemination

The cocoa tree, scientifically called *Theobroma cacao L.*, is a tropical woody species from the Sterculiaceae family and it originated from the Amazon region of Brazil (Dillinger *et al.,* 2000; Wood and Lass, 2008; Gianfagna and Cooper, 2012; Livingstone *et al.,* 2012). Historically, there is no proof on the particular period when people started consuming the fruit of the cocoa tree. In fact, the initial account of cocoa in history dated to the Spanish colonization of the Americas. Thus, the 16th century is considered the era during which the European first discovered cocoa, which had been eaten by Aztecs and Mayan prior to contact with Europeans (Wood and Lass, 2008). However, cocoa was produced mostly by the Mayan. Many other components such as chili and vanilla (Wood and Lass, 2008; Gianfagna and Cooper, 2012) and maize (Dillinger *et al.*, 2000; Wood and Lass, 2008), have been used together with cocoa. Despite the fact that the cocoa bean is the most fascinating part of cocoa today, the original cocoa tasters used to consume only the cocoa pulp. Consequently, the bean was consumed for the first time by unidentified Aztecs, who took that risk after roasting the tropical fruit (Dillinger *et al.*, 2000).

Besides the energetic properties of cocoa, earlier cocoa consumers used it for purposes such as medicine, religion and as currency (Wood and Lass, 2008). In fact, it was usually known as the “food of the gods” in the Aztec civilization (Gianfagna and Cooper, 2012). In addition, chocolate was the major drink of Montezuma, the Aztecs emperor in Mexico in the earlier 1500s as stated by Dillinger *et al.* (2000). Cocoa beans were one of the Aztecs currencies as well (Dillinger *et al.*, 2000).

Christopher Columbus is the one who initially introduced the cocoa beverage to Europe (Dillinger *et al.*, 2000; Gianfagna and Cooper, 2012). After being domesticated in the Amazon forest, the cocoa tree has been disseminated in South and Central America, and in almost all tropical countries in Africa and Asia. According to Presilla (2009), cocoa was propagated in South America and the Caribbean in the 17th century and continued to enlighten that during that same time cocoa got to Asia and was cultivated there as well. The Philippines was the first country in Asia where cocoa was cultivated. Until the 18th century, people were only engrossed in the *Criollo* variety of the cocoa bean. The domestication of *Forastero*, a modified variety of cocoa, happened in 18th century in Ecuador and Brazil. After that, cocoa production disseminated to West Africa during the second half of the 19th century. Ghana and Nigeria were the notable countries in Africa where cocoa was initially introduced (Dillinger *et al.*, 2000).

2.1.2 Cocoa Ecology

Even though *Theobroma cacao* (cocoa) is native to South America, it is now propagated pan-tropically, between latitudes of 10° N and 10° S. The ideal climatic conditions for cocoa growth are in temperature ranges of 18-23°C with harmful effects on growth under long periods below 10°C or above 30°C. Cocoa is extremely drought intolerant species, displaying most positive growth in areas with rainfall ranging from 1,150 mm-2,500 mm (Willson, 1999). The optimum soil pH range for cocoa growth is 5.0-7.5 in the top soil. Soil pH below 4.0 may raise aluminium toxicity. However, a fairly low percent base saturation of 35% is acceptable (Willson, 1999). Coarser soils with a mix of sand and clay are ideal for cocoa root growth as bigger particle size permits for root penetration.

Although the cocoa tree root zone comprises of a thick tap root, a mat of lateral roots (80-85%) are found mainly in the top 0-20 cm of the soil (Kummerow *et al.*, 1982) working as the main channel for moisture and nutrients.

2.1.3 Cocoa Cultivation in West Africa

Cocoa as an understorey tree is usually grown under the canopy of shade trees that may be leftovers of the original forest or may have been purposely planted (Wood and Lass, 1985; Power and Fletcher, 1998; Ruf and Zadi, 1998; Whinney, 1998; Klein *et al.*, 2002; Anim-Kwarpong, 2003). Cocoa has been grown by smallholders in the shade of primary or secondary forest trees for a very long time throughout the tropics (Duguma *et al.*, 2001). The major cultural practice of cocoa establishment in the humid west and central Africa includes cultivating cocoa in secondary forest or forest fallow, selectively cleared and planted to several food crops for one or two seasons (Duguma *et al.*, 1990; Duguma and Franzel, 1996). When a piece of land is cleared, native fruits, medicinal and timber tree species are intentionally reserved to offer both economic and shade benefits for the cocoa trees.

Land clearing is done by hand (though chain saw is used to fell large trees) which together with the zero tillage procedure employed during planting, causes little or no disturbance to the delicate soils (Duguma *et al.*, 2001). The system may be improved by planting extra fruit trees like *Mangifera indica*, *Persea americana*, *Citrus sinensis* and *Elaeis guineensis*, contingent on the concentration of the reserved natural tree species and the mortality of the cocoa seedlings (Oladokun, 1990; Amoah *et al.*, 1995; Duguma *et al.*, 2001). As the cocoa trees and the other components mature, the agroforest system becomes more varied and structurally multifaceted, closed-canopy multi-strata system that look a lot like natural forest (Duguma *et al.*, 2001).

Such systems show a high level of habitat heterogeneity, and they seem to serve as good substitutes of natural forest for many faunal species (Terborgh, 1989; Perfecto *et al.*, 1996). These systems are sustainable, remaining productive for so many years (Power and Fletcher, 1998).

According to Sonwa *et al.* (2007), the main management necessities for cocoa agroforest systems are shade control, weeding, disease and pest control, pod harvesting and processing of cocoa beans. He further revealed that the effect of shade in the management of a cocoa agroforestry system is somewhat multifaceted as it bears an influence on a number of other growth factors, such as reduction in photosynthetic active radiation (PAR) availability, temperature, air movement and relative humidity, and all these indirectly influence photosynthesis and the occurrence of pest and diseases. The level of shade needed for cocoa may differ considerably, depending on the age of the cocoa tree, the farm location or more so the source of the cocoa crop (Duguma *et al.*, 2001). However, Tscharntke *et al.* (2011) stated that optimal growth and productivity of cocoa are supported by a level of shading that allows 20 to 30% of full sunlight to reach the understorey cocoa.

2.1.4 Cocoa production in Ghana

Cocoa is perhaps the most significant export crop for countries in the forest zone of West Africa and is the major foreign exchange earner for some of them (Padi and Owusu, 1998). In Ghana, cocoa plays a key role in terms of foreign exchange returns and national incomes, as well as being the main source of income for the delivery of socio-economic infrastructure (Cocoa Board, 1995; Padi and Owusu, 1998). Cocoa production is usually dominated by smallholder farmers with typical farm possessions ranging from 0.4 ha - 4.0 ha (Cocoa Board, 1998).

Ghana maintained world leadership in cocoa production with market share ranging from 30 - 40% of the world's entire production for 66 years (i.e. from 1910 – 1977) (Bateman, 1988). This production level maximized at 566,000 tonnes in 1964/65 but fell significantly to 159,000 tonnes in 1983/84 and has since then varied over the past years between 150,000 and 350,000 tonnes per annum, and this made Côte d'Ivoire take up the first position of world cocoa production from Ghana (Gill and Duffus, 1989; Jaeger, 1999). A survey conducted by the Government of Ghana Task Force in 1995 revealed that a lot of cocoa farmers were producing below 250 kg dry beans of cocoa per annum, with productivity of land projected at about 390 kg per hectare (Cocoa Board, 1995). This cocoa yield rate was identified to be lower compared to countries such as Côte d'Ivoire and Malaysia, with their yields of 600 kg and 800 kg per hectare respectively. The total land area of cocoa establishment in Ghana has been reported to be around 1.2 million hectares (Cocoa Board, 1998). This value signifies a drop of 0.6 million hectares as compared to the area of productive land in the sixties. Furthermore, production of dry cocoa beans has dropped from an average of 400,000 tonnes in the 1960s and 1970s to a static average of 370,000 tonnes from 1995 to 2000, even though there are evidence that production is increasing (Cocoa Board, 2000).

2.2 SHADE IN COCOA PLANTATIONS

According to WCFSD (1999), about 14 x 106 ha of forests have been lost every year since 1980 as a result of changes in land use from forest to agriculture. The fast rate of deforestation has posed a challenge to conservationists to protect and conserve the remaining forested land. Usually ignored, however, is that converting tropical forest for agricultural use is hardly complete, and usually temporal. Within the agricultural setting, one can observe a significant amount of forested area in the form of managed multi-storey agroforestry systems, whose attributes of structural complexity buffer microclimate, and diversity of canopy food plants maintain high biodiversity and help ensure the protection of forest biota (Beer, 1987; Alcorn, 1990; Michon and de Foresta, 1995; Perfecto *et al.*, 1996). Cultivated areas of cocoa and coffee represents one of the most significant forms of land-use and have vast economic benefits for developing nations (Wood and Lass, 1985). The cocoa tree species are often cultivated under shade trees in agroforestry systems based on two or more perennial species (Nair, 1993). Conventionally, shade of cocoa relates to the concentration of forest tree species left over in the field after the first clearing of the forest in West Africa. Cultivating cocoa under shade is as a result of the notion that cocoa, being a second storey tree, grow well under dense forest shade (Padi and Owusu, 1998; Ruff and Zadi, 1998). It has been pointed out that the major aim for cultivating cocoa under dense shade, was to prolong the economic life of the cocoa tree, with other reasons having to do with the technical difficulty of cutting down big trees due to lack of appropriate equipment in the past, or for socio-cultural motives (N'Goran, 1998; Ruff and Zadi, 1998).

However, this previous notion of cocoa growing best under dense forest shade has given way to a prescription of low shade, for both yield levels and maturity (Padi and Owusu, 1998). The suggestion in Ghana is to decrease overhead shade levels to at most 10 large and 15 medium sized trees per hectare or 4 trees per acre (Osei-Bonsu and Anim-Kwarpong, 1997). In Côte d'Ivoire, however, the suggestion is to cultivate cocoa without shade (Freud *et al.*, 1996; Ruff and Zadi, 1998). A research by Freud *et al.* (1996) into the intensities of permanent shade in cocoa farms in Ghana and Côte d'Ivoire revealed that about 50% of the entire cocoa area in both countries was under low permanent shade while an average of about 10% in Ghana and 35% in Côte d'Ivoire was under zero or no shade; signifying a gradual change towards eradicating shade trees from the cocoa agroecosystem. Different types of shade management systems employed in cocoa agroforestry have been observed.

Ruff and Zadi (1998) reported that mature cocoa farms can be categorized into six forms of shade management systems, namely;

(i). Selected forest trees kept by selective cutting and incomplete burning. In this case, the shade trees form a stratum 20 – 40 metres above the cocoa stands,

(ii). Spontaneous and selected regrowth of forest trees initially cut down (and burnt but the fire does not destroy the whole root system). The shade layer is much lower than in the former case,

(iii). Trees established by farmers. The most common are leguminous trees that are expected to have positive effects in terms of shade and nitrogen supply,

(iv). Tree crops like several fruit trees grown for direct agricultural and economic benefits but which may also offer services such as shade and wind breaks to cocoa, (v). Plantains and bananas which are expected to deliver only short-term shade to young seedlings but in most cases mats renew every year,

(vi). 'No shade' systems or pure monoculture after whole forest clearing and consistent removal of any shoots during weed control.

However, Greenberg (1998) and Rice and Greenberg (2000) identify three basic shade management systems in cocoa, namely:

(i). Rustic cocoa management: This is extensive in humid West Africa and indigenous in Latin America and is considered as the establishment of cocoa under the canopy of thinned or older secondary forest;

(ii). Planted shade systems: These differ extensively and range from:

a. Conventional poly-cultural system – This refers to having several species of established shade trees with occasional leftover forest species,

b. Commercial shade – This is where other tree crops are scattered amongst planted shade trees and the cocoa,

c. Monocultural specialized shade – This occurs where the shade is subjugated by one or a small number of tree species. Some native shade systems are actually varied agroforests. However, in most established systems where a mass of shade species are located, usually one or a few species represent the "backbone" shade in which other fruiting and timber species are introduced. In some areas, cocoa is established under or intercropped mostly with fruit trees; iii. Zero shade cocoa or cocoa systems without shade – This is cocoa farming without shade and it's common in Malaysia and gradually becoming more prevalent in parts of Colombia and Peru.

N'Goran (1998) identified two main types of cocoa shade management systems in Côte d'Ivoire. These include planting cocoa under shade trees and planting cocoa without shade. The first technique is extensively adopted by smallholder cocoa farmers in West Africa and involves three shade management methods, reported by N'Goran (1998):

(i). Planting cocoa on the cleared forest floor. This comprises clearing all the undergrowth on the forest floor, and then removing specific tree species that are detrimental to cocoa trees, either through their competition for soil moisture, particularly in regions of low rainfall, their function as host to diseases and pests that harm cocoa trees, or by virtue of their canopies being too heavy or too low. This technique is the same as the rustic shade management method observed by Greenberg (1998) and Rice and Greenberg (2000) and that reported by Ruff and Zadi (1998);

(ii). Planting cocoa in areas of natural regrowth. This involves clearing forest land for a number of months before establishing and tending the regenerating trees for shade; (iii). Planting cocoa under man-made shade. This technique comprises of establishing shade trees according to a particular plan including the clearing of forest land, thereby eradicating all detrimental tree species, and introducing fresh indigenous or foreign tree species. N'Goran (1998) however, concludes that no investigation has been done on this technique unlike the previous two techniques above which have been explored in Côte d'Ivoire.

N'Goran (1998) however reported that over the past few years, the absence of remaining forest land has pressurized farmers into making use of their last option, that is, growing cocoa trees in previous plantations or on land left uncultivated and inhabited by *Chromolaena odorata*, which significantly hinders forest regeneration. The source of the usage of shade in cocoa systems is generally credited to initial farmers imitating the natural sub-canopy setting of cocoa tree species in the forest environment, as noted by Isaac *et al.* (2007), of the upper Amazon and Orinoco river basin (Simpson and Ogorzaly, 1986).

