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Publication date:
2016

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Dedication

To my dear daughters Melanie Yaa Ampomaah Asare and Claire Adjoa Asabea Asare, I dedicate this work to you for your profound love and understanding at all the times that I was away from you due to work.

I love you girls and May God Richly Bless you.

Acknowledgements

Contents

Summary

There is a general agreement among scientists that the use of shade trees in cocoa plantations (cocoa agroforests) may provide ecological and economic benefits. Shade trees influence growth, development and yield through competition and facilitation by affecting temperature, humidity, and availability of light, water and soil nutrients. Particularly, for smallholder farmers using low input agriculture, a stable and sustainable income may be more important than maximization of productivity, which may be achieved by the use of shade trees. Modeling studies indicate that climate change may have a negative impact on the climatic suitability of cocoa in the West African Sub-Region. In order to adapt cocoa systems to effects of climate change, it has been recommended that cocoa producing countries implement policies that will favor shade trees in cocoa. To date, however, there have been limited studies on how cocoa is affected by shade trees, in particular in response to climate.

This thesis hypothesizes that canopy cover of shade trees in low input (low-to-no fertilizer application) cocoa growing systems can improve cocoa yield under the current climatic conditions. The thesis includes a review on cocoa production systems in Ghana and the role of shade trees in cocoa growing systems, in particular how shade trees may improve the environmental integrity of forest areas. The main part of the fieldwork was carried out on-farm on approximately 86 farms in the Ashanti and Western regions in Ghana, and comprised investigations on the diversity of shade trees, and studies of yield at plot and whole-farm levels.

The thesis consists of four research papers, including three manuscripts and one published paper. Paper I specifically addresses factors influencing shade tree diversity and canopy cover in cocoa growing systems. Results show that gender plays an important role with men having larger farms, higher tree density and diversity than their female counterparts. However, gender did not have any effect on canopy cover but there was an inverse relation between farm size and canopy cover. Also there was a significant correlation between diameter at breast height (DBH) and projected crown area of trees found on cocoa farms, indicating the possibility of using the DBH as a predictor of the canopy area.

Paper II investigates the influence of shade trees on yield, temperature and soil nutrient status in on-farm plot experiments in 4 district locations. Results show no significant relationship between canopy cover of shade trees and cocoa yields in the minor harvest season (light crop). In the major harvest season (main crop), there were slightly higher yields on un-shaded plots compared to shaded plots in 2 locations, but there was a positive effect of increased canopy cover of shade trees on cocoa yields within the shaded plots. A baseline soil nutrient analyses show no significant differences between shaded and unshaded plots, but adequate levels of N, K^+, Fe^{2+}, Cu^{2+} and Zn^{2+} were recorded across locations. P, C, Mg^{2+}, and Ca^{2+} levels recorded were found to be lower than the threshold required for cocoa production. Finally, peak temperatures recorded in the cocoa canopies were above the optimal range for cocoa production and even though shade cover had a slight modifying effect on peak temperatures, the magnitude was too small to have any practical effects on projected temperature increases in the cocoa growing belt of Ghana.

Paper III was a follow up study to Paper II with the objective of determining the effect of shade tree cover and other management and social factors on cocoa yields under farmers' field conditions over a four year period. Results show that whole-farm cocoa yields increased significantly with increased canopy cover of shade trees from zero crown cover to approximately 30%. Application of fertilizer

by farmers resulted in a 7% yield increase with farms located in the Western region having higher yields compared to Ashanti region. Cocoa cultivated on short fallows had lower yields compared to recent forest clearings and old fallows. The study found no significant effect of fungicide use, seed sources and land ownership on cocoa yields in the study locations.

Finally, Paper IV consists of a study that presents a strategy on how to use shade grown cocoa (cocoa agroforests) to connect two forest reserves in Ghana and how farmers could be compensated to adopt cocoa agroforests to improve livelihoods and also environmental integrity. The study uses satellite images and expert data from a decision support system to delineate suitable candidate sites for corridors within a Geographic Information System framework. Results from socio-economic assessments of the opportunity costs of alternative farming systems to cocoa agroforestry around the forests show that on-farm benefits of cocoa agroforestry alone cannot justify its adoption in the delineated corridor as a management strategy. However, paying farmers premium prices for cocoa and substantial off-farm environmental and ecosystem services under agroforestry systems can influence farmers' decision to adopt.