2.2.1 The importance of shade in cocoa

Several reasons have been pointed out in support of the inclusion of shade trees in cocoa agroforestry systems. First of all, conventional, shade-grown cocoa has proven to be well incorporated with native agricultural practices and traditions, and are biodiversity conservation friendly (Perfecto e*t al.*, 1996; Beer *et al.*, 1998). Cocoa as a natural understorey tree in the humid tropical forests, a multifaceted forest system remains the best environment for its establishment and sustainability. Cocoa cultivated in this kind of system holds huge prospects for environmental and cultural protection in areas under extreme pressure from logging, development and conventional, monocrop agriculture (Whinney, 1998).

The inclusion of shade in cocoa systems is an olden practice starting from the period the crop was domesticated. As the adoption of leguminous shade trees like *Gliricidia sepium* for cocoa occurs at what is usually regarded to be the points of taming, it was usually expected that shade trees, and more particularly leguminous shade trees, were vital for the propagation of the cocoa species (Sanchez *et al.*, 1990). Subsequently, permanent shade trees in tree crop systems have been a conventional package (Haggar *et al.*, 2011).

2.2.2 Shade and cocoa productivity

In Ghana, cocoa is generally grown under the shade of thinned forest (Wood and Lass, 1985). This agroforestry system is apparently perfect for the establishment of the cocoa crop because the leaves of cocoa have low light saturation point of 400 μ E m^{-2} s^{-1} and a low maximum photosynthetic rate (7mg dm^{-1} h^{-1}) at light saturation (Hutcheon, 1981). Raja Haru and Hardwick (1998) and Isaac *et al.* (2007) reported that the photosynthetic rate of cocoa is identified to decline if the photosynthetic mechanism is open to light intensities beyond 60% full sunlight, while persistent exposure to high light intensities destroys the photosynthetic apparatus of the leaves.

While the inclusion of shade seems to have been a world-wide practice previously, in this century the shade prerequisite of the cocoa tree has been interrogated and the practice has been liable to extensive investigation. In the 1950s and 1960s the debate over cocoa shade and productivity deepened with the evolving global accessibility of agrochemical technologies and, most prominently, the development and institution of new cocoa varieties that need little or no shade. Efforts to integrate these technologies were mainly directed by state funded research in Latin America and Africa.

A primary point of investigation was to reveal whether shade was an inherent necessity of the cocoa tree itself or whether it serves a secondary function by conserving appropriate soil, insect population, and other environments for the cocoa plant; environments that could be possibly conserved with the use of appropriate chemical inputs (Johns, 1999).

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It has been reported that on the most suitable areas, the production of cocoa usually upsurges if shade is reduced (Beer *et al.,* 1990; Johns, 1999; Zuidema *et al.*, 2005; Isaac *et al.,* 2007; Somarriba and Lachenaud, 2013; Gyau *et al.*, 2014). It has also been pointed out that heavy shade or low available light levels reduce or inhibit flower production in cocoa trees, and that light intensities below 1800 hours per year have a substantial depressing outcome on production, all other factors being constant (Gerritsma and Wessel, 1994; Zuidema *et al.,* 2005; Isaac *et al.*, 2007). Such variations, however, bring on other complications (Johns, 1999). The augmented yield under no-shade situations is normally accompanied by significant yield reductions due to several factors such as: persistent loss of exchangeable bases in the soil; destruction by insect pests; high soil moisture evaporation and too much leaf transpiration (Nunkyer, 2005; Ngala, 2015).

Trees in agroforestry systems bring about microclimate changes in their sub-canopies by decreasing soil and air temperature, irradiance and wind speed. These variations will have direct effect on soil water evaporation and relative humidity, which in turn may considerably influence crop growth, depending on the climatic conditions (Rao *et al.,* 1998). The decreased radiation capacity and wind speed in the sub-canopies decrease water demand by crops and soil evaporation, which are principally essential during the drier seasons (Rao *et al.*, 1998).

According to Wallace (1996), trees play a significant role in terms of rainfall loss through evaporation of canopy interception, and change conditions in the subcanopies by shading and redistributing intercepted rain through stem flow and canopy drip. Wallace *et al.* (1999), in a study at a semi-arid area in Kenya, anticipated that the decline in soil evaporation under tree canopies would be adequate to compensate the augmented losses due to canopy interception, depending on rainfall levels and annual overall rainfall quantity. Shade decreases photosynthesis, transpiration, metabolism and growth and hence, the request on soil nutrients and therefore allows a crop to be acquired on soils that are less fertile (Duguma *et al.*, 2001). Dependent on the tree species at hand, shade trees can as well fix atmospheric nitrogen and grip it inside the soil layer (Beer, 1987). New cocoa trees get advantage from the shield of shade trees and the effect shade has on growth form. The shade trees also function to decrease the winds at or close to the ground level within the cocoa agroforestry system (Rice and Greenberg, 2000). In Ghana, for instance, Ahenkorah *et al.* (1987) assessing the result of shade and fertilizer trials, observed that shade supports more sustainable production of mature cocoa plants with low intensities of fertilization. While shade is always suggested for the cultivation of cocoa it has also been suggested that the shade should be slowly eradicated on ideal areas as the cocoa turn out to be self-shading (Johns, 1999; Somarriba and Lachenaud, 2013). Beer (1988) however reports that in circumstances where demanding management practices such as the consistent application of fertilizers cannot be assured, some shade trees should be reserved for cocoa. The additional spending connected with clear-felling and growing unshaded cocoa with enormous quantities of fertilizers would perhaps be defensible only when yields of 3,360 kg/ha and above are acquired (Ahenkorah *et al.*, 1987).

2.3 DESCRIPTION OF THE SHADE TREE SPECIES

2.3.1 *Entandrophragma angolense*

Entandrophragma angolense belongs to the family Meliaceae, and is usually referred to as Edinam in Ghana. It is a large deciduous tree with deep rooting system (Hawthorne, 1995). It is one of the emergent trees in the high forest, with a circumference of about 4.6 m above buttresses. The stem is generally not as straight as the other *Entandrophragma* species. The deciduous time is from around midSeptember to November, although individual trees start to shed off their leaves in August (Hall *et al.*, 2004). Flushing of fresh leaves start in December, along with flowering which last until February, although some flowering can be observed after this time (Hawthorne, 1995; Hall *et al.*, 2004).

2.3.2 *Newbouldia laevis*

This tree species belongs to the family Bignoniaceae. In Ghana, its common name is Sesemasa (Hawthorne, 1995). It is a medium-sized tree with narrow crown construction (Amanor, 1994). It is an evergreen species with a deep rooting system (Hawthorne, 1995).

2.3.3 *Terminalia ivorensis*

This tree species belongs to the family Combretaceae and it is locally called Emire. It is a big deciduous tree and very common in secondary forest, with black bark and elegant, spreading crown of whorled branches and crowded leaves. The tree is deciduous just before the end of February and continues in March. The flush of fresh leaves appears in April and with them come the flowers. It is a deep rooting species (Hawthorne, 1995).

2.3.4 Terminalia superba

Terminalia superba belongs to the family Combretaceae. It is normally known in Ghana as Ofram. It is fundamentally a tall tree of the deciduous forest and drops its leaves in the drier season. Leaves are simple, alternate, in clumps at the ends of the branches, leaving distinct marks on branches when dropped. It has a deep rooting characteristic (Hawthorne, 1995).

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2.3.5 *Alstonia boonei*

Alstonia boonei belongs to the family Apocynaceae. It is a large deciduous tree, up to 45 m tall and 1.2 m in width; bole mostly deeply grooved to 7 m with minor buttresses, bark greyish-green or grey, slash rough-granular, displaying a profuse milky latex; branches in whorls. Locally known as Nyamedua in Ghana. It has a medium canopy height with a deep rooting system (Hawthorne, 1995).

2.3.6 *Antiaris toxicaria*

Antiaris toxicaria belongs to the family Moraceae. It is an outstanding tall deciduous tree of the forest canopy, often 20- 40 m tall with a dome-shaped crown, losing branch lets and hairy branches. Huge trees have distinct boles and are supported at the base. Bark is smooth, pale grey, noticeable with lenticel spots and ring marks. When cut, thin milky latex drops out, becoming darker on exposure to air. It is deep rooting and usually called Kyenkyen in Ghana (Hawthorne, 1995).

2.3.7 *Citrus sinensis*

Citrus sinensis belongs to the family Rutaceae. It is a small, shallow-rooted evergreen tree about 6-13 m tall with a bounded conical top and often has prickly branches. The branches are angled when new, usually with dense spines. It is generally called Orange and has a comparatively low canopy height (Hawthorne, 1995).

2.3.8 *Elaeis guineensis*

Elaeis guineensis belongs to the family Palmae. It is a low canopy tree attaining a total height of about 20 m or more when matured. The bole is characterized by tenacious, spirally organized leaf bases and bears a crown of 20-40 enormous leaves. The root system is shallow and has an evergreen leafing phenology. It is normally called Oil Palm (Hawthorne, 1995).

2.3.9 *Funtumia africana*

Funtumia africana belongs to the family Apocynaceae. It is a tropical tree up to 30 m tall (generally shorter) with a straight, cylindrical trunk and a narrow tree crown. The bark is brown to dark in colour, thin and somewhat fissured becoming granulated on matured trees. It is called Sesedua in Ghana. *F. africana* is a deciduous tree species with a shallow rooting system (Hawthorne, 1995).

2.3.10 *Ficus capensis*

Ficus capensis belongs to the family Moraceae. It is a deciduous and a medium canopy height tree species. It is locally known in Ghana as Odoma. It has a deep rooting system (Hawthorne, 1995).

2.3.11 *Ficus exasperata*

Ficus exasperata belongs to the family Moraceae. It is a medium canopy height tree species and locally known as Nyankyerene in Ghana. It is a deciduous tree species with a deep rooting system (Hawthorne, 1995).

2.3.12 *Milicia excelsa*

Milicia excelsa belongs to the family Moraceae. It is a large and tall deciduous tree attaining a height of 30-50 m, with a diameter of 2-10 m. It has deep rooting system and the species is commonly called Odum in Ghana (Hawthorne, 1995).

2.3.13 *Mangifera indica*

Mangifera indica belongs to the family Bignoniaceae. It has a low canopy height reaching about 20 m tall with a dark green, umbrella-shaped crown. The trunk is firm, 90 cm in width; bark brown with many thin cracks; dense, becoming darker, rough and scaly; branch lets rather firm, pale green and hairless. It is an evergreen and shallow rooted tree species and usually called Mango (Hawthorne, 1995).

2.3.14 *Morinda lucida*

Morinda lucida belongs to the family Rubiaceae. It is deep rooted and an evergreen species. It has comparatively medium canopy height. It is one of the popular shade tree species observed in cocoa systems in Ghana and usually called Konkroma (Hawthorne, 1995).

2.3.15 *Persea americana*

Persea americana belongs to the family Lauraceae. It has a low canopy height, that is, it attains a total height of about 9-20 m. The Avocado, as it’s commonly known, is categorized as an evergreen, even though some varieties drop their leaves for a short period before flowering. The tree canopy ranges from low, thick and regular to straight and irregular. It has a shallow rooting character (Hawthorne, 1995).

2.3.16 *Spathodea campanulata*

Spathodea campanulata belongs to the family Bignoniaceae. It is a large and tall deciduous tree species with a deep rooting system. It is commonly called Kokuonisuo in Ghana (Hawthorne, 1995).

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2.4 TREE-CROP INTERACTIONS

The interactions between shade trees and crops in agroforestry systems have been extensively stated by several authors (Beer *et al.*, 1998; Araya, 1994). Even though competition is unavoidable when more than one species are using similar resources, it is assumed that the system in totality can profit from their interactions (Somarriba *et al.*, 2001).

From a physiological perspective, the major advantage that crops such as cocoa obtain from shade trees is a decrease of the biotic stress mounted on the plant because of an improvement of microclimate, changed soil conditions and a decrease in the amount of light transmitted to the sub-canopy cocoa (Beer *et al.,* 1998).

By buffering extreme climatic conditions, shade trees are recognized to stabilize cocoa yields all the way through the seasons, making planning and harvesting more efficient and effective for the farmer and extending the life span of the crop. Because of the reduced pressure, crops can tolerate physical conditions of lesser quality or minor external inputs, like fertilizer, and turn into a more appropriate choice for smallholder farmers in tropical countries (Beer, 1987; Duguma *et al.*, 2001). The prevalent physiological advantages that cocoa obtain from shade trees can be categorized into two major forms both related to decreased plant stress, viz.;

1. Improvement of microclimatic and site conditions through:

i. Buffering of soil and air temperature extremes, ii. Decrease of
wind speed; iii. Ensuring ideal relative humidity and soil moisture
availability; iv. Conservation of soil fertility together with erosion
control, and

2. Decrease in the quantity and quality of transmitted available light and therefore prevention of overbearing and/or extreme vegetative growth such as flushing in cocoa. Moreover, shade decreases nutritional discrepancies and die-back.

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However, the major physiological disadvantage with shade trees is competition for light, water and nutrients (Beer *et al*., 1998).

Beer (1987) pointed out that there is a decrease of net photosynthetic active radiation during the day below the tree canopy, since a reduced quantity of the radiation reaches the sub-canopy, and Brenner (1996) concludes that this is predominantly advantageous at the start of the season when soil can attain high temperatures causing harm to the crop.

The necessity for some level of shade inclusion in a cocoa system is also buttressed by the fact that cocoa growth and pod yield decline with high photosynthetic active radiation intensities (Zuidema *et al.*, 2005; Isaac *et al.*, 2007).

Shade tree species can influence the speed and tempestuous structure of wind pattern in a cocoa system, thereby decreasing the vulnerability of cocoa to damage and drought (Beer *et al*., 1998). They decrease photosynthetic quantum flux density, vapour pressure shortage and leaf temperature and (Brenner, 1996). Competition for water between the shade trees and understorey crops considerably influence the response of the stomata by modifying leaf water status and microclimate. Hence, crops growing in the sub-canopies of shade trees may attain different entire conductance from those cultivated in monoculture, altering both their evapotranspiration and photosynthetic levels (Brenner, 1996).

2.5 RESOURCE CAPTURE AND USE

The virtual significance of the different influence of shade trees, and therefore the requirement for shade, is highly dependent on site conditions (Beer, 1987; 1988). Trees and crops in an agroforestry system interact wherever they are cultivated in adjacent temporal or spatial closeness, and the influence of this on crop growth and yields can be divided into positive interactions such as those which increase soil fertility levels or

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ensure improved microclimatic environments, and adverse interactions like those which compete for light, water and nutrients (Vandenbelt *et al.,* 1990). Several positive and detrimental interactions have been suggested for the tree and crop constituents of agroforestry systems, and the path and extent of these interactions are largely influenced by the forms of resource allocation (Gillsepie *et al.,* 2000). By altering resource accessibility, trees can either improve or decrease cocoa productivity of the sub-canopy (Belsky *et al.,* 1993; Anderson *et al.,* 2001). According to Scholes and Archer (1997), trees significantly influence nutrient, light and water accessibility of the sub-canopy crops. It has been reported by several workers that cultivating trees in association with crops is only advantageous when trees utilize resources that are unavailable to the crop and/or produce significant value per unit of resources attained in competition with the crop (Cannell *et al.*, 1996; Vandermeer *et al.*, 1998).

Howard *et al.* (1997) have proposed that the level of competition, and eventually crop yield, in agroforestry systems is reliant on the dividing of resources such as light, water, and nutrients. The achievement of a multifaceted agroforestry system is determined principally by reducing the adverse interactions between trees and crops both aboveground (usually for photosynthetic active radiation) and belowground (usually for moisture and nutrients) (Jose *et al.,* 2000; Friday and Fownes, 2002). Friday and Fownes (2002) further revealed that in agroforestry systems competition for light, water and nutrients between the tree and crop components is a key limitation. Nair (1993) also pointed out that the existence of shade trees may possibly result in limited photosynthetic active radiation availability, ameliorated temperature extremes and modified plant water associations in the sub-canopy.

The aboveground competition for light or photosynthetic active radiation is expected between elevated trees and shorter crops under humid environments, whereas belowground competition for water may perhaps prevail in semiarid environments. It has been pointed out that competition can be decreased by choosing trees species which have restricted lateral root extension and/or are deep rooted than the adjacent crops, by pruning the tree roots to decrease their intensity in the sub-canopy and by pruning the tree crowns as well (van Noordwijk and Purnomosidhi, 1995; Schroth, 1995). Information on the exact procedures of competition would permit for the advancement of ideal management approaches and prevent technologies which have slim chance of success in a particular site (Friday and Fownes, 2002).

According to Menalled *et al.* (1998), the choice of trees to integrate in diversified planting systems require much consideration to the compatibility of growth features. The idea of competitive elimination proposes that if two species are alike in their growth features, one will be more effective in a particular locale and ignore the other hence, it is essential to integrate species that vary in such features as growth height, shade tolerance, crown construction, phenology, or rooting depth. If the species vary significantly, they will occupy growing space and utilize resources in a different way when planted together in combination. Such species will have the capability to cohabit and are regarded to possess complementary features (Menalled *et al.*, 1998). The level of interspecific competition in such combinations is expected to be lower than that of intraspecific competition, and this has been reported in some instances to result in maximum productivity in the combinations than in monocultures of the constituent species, that is an effect known as the competitive production effect

(Vandermeer, 1989; Kelty, 1992; Menalled *et al.*, 1998).

However, the potential for alternative use of resources between species is limited by the point that all plant species usually compete for the same, mostly fixed resources, such as photosynthetic active radiation (light), carbon dioxide, water and nutrients (Ong *et al.*, 1996). Ong *et al.* (1996) stated that the constituents of agroforestry systems frequently vary significantly in size, with the outcome that the growth of the sub-canopy species may be limited by shading, and probably by competition for water and nutrients. Competition for light is the principal constraint when water or nutrient accessibility rather than light is the main inhibiting factor. They however stressed that it is not all the time direct to establish which the principal drawback is when more than one influence is marginal. Irrespective of the obvious straightforwardness of the principle used in resource capture, very minimal efforts have been made to measure resource capture in agroforestry systems, mainly due to the technical complications and costs associated with thorough studies of light and water utilization (Ong *et al.*, 1996).

2.5.1 Light capture

2.5.1.1 Photosynthetic Active Radiation interception

Light or photosynthetic active radiation (PAR) is a principal energy source for plant species (Stuefer and Huber, 1998) and its availability to plants is influenced by two main factors: first and foremost the proportion of the available PAR that is intercepted by each tree species, and secondly the conversion efficiency of the intercepted light by photosynthesis (Ong *et al.*, 1996). Shading may possibly affect crop development by decreasing the availability of PAR, and therefore assimilate production (Lott *et al.*, 2000). Photosynthetic active radiation has been well-defined by many authors as a radiation in the visible portion of the spectrum from 400 – 700 nm (McCree, 1981; Alados *et al.*, 1996; Ross and Sulev, 2000; Bellow and Nair, 2003; Finch *et al.*, 2004). It is the energy source for the photosynthetic decrease of carbon dioxide to carbohydrates by shade trees foliage, and an important determining factor of the quantity of PAR accessible for photosynthesis is the capability of the different tree canopies to intercept the incident light. An intercepted radiation is hence, an essential element in canopy photosynthesis and net principal production, and can be defined as the product of available radiation and the fractional interception efficiency of the tree canopy (Hanan and Bégué, 1995). Ong *et al.* (1996) pointed out that intercepted PAR is usually basically considered as the variation between the amount of light energy reaching the tree canopy and that transmitted to the understorey. They further stated that this technique of expressing intercepted radiation does not allow provision for the proportion of available light that reflected from the tree canopy surface. PAR interception by plants cultivated in dissimilar climatic zones may possibly be better likened by using the fraction, intercepted radiation divided by the quantity of solar radiation incident upon the tree canopy to define the fractional interception, instead of the total values for intercepted PAR, as these total values differ between sites (Ong *et al.*, 1996).

With respect to monocrops, they described a function between fractional interception leaf area index (L) for locations where water is not a restraining factor, by the relation: $f = 1 - \exp(-k\,L)$, where k is an extinction coefficient for the tree canopy which is reliant on the angle of the leaf and distribution. Fractional interception is however, directly proportional to k and L. With regard to this assumption, they concluded that PAR transmission into the tree sub-canopy is higher when the leaves are straight or vertical (low k value) than when they are horizontally inclined (high k value). The values for k vary significantly between species with diverse canopy constructions.

2.5.1.2 Canopy shape and crown construction

Méthy and Roy (1993) suggested that canopy shape does not only decrease light quantity but also alters light quality and mostly signifies one of the most vital stresses that plant species experience in competitive sites, and that photosynthetic rates are inversely proportional to light intensity. They pointed out that since green vegetation specially capture red and blue light, the spectral composition of light under tree subcanopies is dissimilar to natural energy and is mostly dominant in far-red wavelengths. The red: far red ratio, which is the photon flux density ratio in 10 nm bandwidths, concentrated, respectively, in the red (655 – 665) and far-red (725 – 735) wave bands is significantly decreased, reliant on the optical characteristics of the species canopy (Smith, 1982; 1994). Generally, the consequences of a small red: far red ratio are the same as those of a low photosynthetic active radiation, and a mixture of a small red: far red ratio and reduced photosynthetic active radiation usually has a bigger consequence than those initiated by only one of the factors (Smith, 1982; Deregibus *et al.,* 1985; Casal *et al.,* 1986; Méthy and Roy, 1993). In a complex agroforestry system, transmitted photosynthetic active radiation is mostly a limiting factor to the growth and yield of the understorey components. Information on the radiative microclimate under a given stand is therefore of key importance for the effective management of complex agroforestry systems (Mialet-Serra *et al.,* 2001). Tree crown construction signifies an essential factor influencing individual tree subcanopy growth and development (Cannell *et al.,* 1987; Dalla-Tea and Jokela, 1991). Several factors like inclination and orientation of leaves and geometric characteristics of twigs and branches, can add to differences in crown features (Wang and Jarvis, 1990). The morphology of shoot and distribution of shoot varieties within the branching structure of a plant species are key to the typical form or construction of that plant species (Seleznyova *et al.,* 2002).

Tree crown features, which are influenced by several factors like inclination and orientation of leaves and the geometric characteristics of twigs and branches, affect the capture of photosynthetic active radiation (Stenberg *et al.,* 1994; McCrady and Jokela, 1998). According to De Reffye *et al.* (1995), tropical tree species could be defined in terms of 23 architectural models, as a result of the activities of apical meristems in generating branching systems. Further investigations have revealed that leaf assignments and branching positions are extremely efficient for photosynthetic active radiation interception in reasonable zones of the humid tropics (Chazdon, 1985; Ackerly and Bazzaz, 1995). However, Fisher and Hibbs (1982) and Fisher (1986) pointed out that crown form and branch scopes may differ significantly within a specific construction model.

2.5.1.3 Tree phenology

Tree species are usually categorized as either ‘evergreen’ or ‘deciduous’, according to whether they retain or shed off their leaves, usually seasonally. The evergreen tree species are at times known as ‘leaf-retainers’ as this denotes a broader range of functional outcomes (Huxley, 1996). However, these groupings are not different and a tree species may act in a more deciduous way as the dryness of the environment upsurges (Huxley, 1996). According to Reich (1995), an increasing percentage of tropical tree species become deciduous as the level of the dry season intensifies, whereas both evergreen and deciduous tree species usually produce leaves periodically. Broadhead *et al.*, (2003b) describe phenology as the study of the measure of repetitive biological events, the abiotic and biotic sources of these events, and the link between the times during which particular phenological events take place for separate or dissimilar tree species.

Huxley (1996) stated that the controlling mechanisms that induce these phenological responses are not clearly understood, even though there is perhaps a fundamental underlying control that starts shoot growth stages, and that immediately a phenophase has been initiated, its continuance will largely be reliant on the accessibility of environmental resources.

The best evident means through which phenological events will have an influence is in identifying the tree species' capability to capture resources effectively. The period of growth and time length of the canopies of taller deciduous tree species will obviously have an effect on the environment and therefore the resource capture of lower canopy plants in several ways. They can as well reduce moisture loss from the surface of the soil, which may largely be dependent on the quantity of rainfall (Huxley, 1996). The spatial parting of resource usage by tree species and adjacent crops provides an essential prospect of decreasing competition in agroforestry systems (Broadhead *et al.,* 2003a).

The significance of temporal parting of resource capture has been clearly established for sorghum/pigeon pea combinations, for which periodic photosynthetic active radiation interception was higher than in the corresponding monocrops as a result of the inherent variations in the length and scheduling of canopy growth (Broadhead *et al.,* 2003a). The temporal complementarity concerning tree species and crops reduce competition for soil moisture and nutrients and upsurges the use of rainfall in the dry seasons (Broadhead *et al.,* 2003b). Although, Ong and Black (1994) proposed that intercropping in savannah systems showing positive interactions in the combinations is contingent on the temporal complementarity, however, tree phenology is largely an area of limited agroforestry investigations (Broadhead *et al*., 2003a).

Moreover, Huxley (1996) observed the scarcity of studies regarding the significance of tree phenology in agroecosystems, notwithstanding its possible influence on subcanopy crops, whereas Broadhead *et al.,* (2003b) highlighted that clarification of the leafing arrangements of tree species comparative to the usual microclimatic conditions and growth times of related crops is indispensable for a thorough understanding of the useful features of agroforestry, and that in depth data concerning the form and sources of periodic vicissitudes in leafing configurations would permit investigational outcomes to be deduced to other climatic zones and make available standards for assortment of appropriate genotypes.

2.5.2 Water and nutrient uptake

Even though the existence of trees in agroforestry systems expands farm revenue and delivers alternative sources of income when crops become unsuccessful, the tree species, however, have a tendency to compete with the crops for water, nutrients and light (Deans and Munro, 2004). A prospect for spatial and temporal complementarity for moisture usage is presented by agroforestry systems, leading to enhanced utilisation of accessible water comparative to mono crops. However, the chance for important complementarity could probably be restricted unless the constituent species vary significantly in their rooting depths as this would allow utilisation of diverse soil resources (Ong *et al.*, 1996). According to Cannell *et al.* (1996), agroforestry could upsurge productivity on condition that the trees capture reserves which are least exploited by the crop plants. The perpendicular uptake and supply of moisture and nutrients from soil is a significant research area since soil resources are not equally distributed all the way through the soil profile (Lehmann, 2003). Van Noordwijk *et al.* (1996) highlighted that in diverse cropping schemes with trees, information of the perpendicular distribution of roots is vital for the optimal exploitation of resources, although it has been stressed that the capability of trees to obtain sub-soil nutrients and water hinge on numerous aspects like tree species, physical and chemical characteristics of soil, management of tree species and the cropping system (Lehmann, 2003). Deep rooting trees species can possibly intercept nutrients leaching down soil profiles and ‘capture’ nutrients gathered in sub-soil beneath the rooting depth of crop plants (van Noordwijk *et al.*, 1996). It has been pointed out that in annual cropping schemes, tree roots can prolong further than the rooting depth of the annual crop plants (Torquebiau and Kwesiga, 1996; Stone and Kalisz, 1991; Mekonnen *et al.*, 1997). Buresh (1995) concluded that the prospect of tree species to reclaim sub-soil resources is usually highest when tree species are deep rooting and have strong request for resources, moisture and/or nutrients stress happens in the soil surface and finally, substantial assets of available plant resources or weatherable minerals take place in the sub-soil. Current research have revealed that significant quantities of available plant water and nutrients can be available beneath the sub-soil, that is, more than 10 – 30 cm or even lower than 1 m depth, and that these resources may be utilized by crop plants (Stone and Comeford, 1994).