The research work presented in this thesis come from work conducted in Ghana. However, the results and conclusions seem relevant to smallholder cocoa farmers in the cocoa growing belt across West Africa. The results can be used to enhance and optimize cocoa agroforestry, in particular when addressing smallholder farmers through training programs. This will help farmers to actively incorporate shade trees in cocoa for productivity gains. It will also help to ensure sustainable production by contributing to tree species conservation. However, the potential for agroforestry in adaptation to climate change is not clear. Finally, the thesis emphasizes the need to invest in long term research in smallholder cocoa agroforests in order to sustain cocoa production without compromising further on the environment.

Dansk resumé

Der er generel enighed om, at brugen af skyggetræer i kakao-plantager (kakao agroforestry) potentielt kan give betydelige økologiske og økonomiske gevinster. Skyggetræer påvirker vækst, udvikling og udbytte gennem konkurrence og synergier ved at influere på temperatur, fugtighed og tilgængelighed af lys, vand og næringsstoffer. Især for småskala-bønder, som dyrker jorden ekstensivt, kan et stabilt udbytte og bæredygtighed være vigtigere end at opnå et maksimalt udbytte, og her kan skyggetræer spille en vigtig rolle. Modelleringsstudier antyder, at klimaændringer kan få en negativ indflydelse på kakaos egnethed i Vestafrika. Som et led i tilpasningen til klimaændringer er det blevet anbefalet, at kakaoproducerende lande gennemfører politikker, som favoriserer skyggetræer i kakaodyrkningen. Imidlertid har der indtil nu kun været få studier af, hvorledes kakao bliver påvirket af skyggetræer, især i relation til klimaet.

Hypotesen i denne afhandling er, at kronedække fra skyggetræer i ekstensive systemer (med lav eller ingen tilførsel af gødning) kan øge udbyttet fra kakao under det nuværende klima. Afhandlingen indeholder en gennemgang af kakaodyrkningen i Ghana og skyggetræers rolle i kakaosystemer, med særlig fokus på hvordan skyggetræer kan forbedre den økologiske sammenhængskraft i skovområder. Hovedparten af feltstudierne blev gennemført på 86 kakao-farme i Ashanti og Western Regions i Ghana, og inkluderede undersøgelser af diversiteten hos skyggetræer og studier af udbyttet i prøveflader og på hele kakaofarme.

Afhandlingen er baseret på af fire videnskabelige artikler, hvoraf tre er manuskripter og ét er publiceret. Den første artikel undersøger hvilke faktorer, der påvirker diversitet af træer og kronedækket i kakaosystemer. Resultaterne viser, at kønnet hos ejerne har en vigtig rolle, da mænd har større farme, et højere antal træer per areal og også større træartsdiversitet end kvinderne. Kønnet spillede ikke nogen rolle for andelen af kronedækket, men der var en negativ sammenhæng mellem størrelsen af farmen og kronedækket. Desuden viste studiet, at der var en statistisk signifikant sammenhæng mellem diameteren i brysthøjde og det projicerede kroneareal, hvilket indikerer at det er muligt at benytte diameteren til at anslå kronearealet.

Den anden artikel undersøger skyggetræers indflydelse på udbytte, temperatur og næringsstoffer i jorden. Eksperimenterne blev foretaget i prøveflader på kakaofarme i 4 distrikter som nævnt ovenfor. Resultaterne viste ingen sammenhæng mellem skyggetræer og kakaoudbytte i den lille høstsæson (februar-august). I den store høstsæson (september-januar) var der let forhøjede udbytter på prøveflader uden skyggetræer på to af lokaliteterne, men der var en positiv sammenhæng mellem graden af skygge og kakaoudbytte på de skyggede prøveflader. Jordbundsanalysen viste ingen forskel mellem skyggede og ikke-skyggede plots. Niveauet af N, K^{2+}, Fe^{2+}, Cu^{2+} og Zn^{2+} var tilstrækkeligt på alle lokaliteter, mens niveauet af P, C, Mg^{2+}, and Ca^{2+} var under den anbefalede grænse for kakaoproduktion. De højeste temperaturer, som blev registreret, var højere end det niveau, som angives at være optimalt for kakaoproduktion. Selvom skygge havde en lille og modererende effekt på temperaturen, var størrelsen af denne effekt for lille til at have nogen praktisk forbedrende effekt i forhold til de forudsagte temperaturstigninger i Ghana.