Several investigations have also pointed out that soil water levels can be the same or greater in the sub-soil than in the top-soil. The proportion of sub-soil to top-soil water differs significantly, however it is usually greater with higher ground water accessibility and evaporation (Lehmann, 2003). Citing other authors, Lehmann (2003) emphasized that moisture usage and tree phenology of certain multipurpose tree species in tropical dry forests such as *Gliricidia sepium* is reliant on sub-soil moisture accessibility. He established that sub-soil moisture usage determined tree crop performance.

Least apparent than water accessibility are the quantities of sub-soil resources accessible to plants and their part in tree crop productivity. The organic matter contents of soils are generally greater in the top-soil and are in charge of the preservation and discharge of nutrients. Moreover, nutrients supplemented to soil by litter fall decomposition and fertilization generally accrue at the top-soil. Higher amounts of rainfall and temperature result in quick mineralization leaching, which conveys nutrients down in the soil horizon in several sections. These nutrients represent an essential resource for the cropping system but then are generally percolated beneath the root area of the tree species (Lehmann, 2003). A study by van Noordwijk *et al.* (1996) pointed out that tree species may intercept penetrating nutrients and act like ‘safety net’ against extreme nutrient losses by leaching.

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Tree root spreading is horizontally not the same, as roots pursue zones where they can mature effortlessly and often follow soil water and nutrients (Lehmann, 2003). The deep nutrient capture by certain tree species upsurge the over-all nutrient obtainability in the agroforestry system. In contrast to fallows, the nutrients in the tree biomass in agroforestry systems do not essentially become accessible to the crop plants. Resources such as nutrients are released from the tree species into the soil through prunings, decomposing litter and roots, or are leached from the top by through fall and stem flow (Schroth *et al.,* 2001b). Trees, however, recompense these losses through uptake of nutrients to provide fresh roots and leaves. Hence, the incorporation of deep rooting tree species into an agroforestry system only upsurges the nutrient obtainability in the top-soil if the amount of nutrients taken up from below the crop rooting area is higher than the amount kept in the tree species biomass and in undecomposed tree litter (Beer, 1988).

According to Schroth *et al.* (2001a), this is simply most possible to happen in soils with greater sub-soil richness, which are uncommon in the tropics, or when the crop plants compete competently with the trees for nutrients in the top-soil. They further pointed out that competitive crop plants could force the tree species to pick up a greater part of their nutrients from the sub-soil and may then hunt these from nutrients from the decaying tree litter. The entire size of soil explored by a root system is mainly essential when making an allowance for uptake of transportable resources such as water and nitrogen. Lateral exploration by crop plants is inhibited by competition with their neighbours, and so the capacity explored can only be effectually augmented by intensifying tree rooting depth (Rowe *et al.,* 2001). The benefits of deep rooting emerge from obtaining a powerfully restraining resource, which is probable to be moisture in dry locations but may be nitrogen in moist locations relative to quick nitrogen leaching (Rowe *et al.,* 2001). A positive outcome of deep nutrient uptake is most probable to happen in the instance of leguminous service trees, whose nutrient rich leaf and branch biomass are frequently reverted back to the soil, and the net nutrient build-up in the trees is minor.

In terms of timber and fruit tree species, which are not frequently pruned, little competition is mainly essential. When these tree species are further competitive in the top-soil than the crop plants, their presence in an agroforestry system will decrease instead of up surging nutrient obtainability (Schroth *et al.,* 2001a). The most difficult challenge in handling concurrent agroforestry is how to maintain the favourable impacts of tree species roots and canopies on chemical and physical characteristics of soil while decreasing the adverse impacts of below-ground competition for scarce resources (Schroth, 1995; Ong and Leakey, 1999).

Many researchers have emphasized that an improved information on belowground interactions between tree species and crop plants is required before the actual advantages of agroforestry associations can be completely realized (Sanchez, 1995; Gregory, 1996; Rao *et al.,* 1998).

Odhiambo *et al.* (2001) pointed out that the spatial or temporal complementarity in the site of tree species and crop plants root systems is a critical matter in agroforestry. It has been pointed out that using the diverse rooting depths of tree species and crop plants may upsurge resource capture in agroforestry systems without presenting strong belowground competition (Huxley, 1996). For instance, *Grevillea robusta*, which is a treasured versatile agroforestry tree species well known with farmers in East Africa, is assumed to be deep rooting and possesses little shallow horizontal roots (Mwihomeke, 1993). Current sap flow investigations in the roots of this tree species have revealed that its root system has the ability of removing 80% of its water from beneath the crop rooting area which proposes good prospect for belowground complementarity (Lott *et al.*, 1996; Howard *et al.*, 1997). Moreover, Huxley *et al.* (1994) exposed that the clumped allocations of trees roots within the soil, as observed in the proteoid roots of *Grevillea robusta*, could as well decrease interspecific competition. However, several studies have revealed that most tree roots, particularly those of rapid developing species, utilize the same soil depths as crop roots (Jonsson *et al.*, 1988; Daniel *et al.*, 1991; van Noordwijk *et al.*, 1996). Investigations in some dry regions of Africa and elsewhere have also challenged Ong *et al.* (1999) to suggest that in arid areas, competition between tree species and crop plants was most severe at belowground and was mainly for soil moisture.

Recent work on root competition between coffee, *Eucalyptus deglupta* (rapid developing timber species) and *Erythrina poeppigiana* (traditional service tree) in perennial tree cropping systems, are stimulating the assertion that tree roots usually grow beneath crop roots and therefore, recover nutrients to the crop plant through aboveground litter fall decomposition (Somarriba *et al.*, 2001). Citing other workers, the *E. deglupta* fine roots in coffee establishments are generally seen at 0 – 10 cm depth, while *Coffea arabica* roots are dominant in lesser depths. Limited data on belowground dynamics happens largely due to it being either too expensive or too damaging for the orthodox approaches such as trench profiles, ingrowth cores and soil cores of fine root valuation to produce data on root construction, death and durability features at the essential high occurrence (Heeraman and Juma, 1993; Gregory, 1996). Notwithstanding the significance of roots, little is known about their morphology and construction. Research on roots is fewer than those of the shoot which could largely be due to the tiresome and timewasting work associated with enumerating and detecting roots in their natural setting (Masi and Maranville, 1998). Furthermore, conventional approaches used to define root systems, based on root biomass or length of distribution in space, have not confirmed useful in enumerating morphology with respect to root branching and construction and its association to the function of roots (Fitter and Stickland, 1991).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The Atwima Nwabiagya District, which is located in the Ashanti Region of Ghana, was the area where the study was conducted. The District lies approximately between Latitude 6° 32’N and 6° 75’N and between Longitude 1° 45’W and 2° 00’ W and covers an estimated area of 294.84 sq. km (Ghana Districts, 2015). The major occupation of the people in the District is cocoa farming and hence makes the area suitable for the study.

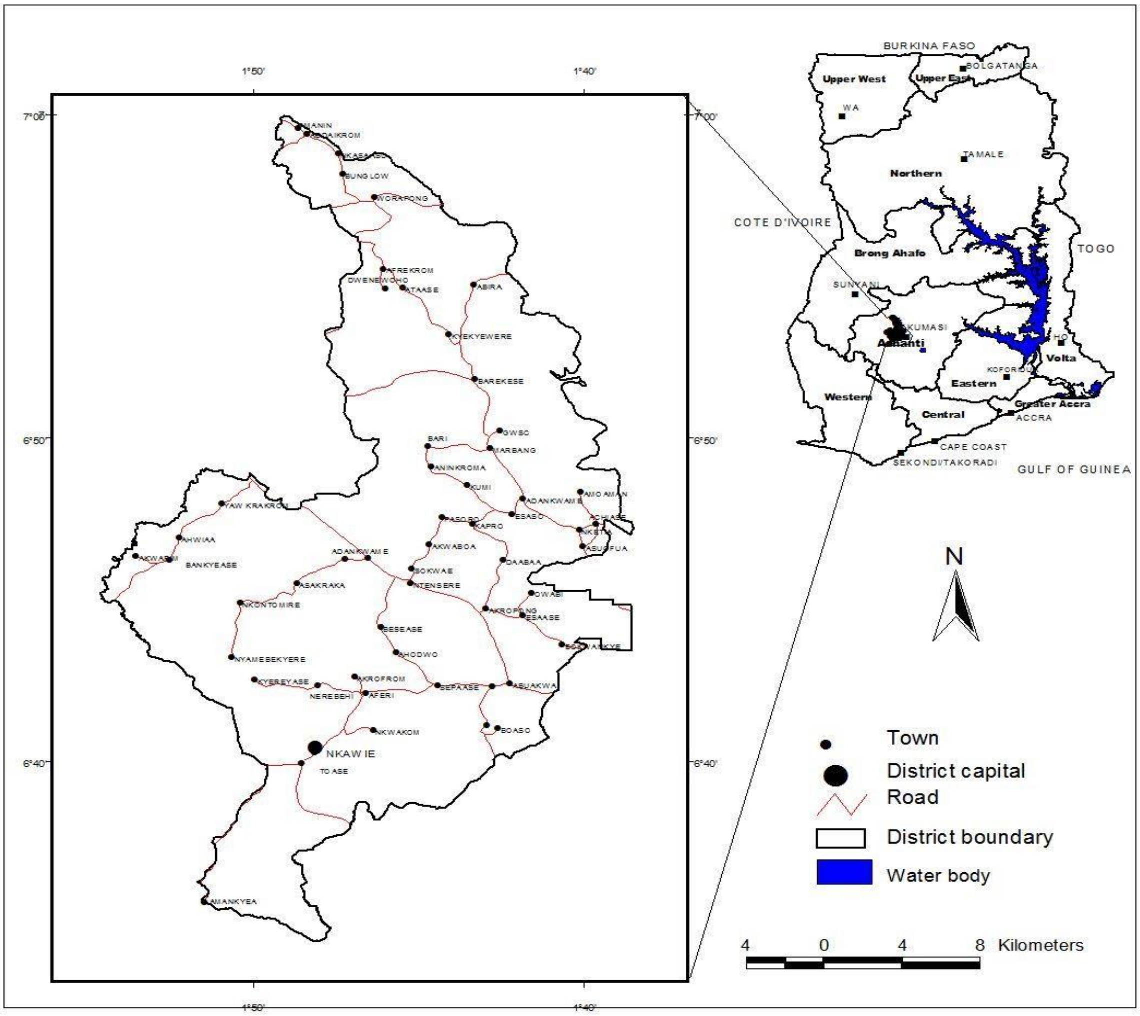

Figure 3.1: Map of Atwima Nwabiagya District

3.1.1 Topography and Drainage

The District has a rise and fall topography. The lands have typical heights of about 77 meters above sea level. There are moderate to steep slopes in the high lands. The uppermost points in the District can be located at the Barekese and Tabere regions. There are several broader valleys with no proof of stream flow. These valleys make available prospects for vegetables, rice and sugar cane agriculture (Ghana Districts, 2015). The Owabi and Offin are the major rivers which channel the surface zone of the

District. There are two major dams, namely, Owabi and Barekese have been built across the Owabi and the Offin rivers respectively. These dams provide pipe borne water to the inhabitants of Kumasi and its vicinities, together with some communities in the District (Ghana Districts, 2015). Agricultural activities take place around the banks of some of the streams and rivers in the District, which leads to siltation and eutrophication of the rivers necessary to care for and preserve the flora of the District, particularly around water bodies (Ghana Districts, 2015).

3.1.2 Climate

The Atwima Nwabiagya District lies within the wet semi-equatorial zone obvious by dual maximum precipitation ranging between 1700 mm and 1850 mm annually. The main precipitation period is from mid-March to July and minor period is between September and mid-November. Precipitation in the District is not evenly distributed all through the year and not very dependable as well. Therefore it is not advisable to only practice rain-fed agriculture. Agricultural activities within the District must integrate water and soil maintenance mechanisms to warrant all year good crop growth and development. The temperature is fairly unvarying ranging between 27ºC in August and 31ºC in March.

The mean relative humidity is between 87 and 91 percent. The least relative humidity typically happens in February/April (Ghana Districts, 2015).

3.1.3 Vegetation

The type of vegetation identified in the District is mainly the semi-deciduous kind. This vegetation has mainly been altered by human actions such as farming, logging and bush fires, therefore, preventing it from its principal valued flora, fauna and other forest crops

(Ghana Districts, 2015). There are some compartments of forest reserves existing in the District. These are the Barekese Water Works Forest Reserve and

Owabi Water Works Forest Reserve which function as water shed protection for the Offin and Owabi rivers. Moreover, a percentage of the Gyemena Forest Reserve is found in the District (Ghana Districts, 2015). These reserved forest have been intruded upon by farmers, illegal chain saw operators and sand winners in the fringed communities. These practices remain to threaten the conservation of the Offin and Owabi rivers, and the Barekese and Owabi reservoirs as well. Community awareness, appropriate implementations of current regulations and other preservation remedies are clear proofs of the detrimental impacts of climate change in the Atwima Nwabiagya District. These are fluctuations in precipitation patterns, storms, changed patterns of agriculture and related crop failures, erratic flow of streams, and augmented occurrence of diseases particularly malaria, among others. These alterations are detrimental to the attainment of the growth urgencies of the District (Ghana Districts, 2015). Therefore, there is the necessity to decrease the susceptibility of natural and human systems to climate change impacts, and also decrease the release of greenhouse gases or improve the elimination of these gases from the atmosphere.

Growth efforts of the District must thus be well-suited with this objective.
Decrease in haphazard solid and liquid waste dumping, betterment of drainage systems, decrease in random construction of physical structures, decrease in degradation of water bodies and deforestation would play a significant role to improve natural and human adaptation to climate change impacts (Ghana Districts, 2015).

3.1.4 Soils

The Atwima Nwabiagya District is underlain by the Lower Birimian rocks, which comprise of phyllites, greywaches and the Cape Coast Granite. The Cape Coast Granite and the Lower Birimian are of substantial economic significance because they contain gold and good clay deposit for ceramics and brick manufacture. The Cape Coast Granite has a good prospect for the construction and road building industry (Ghana Districts, 2015).