Tredje artikel baseres på de to foregående artikler, og har til formål at bestemme effekten af skyggetræer, management og socio-økonomiske faktorer på kakaoudbyttet over fire år. I modsætning til artikel 2 inkluderer dette studie hele farme og er ikke begrænset til prøveflader. Kronedækket varierede fra 0 til 30%, og resultaterne viser, at udbytterne var stigende med større kronedække fra skyggetræerne. Anvendelse af kunstgødning resulterede i en øgning på 7 % i

udbyttet. Kakaofarme i Western Region havde højere udbytter end farme i Ashanti Regionen. Kakao dyrket efter en kort brakperiode havde lavere udbytte, sammenlignet med dyrkning efter en nylig skovrydning eller efter en lang brakperiode. Studiet viste ingen signifikant effekt af fungicider, frøkilder (varietet af kakao) og typen af ejerskab til jorden.

Artikel 4 præsenterer en strategi for anvendelsen af kakao agroforestry til at forbinde to fragmenterede, beskyttede skove i Ghana, og for hvordan kakaofarmere kunne kompenseres for både at forbedre levevilkårene og den miljømæssige sammenhængskraft. Studiet benytter satellitfotos og ekspertdata fra et beslutningsstøttesystem til at afgrænse forslag til korridorer mellem skovene. Resultater fra socioøkonomiske analyser af alternative omkostninger ved forskellige dyrkningssystemer viser, at fordelene ved kakao-agroforestry ikke alene kan få farmerne til at benytte denne dyrkningsmetode. Højere priser for skygge-dyrket kakao, og betaling for miljømæssige og økologiske services ved dyrkningssystemet kan influere farmernes beslutninger i retning af at indføre systemet.

Forskningen i denne afhandling er foretaget i Ghana, men resultaterne og konklusionerne synes relevante for småskala-kakaobønder i kakao-bæltet i hele Vestafrika. Resultaterne kan bruges til at øge og optimere kakao-agroforestry især når små-skala farmere undervises på træningsskoler. Dette vil hjælpe farmere til at inkludere skyggetræer i kakaoplantager for at øge produktionen, og til at sikre en bæredygtig produktion ved at bidrage til bevaring af truede træarter. Imidlertid er potentialet for agroforestry til at dæmpe effekterne ved klimaændringer uklare. Afhandlingen understreger behovet for langsigtet forskning i småskala kakao-produktion for at opretholde kakaoproduktionen uden yderligere negative konsekvenser for miljøet.

1. Introduction and background

1.1 Cocoa production in Ghana

Cocoa (*Theobroma cacao L.*) was introduced into the Ghanaian agricultural landscape in 1872 by a merchant named Tetteh Quarshie, who brought the pods into the country from Fernando Po (now Sao Tome). Over time the crop has been adapted and adopted into the farming system in the forest areas of Ghana (Asare 2014). Over 20% of the world's cocoa production comes from Ghana, making this West African country the world's second largest producer of cocoa beans over the past decade (Asante-Poku and Angelucci 2013). With an annual production level of over 700,000 metric tons between 2003 and 2013 (ICCO 2014), and an estimated cultivation area of approximately 1.6 million hectares (FAOSTAT 2015), cocoa production has been a major contributor to the economy of Ghana (see Figure 1).
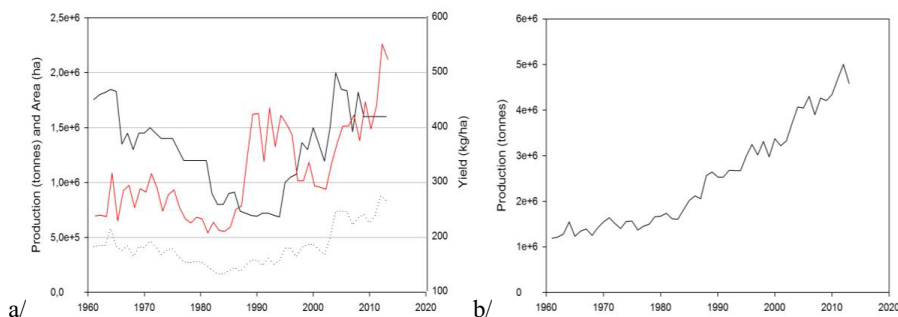
Figure 1: Overview of cocoa production (tonnes), area (ha) and yield (kg ha^{-1}) in Ghana and the world from 1960-2013. Figure 1a represents Ghana: the dotted line = Annual production (tonnes), Red line = Yield (kg ha^{-1}) and Black full line = Area (ha). Figure 1b represents the world production (FAOSTAT 2015)