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3.2 Data Collection Method

3.2.1 Selection of trees

To study the effects of single standing shade trees in microclimate properties and cocoa productivity, 16 tree species (4 replicates per species, 64 trees total) were selected based on their relative abundance in cocoa farms. The selected shade tree species were: *Entandrophragma angolense* (Edinam), *Funtumia africana* (Sesedua), *Newbouldia laevis* (Sesemasa), *Ficus capensis* (Odoma), *Spathodea campanulata* (Kokuonisuo), *Terminalia ivorensis* (Emire), *Milicia excelsa* (Odum), *Mangifera indica* (Mango), *Morinda lucida* (Konkroma), *Antiaris toxicaria* (Kyenkyen), *Citrus sinensis* (Orange), *Persea americana* (Avocado), *Elaeis guineensis* (Oil Palm), *Alstonia boonei* (Nyamedua), *Ficus exasperata* (Nyankyerene) and *Terminalia superba* (Ofram) (Table 3.1).

Species selection was done ensuring equal distribution of species across three canopy height categories based on the height of their lowest foliage of a shade tree: tall (elevated >15 m above cocoa), medium (elevated between 5-15 m above cocoa) and low canopy species (not elevated above cocoa, below 5 m). The trees were carefully selected such that they are really single standing with no other tree species interfering with them in the plot. To characterize the canopy architecture of each tree, the canopy diameter in the cardinal directions (North, South, East, and West), the total tree height, the lower canopy height and diameter at breast height (DBH) of all single standing focal trees were measured. The tree species as shown in Table 3.1 were categorized in terms of leafing phenology as evergreen (retaining foliage all year round) and deciduous (shedding of leaves at some point in the year). Their rooting depths were also grouped as shallow rooting (active lateral root zone within the top 0-

20 cm) and deep rooting (active lateral root zone beyond 20 cm) (Schroth, 1995).

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Table 3.1: List of tree species and their relevant characteristics

Tree species	Canopy height	Leafing phenology	Rooting depth
C. sinensis	Low	Evergreen	Shallow
E. guineensis	Low	Evergreen	Shallow
M. indica	Low	Evergreen	Shallow
P. americana	Low	Evergreen	Shallow
A. boonei	Medium	Deciduous	Shallow
F. africana	Medium	Deciduous	Shallow
F. capensis	Medium	Deciduous	Deep
F. exasperata	Medium	Deciduous	Deep
M. lucida	Medium	Evergreen	Deep
N. laevis	Medium	Evergreen	Deep
T. ivorensis	Medium	Deciduous	Deep
A. toxicaria	Tall	Deciduous	Deep
E. angolense	Tall	Deciduous	Deep
M. excelsa	Tall	Deciduous	Deep
S. campanulata	Tall	Deciduous	Deep
T. superba	Tall	Deciduous	Deep

Source: Schroth (1995)

3.2.2 Plot Design

For each selected tree, circular paired (sub canopy and open area) plots were set. The sub canopy area was the zone where the tree species had direct influence on the cocoa trees while the open area was the zone without any tree influence serving as the control. All measurements were taken from these paired circular plots (sub canopy and open area).

3.3 Research Design

3.3.1 Volumetric soil moisture content

To evaluate the effects of trees on volumetric soil moisture content in a cocoa agroforestry system, soil moisture measurements were done using a hand held Time Domain Reflectometry (TDR) sensors (Probe model: CD658, 20 cm rods). Eight TDR measurements were recorded in the top soils (0-20 cm) in the sub canopy area at 2 m from the centre of the tree trunk in the four cardinal directions as well as in between, that is S, SE, E, NE, N, NW, W, SW using a compass as a guide. Eight TDR readings were as well taken 2 m away from a point in the middle of the open site serving as the control. Measurements were limited to the top 20 cm as this is the active lateral root zone of cocoa (Kummerow *et al.* 1982). Measurements were taken in late January as this is the driest month of the year.

3.3.2 Photosynthetic Active Radiation (PAR) availability

The PAR photon flux sensors were used to determine the amount of light available to the cocoa in the sub canopy as well as in the open area. PAR measurements were done between 10:00 to 14:00 GMT when the sun was in the zenith. Two PAR sensors were used for the light measurements. One of the two was attached to a DECAGON Em50 Logger, which was set to log at every one minute. This logger was installed in the open above the cocoa as a control to check the open sky conditions at all time.

The other was attached to a ProCheck Hand held device and this was used to take eight readings in the sub-canopy above the cocoa. In the sub-canopy area, readings were taken 2m away from the centre of the tree trunk in the four cardinal directions as well as in between, thus S, SE, E, NE, N, NW, W, SW using a compass as a guide. Measurements on light were done in early November as this was the flowering period of cocoa for the minor season.

3.3.3 Temperature and Relative Humidity

The Temperature and Relative Humidity were measured during the hottest month of the year, around mid-February. The VP3 Decagon Sensor was used to perform this measurement. All measurements were executed between 13:00 to 16:00 GMT as this is the hottest time of the day. Eight readings each were taken both in the open and in the sub-canopy areas above the cocoa in the four cardinal directions as well as in between, thus S, SE, E, NE, N, NW, W, SW using a compass as a guide. The open area readings were taken at 2 m away from a point in the middle of the site and at 2 m away from the centre of the tree trunk for the sub-canopy area readings.

3.3.4 Cocoa aboveground biomass (AGB)

To assess the effect of shade trees on cocoa above ground biomass, the Diameter at Breast Height (DBH) and total height of eight cocoa trees each in the sub-canopy and open areas were selected and measured. A calliper was used to measure DBH and a hypsometer was used to measure total height of the cocoa trees. The AGB of the cocoa trees were estimated using the pantropical allometric model by Chave *et al*.

(2014);

$AGB_{est} = 0.0673 \times (\rho D_2 H)_{0.976}$ where AGB_{est} = Estimated Above ground Biomass in kg, D=DBH in cm, H=Height in m, and ρ is the specific wood density of cocoa= 0.42 g cm^{-3}.

3.3.5 Potential cocoa pod yields

Potential yields were assessed based on the number of mature, healthy cocoa pods (above 10 cm long) and immature pods (below 10 cm long) (Koko *et al.,* 2013) in each paired plot using the Hand Tally Counter.

3.4 Data Processing and Statistical Analysis

An effect ratio comparing the sub-canopy effects to the open area effects was used to test for differences between low, medium and tall trees as well as differences between the individual tree species. The tree effect ratio, adopted from Blaser *et al.* (2013), is expressed as; (Sub- Open)/ (Sub+ Open), where a positive output means the tree sub-canopy effects are bigger, a negative output means the open sun (control) effects are bigger and a zero output means there are no effects.

Data were analyzed as one-way analysis of variance (ANOVA) using the R Statistical Package, version 3.2.2 (The R Foundation for Statistical Computing Platform). For each variable, normal distribution was tested using the Shapiro-Wilk normality test for homogeneity of variances. Significant ANOVAs were subsequently assessed using Tukey's Honestly Significant Difference (HSD) test and probability was set at 0.05 for all statistical tests. The results were presented using boxplots and tables. Detailed information on the analysis of variances are presented in Appendix 1.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Shade trees in cocoa agroforestry systems and volumetric soil moisture content

There was a significant difference in soil moisture content between deep and shallow rooting species (Table 4.1). The leafing phenology of a tree, which is whether it is deciduous or evergreen, did not have any significant effect on soil moisture content in the cocoa agroforestry system (Table 4.1). There were significant differences in soil moisture content between the low, medium and tall canopy height categories as well as between the different tree species (Table 4.1).

Table 4.1: Summary of analysis of variance of soil moisture as affected by rooting depth, leafing phenology, canopy height and different tree species

	Rooting depth	Leafing phenology	Canopy height	Tree species
DF	1	1	2	15
Residual	57	57	56	43
Mean square	0.163^{*}	0.074^{ns}	0.113^{*}	0.045^{*}
P- value	0.012	0.094	0.012	0.018

*= significant at P≤ 0.05, ns = not significant at P = 0.05

4.1.1 Effects of tree rooting depth on volumetric soil moisture content in a cocoa agroforestry system

Soil moisture effect in the sub-canopies of deep rooting tree species was higher (0.08) than that of shallow rooting trees (-0.03) (Fig. 4.1). The deep rooting tree species had higher soil moisture content in the sub-canopy than shallow rooting trees (Table 4.2). The significant differences in soil moisture content between the two depths implies that deep rooting tree species could have beneficial implications on soil moisture availability for cocoa especially in the dry seasons. This could be attributed to the fact that deep rooting tree species take up water deep down the soil and hence do not compete with the cocoa trees for water. The results are in line with the findings of several studies (Schroth, 1995; van Noordwijk *et al.*, 1996; Schwendenmann *et al.*, 2010) which point out the favourable effects of trees with deep rooting depths in cocoa agroforestry systems on soil moisture conservation. Shallow rooting species have roots that compete with cocoa for soil moisture. The active lateral root zone of cocoa is at the top (0-20cm) (Kummerow *et al.*, 1982) and these tree roots take up water from this same zone leading to water stress for cocoa, especially in the dry seasons. This could lead to lower above ground biomass and potential pod yields of cocoa. According to Zuidema *et al.* (2005), cocoa growth and yields are highly dependent on soil moisture availability.

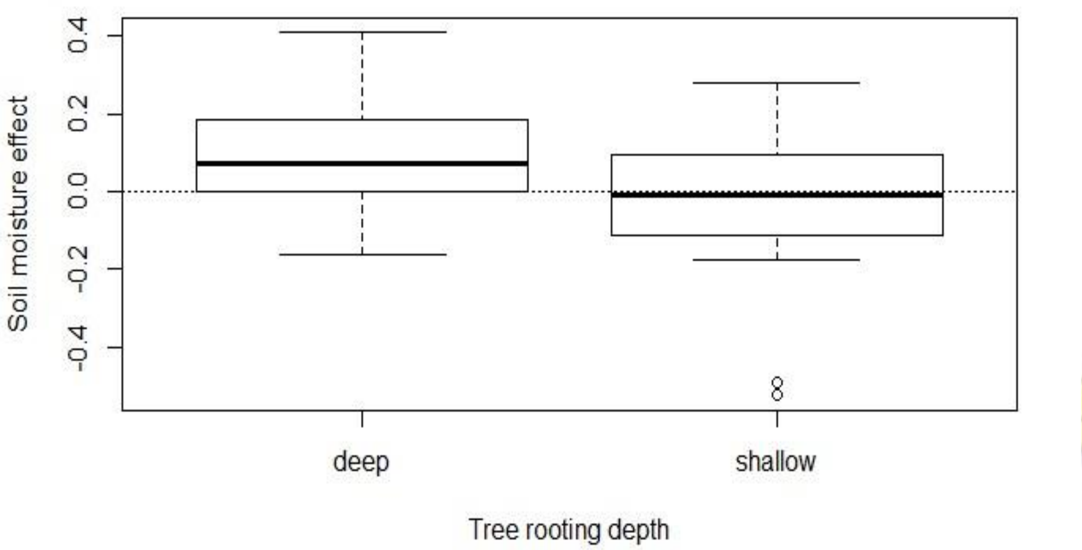

Figure 4.1: Effect of tree rooting depth on volumetric soil moisture effect in a cocoa agroforestry system

Table 4.2: Effect of tree rooting depth on sub-canopy and open area volumetric soil moisture content for cocoa in the dry season

Rooting depth	Sub-canopy	Open area
	Moisture (%)	
Deep	10.40 ± 0.62	8.97 ± 0.55
Shallow	7.69 ± 0.73	8.03 ± 0.58

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4.1.2 Effect of tree canopy height on volumetric soil moisture content in a cocoa agroforestry system

Soil moisture effect for the low, medium and tall trees were -0.07, 0.09 and 0.06 respectively (Fig. 4.2). Soil moisture content in the sub-canopies of medium and tall canopy height trees were similar but were significantly higher than the soil moisture content of the low canopy height trees which had the lowest soil moisture content (Table 4.3). All the tall canopy height species were deciduous with deep rooting systems; the medium canopy height species were either deciduous or evergreen, deep or shallow rooting; and all the low canopy height species were evergreen with shallow rooting systems. Competition for soil moisture may be reduced by planting shade tree species which are deciduous during the drier season (Broadhead *et al*., 2003), or trees with deep rooting systems (van Noordwijk *et al.,* 1996; Schwendenmann *et al.,* 2010). The positive soil moisture effects observed in the medium and tall height categories were not as a result of tree leafing phenology (Table 4.1) but rather the deep rooting characteristic of the tree species (Fig. 4.1) minimizing soil moisture competition. Medium and tall canopy heights are beneficial for soil moisture conservation in cocoa agroforestry systems, at least in the dry season.

Low canopy height trees have adverse effect on soil moisture conservation in the subcanopies making them unsuitable in terms of soil moisture content in cocoa systems. This observation could be attributed to the fact that all the low canopy height trees were shallow rooted and hence might have competed with understorey cocoa for water leading to water stress for cocoa in the dry season (Schroth, 1995; van Noordwijk *et al.,* 1996; Schwendenmann *et al.,* 2010). It should therefore be noted that the negative effect of low canopy height trees on soil moisture content might not be due to the low canopy nature but the fact that these trees are shallow rooted.