Currently, it is estimated that the cocoa sector employs about 6 million people (CanatusAnthonio and Darkoa Aikins 2009), comprising over 800,000 farm families (these include 350,000 farm owners, share croppers and their dependents) who depend on cocoa production for 70% - 100 % of their annual income (Asamoah and Baah 2003). Just as cocoa production is critically important to individual farming families and other players in the cocoa sector, cocoa is also a major cash crop and foreign exchange earner for the country's economy. In 2010 for instance, cocoa accounted for a little over 8% of the country's Gross Domestic Product (GDP) and 30% of total export earnings (Ashitey 2012).

However, cocoa production has not been without its ups and downs. Annual average production and yields per ha dipped from the late 1970s to mid-1980s due to drought conditions, ageing trees, widespread disease, and low producer prices coupled with cocoa smuggling activities that resulted in about 20% of harvests smuggled into neighboring Côte d'Ivoire (Chuhan-Pole and Angwafo 2011). In an effort to stem the tides, the government, through the Ghana Cocoa Board (COCOBOD) embarked on several reform measures beginning in the mid-1980s, which increased production to 400,000 tons and yields from 210 to 404 kg ha^{-1} by the mid-1990s (see Figure 1). These reforms were part of the Economic Recovery Program (ERP) that started in 1983 (Kolavalli and Vigneri 2011). The reform included a cocoa farm rehabilitation project, in which farmers were compensated for replacing swollen shoot virus infected trees with higher-yielding cocoa tree varieties developed

by the Cocoa Research Institute of Ghana (CRIG). There were also the improvements in the road network, and the privatization of cocoa procurement to privately licensed buying companies (LBCs) (Chuhan-Pole and Angwafo 2011) - an operation which before was strictly monopolized by the Ghana Cocoa Board. However, increases in cocoa production became more pronounced in the beginning of 2001, as a result of a combination of factors including high world market prices for cocoa, which meant increased farm gate prices paid to farmers by the government. Also in 2001/2002, the Ghana COCOBOD rolled out the National Cocoa Diseases and Pest Control (CODAPEC) program, (also known as "Mass Spraying") to assist cocoa farmers to control insects and diseases like Capsid/Mirid and Black Pod disease respectively. This was followed in 2003/2004 by the Cocoa High-Technology Program (Hi-Tech) that subsidized adoption of frequent applications of fertilizer (Vigneri and Santos 2007). Some of the growth during this period was also attributed to influx of cocoa smuggled from Côte d'Ivoire (Brooks et al. 2007). In 2010/11 Ghana's production hit the all-time high of a little over a million tons, capturing 24% of the global cocoa production that year (ICCO 2014; Asante-Poku and Angelucci 2013).

1.2 The spread of cocoa cultivation in Ghana

Cocoa is grown in the forest areas of Ghana in six administrative regions, namely, Ashanti, Brong-Ahafo, Central, Eastern, Volta and Western (Figure 2a). Western region has been noted to account for over 50% of total annual production followed by Ashanti, which produces about 16%. Eastern and Brong-Ahafo regions account for 19%, while Central and Volta account for the remaining 15% (Asante-Poku and Angelucci 2013). The cocoa producing areas cut across three agro-ecological zones, namely the Wet Evergreen, Moist Evergreen and Moist Semi-Deciduous Forests (Figure 2b).
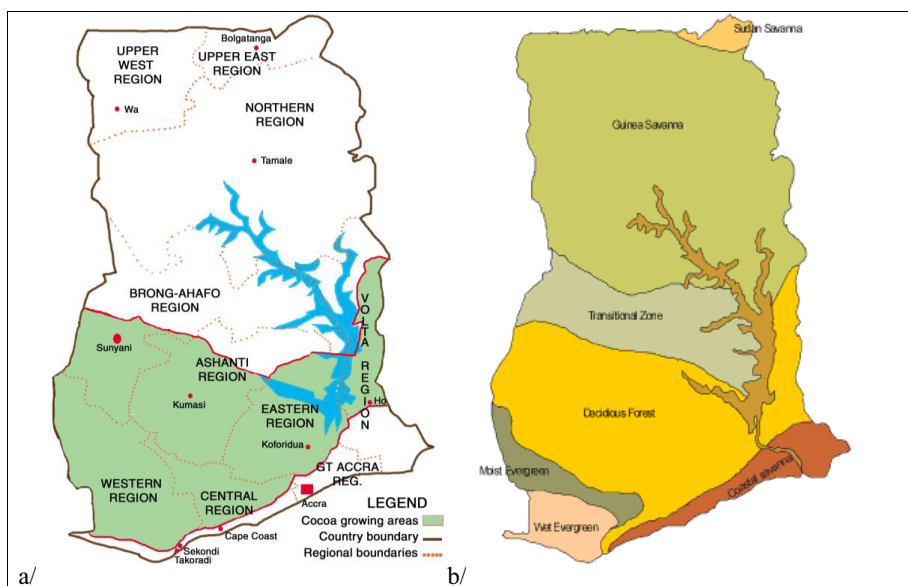
Figure 2a and b: Cocoa growing areas and agro-ecological zones in Ghana respectively

Commercial production of cocoa in Ghana started by the use of the Amelonado cocoa seeds obtained from the farm of Tetteh Quarshie (Asare et al. 2010), which was established in the

Akwapim Mountains in the Eastern Region. Farmers in this region and the rest in southern Ghana embraced cocoa cultivation as it fitted in well with their forest farming practices, and also because they were already accustomed to using forest products as cash crops (Asare 2014). However, cocoa farming started to move to the western parts of Ghana in 1892 (Figure 3) (Hill 1963) into previously uncultivated forest areas as a result of land shortages and disease outbreaks, particularly the Cocoa Swollen Shoot Virus Disease and the Black Pod Disease in 1920s, and changes in cocoa market dynamics. As a result, farmers neglected and abandoned their old farms, and migrated westwards instead of re-investing in their ageing and ailing farms (Asare 2005). By moving from one forest area to another, farmers took advantage of the nutrients in the newly cleared forest lands thereby utilizing what is referred to as the "forest rent" by Ruf and Zadi (1998) to establish new farms. This was done with cocoa seeds from previous farms. The soils of the moist evergreen and moist semi-deciduous forests were favourable for cocoa cultivation as they contain high levels of organic matter and nutrients. However, soils of the wet evergreen forests were not well suited to cocoa, but the perception that cocoa grows best on newly cleared forest soils encouraged farmers to migrate to these new frontiers (Asare 2014).
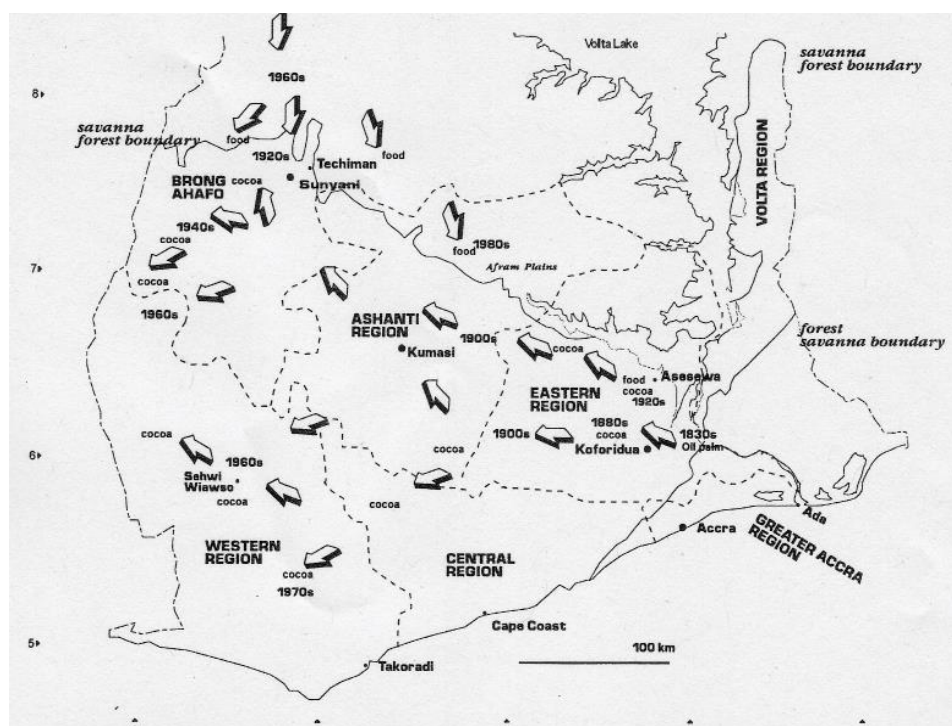
Figure 3: Migration pattern of cocoa farmers from the Eastern to Western regions in Ghana (Amanor 1996).