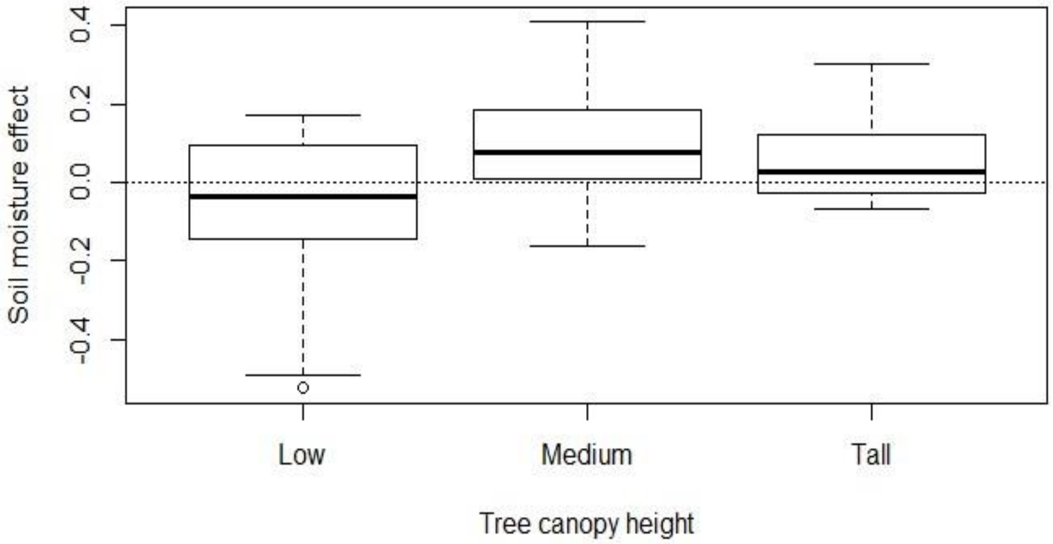

Figure 4.2: Effect of tree canopy height on volumetric soil moisture effect in a cocoa agroforestry system

Table 4.3: Effect of tree canopy height on sub-canopy and open area volumetric soil moisture content for cocoa during the dry season

Canopy Height	Sub-canopy	Open area
	Moisture (%)	
Tall	10.32 ± 0.74	9.48 ± 0.84
Medium	9.88 ± 0.80	8.23 ± 0.57
Low	7.36 ± 1.02	8.14 ± 0.72

4.1.3 Effect of tree species on volumetric soil moisture content in a cocoa agroforestry system

Table 4.4 presents the differences between the individual tree species in terms of their ability to conserve soil moisture in cocoa agroforestry system in the dry season. Soil moisture effect was highest in the sub-canopies of *M. lucida* (0.19) followed by *S. campanulata* (0.16) and then *F. capensis* (0.13) with the least being *C. sinensis* (0.26) (Table 4.4). Soil moisture content under *M. lucida, S. campanulata* and *F. capensis* were significantly higher than *C. sinensis* but similar to *A. boonei, A. toxicaria, E. guineensis, E. angolense, F. africana, F. exasperata, M. indica, M. excelsa, N. laevis, P. americana, T. ivorensis* and *T. superba* (Table 4.4). Tree species with positive soil moisture effects might have the ability to reduce evapotranspiration and therefore increases soil moisture content for cocoa. According to Beer (1987), shade trees decrease evapotranspiration and therefore moisture stress during the dry seasons. These tree species have the potential to conserve soil moisture in cocoa agroforestry especially in the dry seasons. Belowground competition for water may be reduced by planting shade tree species which shed their leaves during the dry season (Broadhead *et al.*, 2003a), or which take up their water from different soil zones than crops (van Noordwijk *et al.*, 1996; Schwendenmann *et al.*, 2010). Thus, leafing phenology and rooting depth could be responsible for the favourable soil moisture effect as most of the tree species were deciduous and deep rooting as well. On the other hand, tree species with negative soil moisture effects may be as a result of the shallow rooting and/or evergreen features (Schwendenmann *et al.*, 2010).

Table 4.4: Effect of different tree species on volumetric soil moisture content in a cocoa agroforestry system during the dry season

Tree species	Soil Moisture Content (%)		Moisture effect
	Sub-canopy	Open area	
M. lucida	8.06 ± 2.25	5.33 ± 1.23	0.19 ± 0.08^{a}
S. campanulata	9.80 ± 2.38	7.56 ± 2.12	0.16 ± 0.08^{a}
F. capensis	12.69 ± 2.29	9.24 ± 1.22	0.13 ± 0.06^{a}
M. excelsa	6.20 ± 1.22	5.27 ± 1.58	0.12 ± 0.10^{ab}
A. boonei	8.09 ± 0.74	7.03 ± 1.51	0.10 ± 0.07^{ab}
F. exasperata	9.29 ± 1.34	8.42 ± 0.81	0.09 ± 0.03^{ab}
P. americana	11.30 ± 2.38	10.81 ± 1.12	0.07 ± 0.04^{ab}
A. toxicaria	11.34 ± 0.87	10.38 ± 0.74	0.04 ± 0.03^{ab}
T. superba	10.79 ± 0.61	10.24 ± 0.95	0.03 ± 0.03^{ab}
T. ivorensis	11.10 ± 2.41	10.11 ± 0.14	0.02 ± 0.10^{ab}
M. indica	6.43 ± 0.65	6.06 ± 0.30	0.02 ± 0.07^{ab}
N. laevis	10.59 ± 3.49	9.36 ± 2.67	0.02 ± 0.11^{ab}
F. africana	8.69 ± 1.87	8.83 ± 1.39	-0.02 ± 0.05^{ab}
E. angolense	12.64 ± 2.47	13.47 ± 2.77	-0.03 ± 0.02^{ab}
E. guineensis	5.96 ± 1.14	8.20 ± 1.38	-0.15 ± 0.17^{ab}
C. sinensis	4.75 ± 1.67	7.31 ± 1.77	-0.28 ± 0.12^{b}

Values with superscripts followed by the same letters are not significantly different at P≤ 0.05 level using Tukey's HSD range Test.

4.2 Shade trees in cocoa agroforestry systems and photosynthetic active radiation (PAR) transmission

Dry matter production of the components of agroforestry systems is often linearly related to the quantity of radiation absorbed by their canopies, in the absence of other limiting factors (Isaac *et al.*, 2007). The amount of light intercepted by the tree canopy and the amount of light that is transmitted to the understory crop determines the productivity of both the tree and the associated crop, and is in turn determined by the crown architecture and leafing phenology of the shading tree (Koko *et al.,* 2013). The percentage tree effect on incident photosynthetic active radiation (PAR) for deciduous species was significantly different from evergreen species (Table 4.5). The differences between low, medium and tall canopy heights in terms of light availability for cocoa in the tree sub-canopy were highly significant (Table 4.5). There were highly significant differences between the effects of the individual tree species on PAR availability to understorey cocoa (Table 4.5).

Table 4.5: Summary of analysis of variance of photosynthetic active radiation as affected by leafing phenology, canopy height and different tree species

	Leafing phenology	Canopy height	Tree species
DF	1	2	15
Residual	58	57	44
Mean square	16.635^{**}	6111.6^{**}	1577.68^{**}
P- value	0.00014	1.571e-07	1.089e-11

**= significant at P<0.01

4.2.1 Effect of tree leafing phenology on available light (PAR) to cocoa

The percentage PAR that was transmitted to the understory cocoa for deciduous species (39.6%) was significantly higher than that of the evergreen (18.1%) (Fig. 4.3). It was observed that deciduous species allowed a greater percentage of light or PAR to be transmitted through their canopies to the cocoa understorey and this may be due to the fact that most of the tree species had already shed off their leaves when measurements were made in November. Broadhead *et al.* (2003a & b) stated that the dry season patterns of lower leaf cover and higher PAR transmission will imply reduce below-ground (moisture) and above-ground (light) competition between the shade trees and the cocoa crop. Thus, for instance, *T. superba*, *A. toxicaria*, *M. excelsa* and *S. campanulata* with their lower leaf cover and higher PAR transmittance in the dry season, compared to the other species, coupled with their larger crown areas appear to present better temporal complementarity with the below-canopy crop, at least in the dry season. However, the higher PAR transmission during this period when the intensity of the sun is higher will also mean higher reductions in shade levels for the cocoa. The evergreen tree species studied in this cocoa agroforestry system had tree cover all year round and were not elevated above the cocoa stratum. The evergreen tree species therefore transmitted lesser percentage of PAR to the understory cocoa (Fig. 4.3). According to Lott *et al.* (2000), shading may influence crop growth by decreasing the supply of PAR, and therefore reduce productivity.

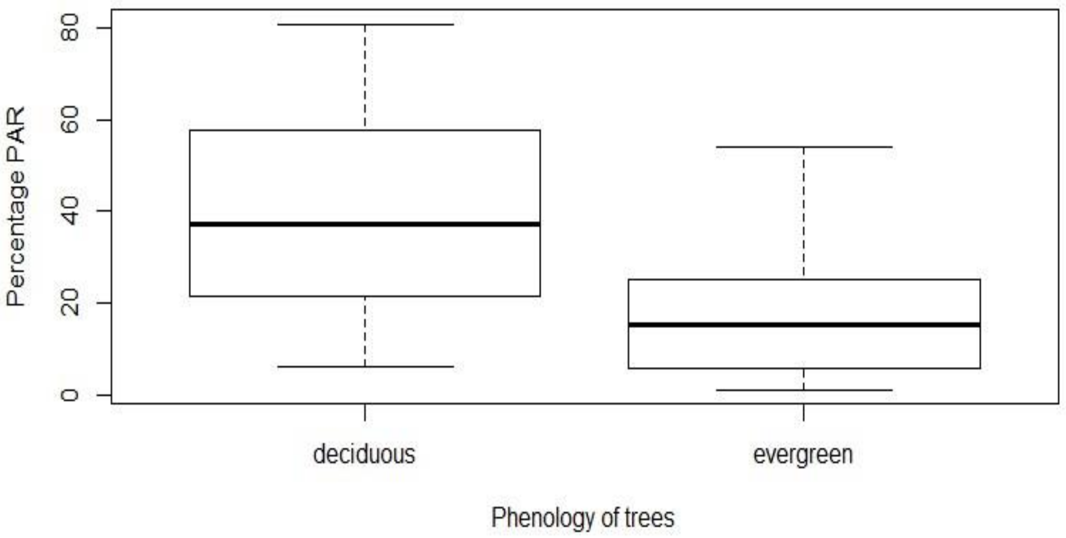

Figure 4.3: Effect of tree leafing phenology on incident photosynthetic active radiation in a cocoa agroforestry system

4.2.2 Effect of canopy height on available PAR to cocoa

The tall canopy height tree species were observed to have the highest percentage PAR transmitted through their canopies to the understorey cocoa trees (48.5%) followed by the medium canopy height species (40%) and the least being the low canopy height tree species (10.7%) (Fig. 4.4). Rao *et al.* (1998) emphasized that understorey microclimatic conditions in a multi-strata agroforestry system are influenced by the shade tree species canopy features such as canopy height in the system. Much of the incident light might have been transmitted through the tall canopy height to the cocoa understorey because these trees were elevated above the cocoa trees. This resulted in light becoming directly available to the understorey cocoa during the mornings (sun rise) and late afternoons (sun set). However, during mid-day the tree canopy intercepts much of the light which ensures optimum light transmission to cocoa.

The study further revealed that all the tall canopy height trees were deciduous and this could have resulted in the increased amount of transmitted light to the understorey cocoa (Fig. 4.4). Cocoa growth is generally maximized at low shade levels as photosynthetic rates of cocoa decrease at high light intensities (Zuidema *et al*., 2005; Isaac *et al.*, 2007). Tall canopy height species (low shade levels) tend to manipulate the amount of light available to the understorey cocoa which could potentially lead to higher cocoa biomass and yields. According to Blaser *et al.* (2013), trees with elevated canopies might reduce physiological stress in cocoa by intercepting sunlight at midday, while allowing enough light to penetrate the understorey during mornings and late afternoons therefore providing an improved microclimatic condition for cocoa. With low canopy species, the canopy is directly spread above the cocoa trees and hence, most light will not reach the cocoa trees in the sub-canopy irrespective of the angle of the sun (time of the day) leading to poor biomass, flowering ability and yield (Blaser *et al.*, 2013; Koko *et al.*, 2013). It was again observed that all the low canopy height species were evergreen with dense shade and this could explain why lower PAR was recorded in the understorey cocoa (Fig. 4.4).

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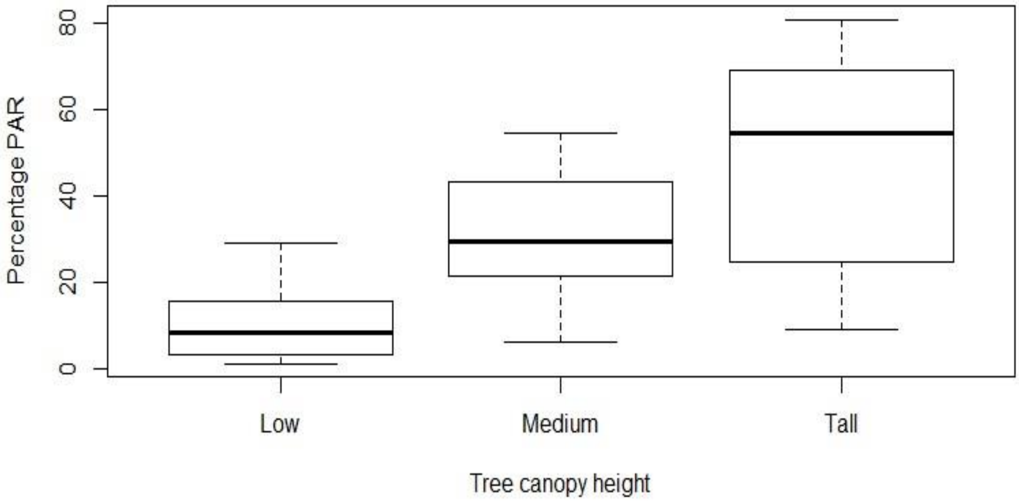

Figure 4.4: Effect of tree canopy height on available PAR to cocoa

4.2.3 Effect of tree species on transmitted percentage PAR to cocoa

The effects of the different tree species on percentage PAR availability to the understorey cocoa are presented in Table 4.6. *Entandrophragma angolense* and *T. superba* had the highest transmitted PAR of 69.2% and 67.1% respectively, and the lowest being *M. indica* (3%) (Table 4.6). With regards to light transmission to the understorey cocoa, Rich *et al.* (1993) reported that the higher PAR recorded in the dry season for all the species could be due to a higher irradiance usually received by the canopy during the dry season, as a result of reduced cloud and leaf cover. *Entandrophragma angolense*, *T. superba*, *M. excelsa* and *A. toxicaria* are deciduous trees and most of them had already shed off their leaves at the time of data collection which might have led to the higher PAR transmitted to the understorey cocoa. Moreover, these tree species are elevated above the cocoa and therefore the understorey cocoa receives much light directly when the sun is at an angle relative to the sub-canopy.

This is in line with a study by Blaser *et al.* (2013) who reported that cocoa under tall trees receive much PAR during the mornings and late afternoons when the sun is at an angle relative to the sub-canopy. Even though *N. laevis* is an evergreen species, it has a narrow crown architecture (Amanor, 1994) and it is slightly elevated above the cocoa which may be the reason why cocoa under this tree species received high PAR as well (Table 4.6). *Mangifera indica*, *C. sinensis* and *P. americana* are evergreen tree species and they were not elevated above the cocoa species which resulted in the low PAR transmission to the understorey cocoa (Table 4.6). Cocoa is highly sensitive to light availability (Zuidema *et al.*, 2005) and because there is limited available PAR irrespective of the angle (relative to the sub-canopy) of the sun during the day, these species when used in cocoa systems could adversely affect flowering leading to lower yields.

Even though *T. ivorensis* and *S. campanulata* are both deciduous and elevated above the sub-canopy cocoa stratum, limited PAR was transmitted (Table 4.6). According to Isaac *et al*. (2007), this might be due to the dense crown construction of these tree species which may have affected light infiltration.

Table 4.6: Effect of different tree species on percentage transmitted PAR to cocoa

Tree species	Transmitted PAR (%)
E. angolense	69.22 ± 5.63^{a}
T. superba	67.14 ± 5.24^{a}
F. africana	51.64 ± 2.22^{ab}
N. laevis	48.11 ± 3.02^{abc}
M. excelsa	44.41 ± 14.34^{abcd}
A. toxicaria	43.88 ± 8.59^{abcd}
F. capensis	33.75 ± 3.77^{bcde}
F. exasperata	25.45 ± 4.58^{bcdef}
E. guineensis	25.21 ± 2.02^{bcdef}
M. lucida	23.33 ± 3.01^{bcdef}
A. boonei	22.89 ± 6.71^{bcdef}
S. campanulata	18.23 ± 5.13^{cdef}
T. ivorensis	14.95 ± 6.51^{def}
P. americana	13.40 ± 1.38^{ef}
C. sinensis	5.63 ± 1.70^{ef}
M. indica	2.95 ± 0.81^{f}

Values with superscripts followed by the same letters are not significantly different at $P \leq 0.05$ level using Tukey's HSD range Test.

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4.3 Temperature and Relative Humidity buffering by shade trees in cocoa Agroforestry

The study revealed that there was no significant difference between deciduous and evergreen tree species with respect to temperature (Table 4.7) and relative humidity (Table 4.8). There were no significant differences among the effects of the low, medium and tall canopy heights on temperature and relative humidity to the understory cocoa. The differences between the effects of the individual tree species on temperature and relative humidity for cocoa were not significant (Tables 4.7 and 4.8).

Table 4.7: Summary of analysis of variance of temperature as affected by leafing phenology, canopy height and different tree species

	Leafing phenology	Canopy height	Tree species
DF	1	2	15
Residual	58	57	44
Mean square	0.014^{ns}	0.091^{ns}	0.072^{ns}
P- value	0.712	0.420	0.831

ns = not significant at P = 0.05

Table 4.8: Summary of analysis of variance of relative humidity as affected by leafing phenology, canopy height and different tree species

	Leafing phenology	Canopy height	Tree species
DF	1	2	15
Residual	58	57	44
Mean square	11.832^{ns}	0.072^{ns}	9.634^{ns}
P- value	0.198	0.068	0.128

ns = not significant at P = 0.05

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4.4 Shade trees and aboveground biomass of cocoa

Aboveground cocoa biomass was significantly influenced by both tree canopy height and different tree species (Table 4.9).

Table 4.9: Summary of analysis of variance of cocoa aboveground biomass as affected by canopy height and different tree species

	Canopy height	Tree species
DF	2	15
Residual	56	43
Mean square	0.415**	0.092**
P- value	2.989e-07	9.086e-07

**= significant at P<0.01

4.4.1 Effect of tree canopy height on aboveground biomass of cocoa

The aboveground biomass effect of cocoa was significantly higher for tall (0.07) and medium (0.01) canopy heights than for low canopy height (-0.24) (Fig. 4.5). Aboveground cocoa biomass was higher in the sub-canopies of tall and medium canopy heights than for low canopy height (Table 4.10). Tall and medium canopy heights have favourable microclimatic implications for cocoa trees such as manipulating optimum PAR and maintaining soil moisture in the sub-canopies, at least in the dry seasons, whereas low canopy heights reduce light and with lower soil moisture status (Figs. 4.2 and 4.4). There is usually a linear relation between cocoa aboveground biomass and pod yields under low shade intensities (Zuidema *et al*., 2005; Isaac *et al.* 2007). Because tall and medium canopy heights provide low shade due to the deciduousness and elevated crown architecture, cocoa aboveground biomass might have been higher in the sub-canopies as a result, but was significantly reduced under low canopy heights because of evergreeness of their foliage, in the absence of other limiting factors. Aboveground biomass estimates were in line with other reported studies (Fassbender *et al.*, 1991; Isaac *et al*., 2005; Isaac *et al*., 2007). The results support previous investigations that point out higher cocoa aboveground biomass benefits under shade trees (Alpizar *et al.*, 1986; Fassbender *et al.*, 1991; Beer *et al*., 1998; Isaac *et al*., 2005; Isaac *et al*., 2007). However, this study reveals that not all shade trees, especially the low canopy height trees, provide cocoa aboveground biomass benefits in their sub-canopies.

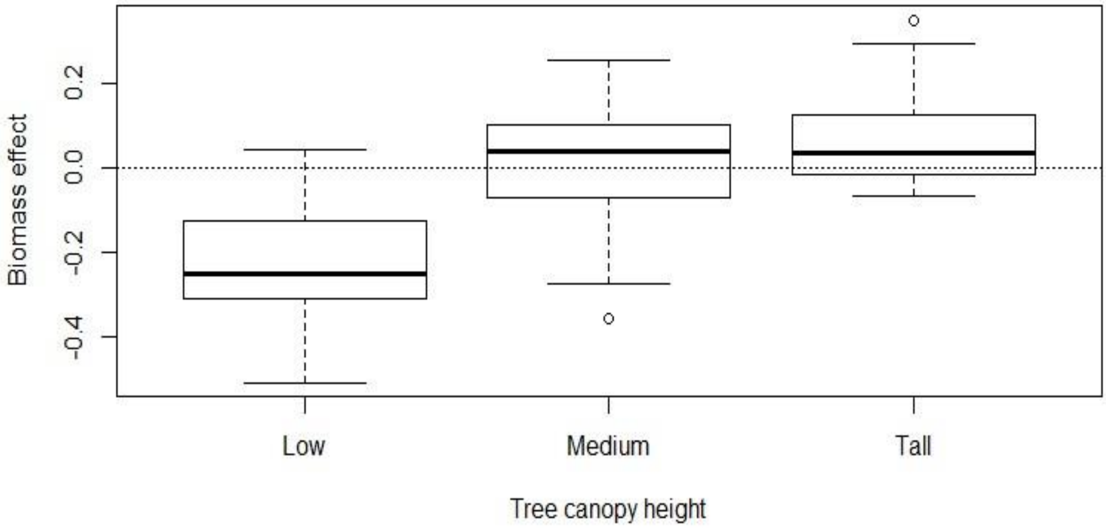

Figure 4.5: Effect of tree canopy height on aboveground biomass of cocoa

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Table 4.10: Effect of canopy height on sub-canopy and open area aboveground biomass of cocoa

Canopy height	Sub-canopy	Open area
	Cocoa Biomass (Kg)	
Tall	28.97 ± 2.77	25.00 ± 2.06
Medium	25.81 ± 2.17	25.02 ± 1.69
Low	17.75 ± 1.80	26.12 ± 1.46

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4.4.2 Effect of different tree species on above ground biomass of cocoa

The aboveground cocoa biomass effect of the different tree species was highest in the sub-canopy of *E. angolense* (0.26) and lowest under *M. indica* (-0.37) (Table 4.11). Cocoa aboveground biomass under *E. angolense* were similar to those under *F. exasperata, N. laevis, A. boonei, M. excelsa, T. superba, S. campanulata, F. capensis, A. toxicaria, F. africana* and *M. lucida* (Table 4.11). The results are in line with a study by Isaac *et al*. (2007) who observed that biomass of cocoa trees was significantly higher for trees grown under shade than with no shade. According to Isaac *et al.* (2007), the inclusion of low-density shade trees such as *N. laevis* and *M. excelsa* in a cocoa system positively affected biomass of neighbouring cocoa trees through light manipulation. These species have medium to tall canopy heights and therefore well elevated above the understorey cocoa (low shade) coupled with deciduousness, except *N. laevis* (evergreen with narrow crown architecture) and *M. lucida* (evergreen), allow optimum PAR to reach the cocoa. The deep rooting nature of the roots of the species also encourage effective water conservation (Schroth, 1995) which decreases water stress for cocoa particularly in the dry periods (Beer, 1987). It has been reported that belowground competition for water may be reduced by planting shade tree species which are deciduous during the dry season (Broadhead *et al*., 2003a) and/or are deep rooting (van Noordwijk *et al.*, 1996; Schwendenmann *et al.*, 2010).

The effect of tree species on aboveground biomass of cocoa in the sub-canopy of *M. indica* were not significantly different from *T. ivorensis, C. sinensis*, *P. americana* and *E. guineensis* (Table 4.11). These species may have lower cocoa biomass in the tree sub-canopies because of their negative microclimatic implications such as reduced light and poor soil water status. They are usually not elevated above the subcanopy cocoa stratum which limited the transmission of PAR through their canopies to the cocoa (Blaser *et al*., 2013).

The shallow rooting nature of these tree species led to competition for limited soil water with the sub-canopy cocoa (Schroth, 1995). This study supports the findings of Koko *et al*., (2013) who reported that vigour and growth of cocoa intercropped with *C. sinensis* and *P. americana* trees were significantly lower than the monocrop (control). Cocoa growth and development is largely dependent on water and light availability (Zuidema *et al.*, 2005), therefore inadequate supply of these requirements could have adverse effects on cocoa productivity.

Table 4.11: Effect of different tree species on aboveground biomass of cocoa in a cocoa agroforestry system

Tree species	Cocoa Biomass (Kg)		Biomass effect
	Sub-canopy	Open area	
E. angolense	39.41 ± 14.2	21.47 ± 5.51	0.26 ± 0.06^{a}
F. exasperata	25.81 ± 6.82	19.33 ± 3.82	0.13 ± 0.05^{ab}
N. laevis	35.75 ± 1.98	28.37 ± 3.43	0.12 ± 0.04^{abc}
A. boonei	23.51 ± 6.64	22.52 ± 3.89	0.08 ± 0.05^{abc}
M. excelsa	25.06 ± 2.93	22.45 ± 4.09	0.06 ± 0.04^{abc}
S. campanulata	32.05 ± 8.71	30.39 ± 8.95	0.04 ± 0.02^{abc}
T. superba	25.35 ± 2.93	23.26 ± 2.05	0.04 ± 0.03^{abc}
F. capensis	34.17 ± 4.79	32.86 ± 5.26	0.03 ± 0.03^{abc}
A. toxicaria	26.23 ± 1.50	26.09 ± 2.10	0.01 ± 0.04^{abc}
F. africana	21.51 ± 4.16	22.49 ± 3.65	-0.03 ± 0.15^{abc}
M. lucida	22.76 ± 3.27	24.91 ± 2.87	-0.05 ± 0.09^{abc}
E. guineensis	20.40 ± 4.98	25.03 ± 1.41	-0.13 ± 0.10^{bcd}
P. americana	20.00 ± 3.69	28.15 ± 2.14	-0.19 ± 0.08^{bcd}
C. sinensis	17.34 ± 2.35	27.64 ± 2.44	-0.23 ± 0.04^{cd}
T. ivorensis	13.39 ± 3.79	20.31 ± 3.99	-0.23 ± 0.06^{cd}
M. indica	13.80 ± 3.38	23.79 ± 4.45	-0.37 ± 0.06^{d}

Values with superscripts followed by the same letters are not significantly different at $P \leq 0.05$ level using Tukey's HSD range Test.

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4.5 Cocoa agroforestry and potential pod yields

The different tree species and canopy heights significantly influenced the potential pod yields of cocoa (Table 4.12).

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Table 4.12: Summary of analysis of variance of cocoa pod yields as affected by canopy height and different tree species

	Canopy height	Tree species	
DF	2	15	
Residual	45	32	
Mean square	0.291*	0.169**	
- value	0.038	0.004	P

*= significant at P≤ 0.05, **= significant at P<0.01

4.5.1 Effect of canopy height on potential yields of cocoa

The yield effect of the low, medium and tall trees on cocoa pod yields were -0.16, 0.06 and 0.12 respectively (Fig. 4.6). Potential cocoa yields were highest for tall canopy height species (Table 4.13) and this may be due to the favourable microclimatic implications they have on cocoa. For instance, the tall canopy height trees were deep rooting (Schroth, 1995) and this characteristic ensured minimal competition of the trees with understorey cocoa for soil moisture (Fig. 4.1). Moreover, tall canopy height trees were deciduous and elevated (low shade) above the cocoa resulting in optimum PAR availability for cocoa (Figs. 4.3 and 4.4) growth and development. This observation confirms Isaac *et al.* (2007) who concluded that there is usually a strong correlation between cocoa tree biomass and pod yield under low shade intensity (mostly elevated canopy trees).

Potential cocoa yields were lower for low canopy height trees. This observation could be due to the fact that these species are shallow rooting and therefore compete with understorey cocoa for soil moisture. The low canopy height species were also evergreen and not elevated above the sub-canopy cocoa trees (Blaser *et al.*, 2013) and this resulted in lower PAR availability (Fig. 4.3) for cocoa leading to poor flowering of cocoa. Schwendenmann *et al.* (2010) reported that under drought conditions, there are fewer flowers, reduced development and maturation leading to lower yields of cocoa. Thus, potential yields of cocoa could be low due to moisture stress in the subcanopy especially during the dry season since cocoa is highly drought intolerant species (Zuidema *et al.*, 2005).

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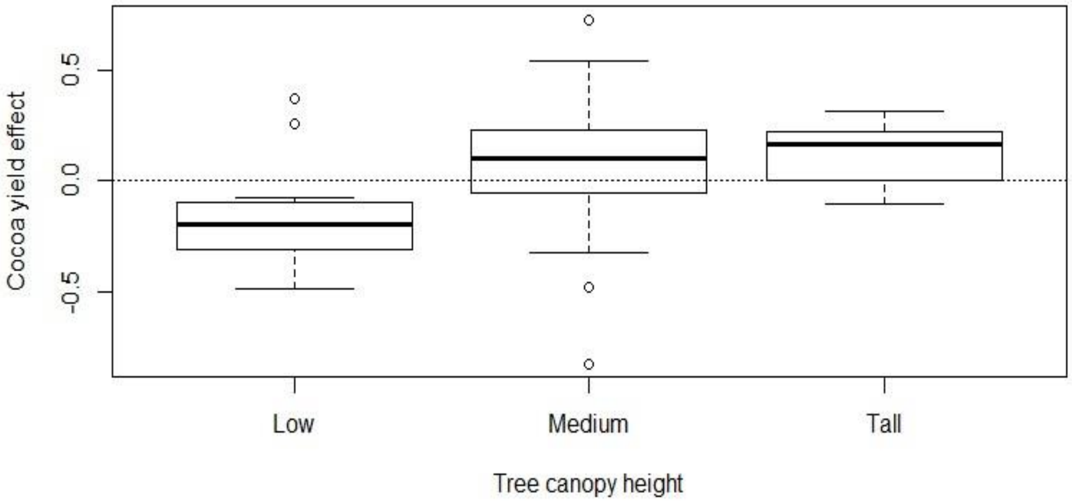

Figure 4.6: Effect of tree canopy height on potential cocoa pod yields in a cocoa agroforestry system

Table 4.13: Effect of tree canopy height on the number of potential cocoa pod yields under sub-canopy and open area in a cocoa agroforestry system

Canopy height	Number of pod yields	
	Sub-canopy	Open area
Tall	14.80 ± 1.31	11.48 ± 1.12
Medium	9.65 ± 1.25	8.79 ± 1.23
Low	7.65 ± 1.10	11.39 ± 2.17

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4.5.2 Effect of different tree species on potential pod yields of cocoa

The yield effect of cocoa was highest under *F. capensis* (0.40) and *F. exasperata* (0.40) and lowest under *T. ivorensis* (-0.55) (Table 4.14). The yield effects under *F. capensis* and *F. exasperata* were not significantly different from *S. campanulata, T. superba, A. toxicaria, E. angolense, N. laevis, A. boonei, and M. excelsa* (Table 4.14). On the other hand, the yield effects under *T. ivorensis* were similar to that of *C. sinensis, M. indica, P. americana, E. guineensis, F. africana* and *M. lucida* (Table 4.14). Higher yields in the sub-canopy could be attributed to low shade because the canopy heights were well elevated above the cocoa and were mainly deciduous trees with the exception of *N. laevis* which has narrow crown construction (Amanor, 1994). Tree species of this nature manipulate PAR to the understorey cocoa during the day (Blaser *et al.*, 2013) to enhance flowering and increase yields of cocoa. Moreover, the species are mainly deep rooting and hence they take up water deep down from the soil and this minimizes below ground competition for soil moisture with the understorey cocoa (Schroth, 1995).

Moreover, there is usually a linear relation between cocoa aboveground biomass and pod yield under low shade (Zuidema *et al*., 2005, Isaac *et al*., 2007).

Lower yields observed in the low canopy height trees may be as a result of unfavourable microclimatic conditions exhibited by the trees species. These tree species were mainly evergreen and not elevated above the understorey cocoa leading to maximum light interception and thereby limiting PAR availability to the subcanopy cocoa trees. Moreover, the trees species are mainly shallow rooting which adversely affect water availability to the understorey cocoa as a result of competition for soil moisture. Because cocoa is highly sensitive to water and light availability (Zuidema *et al.*, 2005), any tree species that do not enhance optimum light and water availability will eventually have an adverse effect on cocoa growth and yield. The results from this study confirms an investigation by Koko *et al.* (2013) who reported that the yields of cocoa intercropped with *C. sinensis* and *P. americana* were significantly lower than the monocrop yield. However, because these are mainly fruit trees and farmers are likely to include them in the system for food and/ or extra income, appropriate planting distances that minimizes detrimental microclimatic effects should be adopted. Koko *et al.* (2013) proposed planting distance between the cocoa and the fruit trees of 10.6 m to minimize adverse effects of trees and ensure optimum yield of cocoa.

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Table 4.14: Effect of different tree species on the number of potential cocoa pod yields in a cocoa agroforestry system

Tree species	Number of pod yields		Pod yield effect
	Sub-canopy	Open area	
F. capensis	10.90 ± 1.80	4.50 ± 1.18	0.40 ± 0.17^{a}
F. exasperata	8.23 ± 0.80	3.83 ± 1.42	0.40 ± 0.14^{a}
S. campanulata	15.87 ± 1.47	11.67 ± 1.42	0.15 ± 0.10^{ab}
T. superba	19.31 ± 2.20	14.08 ± 0.69	0.15 ± 0.06^{ab}
E. angolense	15.05 ± 3.85	12.71 ± 5.09	0.12 ± 0.09^{ab}
N. laevis	9.44 ± 2.76	8.08 ± 2.88	0.12 ± 0.06^{ab}
A. toxicaria	9.26 ± 2.30	6.92 ± 0.74	0.12 ± 0.11^{ab}
A. boonei	20.93 ± 0.69	17.62 ± 3.61	0.11 ± 0.09^{ab}
M. excelsa	14.50 ± 2.49	12.04 ± 0.65	0.08 ± 0.09^{ab}
M. lucida	5.60 ± 0.60	7.42 ± 3.42	-0.03 ± 0.22^{ab}
E. guineensis	10.25 ± 1.26	13.08 ± 4.45	-0.05 ± 0.24^{ab}
F. africana	8.89 ± 1.57	10.00 ± 1.94	-0.05 ± 0.10^{ab}
P. americana	7.36 ± 2.57	11.71 ± 6.90	-0.13 ± 0.22^{ab}
M. indica	6.07 ± 0.14	9.50 ± 1.25	-0.21 ± 0.07^{ab}
C. sinensis	6.93 ± 3.70	11.25 ± 5.64	-0.26 ± 0.02^{ab}
T. ivorensis	3.58 ± 1.68	10.04 ± 1.63	-0.55 ± 0.15^{b}

Values with superscripts followed by the same letters are not significantly different at $P \leq 0.05$ level using Tukey's HSD range Test.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

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5.1 CONCLUSIONS

The following conclusions are drawn based on the findings from this study;

5.1.1 Shade trees and volumetric soil moisture content

The inclusion of tall canopy height trees in cocoa agroforestry systems have positive microclimatic implications. Soil moisture levels were higher in the sub-canopies of medium and tall canopy height tree species. Soil moisture content was higher under sub-canopies of the following tree species in the dry season; *M. lucida, S. campanulata, F. capensis, M. excelsa, A. boonei,* and *F. exasperata.* Soil moisture levels were significantly lower in the sub-canopies of the low canopy height trees.

5.1.2 Shade trees and photosynthetic active radiation (PAR)

PAR availability in the sub-canopies of tall canopy height trees was within the optimal range for cocoa production as PAR levels were effectively manipulated at different times of the day by the trees to the sub-canopy cocoa. The following tree species showed positive implications for light availability to the cocoa sub-canopy; *E. angolense, T. superba, F. africana, N. laevis, M. excelsa* and *A. toxicaria*. Low canopy height trees were mostly evergreen and not elevated above the sub-canopy cocoa leading to lower PAR transmission. The tree species that recorded lower PAR transmission were; *M. indica, C. sinensis, P. americana, T. ivorensis* and *S. campanulata.*

5.1.3 Shade trees, temperature and relative humidity

Temperature and relative humidity were not significantly influenced by the single standing shade trees in a cocoa agroforestry system during the dry season.

5.1.4 Shade trees and above ground biomass of cocoa

Cocoa aboveground biomass was significantly higher in the sub-canopies of tall and medium canopy height trees compared to the low canopy height. The tree species identified with higher cocoa biomass in their sub-canopies included *E. angolense, F. exasperata, N. laevis, A. boonei, M. excelsa, T. superba, S. campanulata* and *F. capensis*. Lower cocoa biomass was observed in the sub-canopies of low canopy height tree species such as *M. indica*, *T. ivorensis, C. sinensis, P. americana* and *E. guineensis*.

5.1.5 Shade trees and potential pod yields of cocoa

Potential yields of cocoa were higher in the sub-canopies of tall and medium canopy height trees such as *F. capensis, F. exasperata, S. campanulata*, *T. superba*, *A. toxicaria*, *E. angolense*, *N. laevis, A. boonei*, and *M. excelsa*. Potential yields of cocoa were low in the sub-canopies of the following tree species; *T. ivorensis*, *C. sinensis*, *M. indica*, *P. americana*, *E. guineensis, F. africana* and *M. lucida.*

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5.2 RECOMMENDATIONS

(i). Tall and medium canopy height tree species are recommended in cocoa agroforestry systems due to their favourable microclimatic properties.

(ii). The following tree species when included in cocoa agroforestry systems will maximize biomass and potential yields of cocoa because of suitable microclimatic effects; *E. angolense, T. superba, N. laevis, M. excelsa, A. toxicaria, S. campanulata, F. capensis, F. exasperata, A. boonei* and *M. lucida.*

(iii). Because most of the low canopy height trees are fruit trees and farmers may include such trees in cocoa systems, further research should be directed at determining appropriate planting distances between the cocoa and the fruit trees to ensure favourable microclimatic interactions leading to improved yield of cocoa. (iv). Future research on the appropriate level of shade in cocoa agroforestry systems that could significantly buffer temperature and relative humidity is recommended.

(v). Even though aspects of soil fertility were not considered in this study, nutrients from tree litter could have an effect on the cocoa biomass and/or yield and therefore further investigation is recommended.

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APPENDIX 1

Appendix a: ANOVA for the effect of tree rooting depth on volumetric soil moisture content

Source of variation	DF	SS	MS	F value	Pr (>F)
Rooting depth	1	0.16295	0.162954	6.7621	0.01184
Residuals	57	1.37360	0.024098		

Appendix b: ANOVA for the effect of tree leafing phenology on volumetric soil moisture content

Source of variation	DF	SS	MS	F value	Pr (>F)
Phenology	1	0.07448	0.074482	2.9037	0.09382
Residuals	57	1.46207	0.025650		

Appendix c: ANOVA for the effect of canopy height on volumetric soil moisture content

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	0.22629	0.113147	4.8359	0.01155
Residuals	56	1.31026	0.023397		

Appendix d: ANOVA for the effect of tree species on volumetric soil moisture content

Source of variation	DF	SS	MS	F value	Pr (>F)
Tree species	15	0.67988	0.045326	2.2751	0.01796
Residuals	43	0.85667	0.019923		

Appendix e: ANOVA for the effect of leafing phenology on available PAR

Source of variation	DF	SS	MS	F value	Pr (>F)

Phenology	1	6442.4	16.635	16.635	0.00014
Residuals	58	22462.5	387.3		

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Appendix f: ANOVA for the effect of canopy height on available PAR

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	12223	6111.6	20.883	1.571e-07
Residuals	57	16682	292.7		

Appendix g: ANOVA for the effect of tree species on available PAR

Source of variation	DF	SS	MS	F value	Pr (>F)
Tree species	15	23665.2	1577.68	13.248	1.089e-11
Residuals	44	5239.7	119.08		

Appendix h: ANOVA for the effect of leafing phenology on temperature

Source of variation	DF	SS	MS	F value	Pr (>F)
Phenology	1	0.0144	0.014356	0.1377	0.7119
Residuals	58	6.0476	0.104268		

Appendix i: ANOVA for the effect of leafing phenology on relative humidity

Source of variation	DF	SS	MS	F value	Pr (>F)
Phenology	1	11.83	11.8323	1.6931	0.1983
Residuals	58	405.33	6.9884		

Appendix j: ANOVA for the effect of canopy height on temperature

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	0.1817	0.090826	0.8804	0.4202
Residuals	57	5.8803	0.103163		

Appendix k: ANOVA for the effect of canopy height on relative humidity

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	37.53	0.071826	2.8178	0.06808
Residuals	57	379.63	6.6601		

Appendix l: ANOVA for the effect of tree species on temperature

Source of variation	DF	SS	MS	F value	Pr (>F)

Tree species	15	1.0774	0.071826	0.634	0.8306
Residuals	44	4.9845	0.113285		

Appendix m: ANOVA for the effect of tree species on relative humidity

Source of variation	DF	SS	MS	F value	Pr (>F)
Tree species	15	144.51	9.6337	1.5546	0.1275
Residuals	44	272.66	6.1967		

Appendix n: ANOVA for the effect of canopy height on cocoa biomass

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	0.83013	0.41506	19.882	2.989e-07
Residuals	56	1.16907	0.02088		

Appendix o: ANOVA for the effect of tree species on cocoa biomass

Source of variation	DF	SS	MS	F value	Pr (>F)
Tree species	15	1.37578	0.091719	6.3263	9.086e-07
Residuals	43	0.62341	0.014498		

Appendix p: ANOVA for the effect of canopy height on cocoa pod yields

Source of variation	DF	SS	MS	F value	Pr (>F)
Canopy height	2	0.5821	0.291054	3.5067	0.03843
Residuals	45	3.7350	0.082999		

Appendix q: ANOVA for the effect of tree species on cocoa pod yields

Source of variation	DF	SS	MS	F value	Pr (>F)
Tree species	15	2.5422	0.169483	3.0558	0.003895
Residuals	32	1.7748	0.055464		

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