The practice whereby farmers collect and propagate cocoa planting materials from their own farms and that of their neighbors has continued to date. This situation, according to Asare et al. (2010), has partially affected yields due to the poor genetic and physical qualities of the seeds and the susceptibility of these materials to most pests and diseases. In order to improve the genetic and physical qualities of the seeds in the country, the government of Ghana, through CRIG, introduced

the Amazonia type of cocoa from Trinidad in 1945 to augment the genetic materials for breeding programs in the country. A cross was then made between the existing Amelonado and the Amazonia varieties to give the early-bearing, high-yielding hybrid cocoa, which has been the main planting material for cocoa farmers since its development in 1964. In the early 1970s, COCOBOD and CRIG released the 'Tafo series', which serve as the main cocoa planting material for cocoa production (Asare et al. 2010).

1.3 Cocoa cultivating systems in Ghana

Despite the fact that cocoa farming is one of the country's dominant land-use activities, it is characterized by relatively small landholdings that range from 0.4 to 4 hectares. In Ghana cocoa is mostly cultivated traditionally under partially cleared forest with remaining trees providing shade to the cocoa trees mixed with food crops (Asare 2005; Osei-Bonsu et al. 2005; Anglaaere et al. 2011) leaving a biodiversity-rich multi-strata system that also maintains a set of ecosystem services. This type of shade grown cocoa systems referred to in this thesis as cocoa agroforests have been shown to play a significant role in biodiversity conservation across West Africa (Zapfack et al. 2002; Gockowski et al. 2004; Bidzanga 2005; Sonwa et al. 2007).

Cocoa agroforests is defined in this thesis as diversified shaded cocoa farms that contain a horizontal and vertical distribution of food crops, native forest trees, and fruit trees at different periods in the life of the cocoa. These systems are essential because they provide farmers with a range of agronomic, economic, cultural, and ecological benefits (Sonwa et al. 2001; Gockowski et al. 2006), in addition to maintaining biodiversity in the landscape. Shade trees play an important role in sustaining the longevity and health of the cocoa farm by maximizing the productivity of all components within the system (Rice and Greenberg 2000). According to Obiri et al. (2007) shade trees increase the economic rotation age of hybrid cocoa trees, and a diversified farm also enables farmers to exploit the different components in the system, as well as their interactions, so as to meet subsistence needs, maximize incomes, and reduce risks against fluctuations in world market prices of cocoa beans (Duguma et al. 2001; DiFalco and Perrings 2003; Rice and Greenberg 2000). In terms of biodiversity conservation, multi-strata cocoa can help to protect forest patches, to regenerate and conserve particular forest tree species, and to provide habitats for key animal species (Schroth et al. 2004; Siebert 2002; Greenberg et al. 2000).

However, not all cocoa farming systems include high levels of tree species diversity as no-shade or low-shade systems are increasingly becoming more common than multi-cohort farms (Padi and Owusu 1998). One reason for the loss of tree diversity in cocoa systems in Ghana is that no shade systems are perceived to be more productive under ideal farming conditions, which include fertilizer and pesticide application, adequate rainfall and rainfall distribution, consistent weeding regimes, and stable market conditions. And yet, because such ideal conditions tend not to exist in the reality of the farming environment, production rarely attains its potential. Cocoa cultivation has been criticized for its contribution to deforestation of Ghana's tropical high forest belt (MSE 2002), but more importantly, in today's farming landscape, it is argued that it has the potential to contribute to the reforestation of already degraded lands through the establishment of diversified shade systems (Ruf and Zadi 1998).

Across West Africa, cocoa agroforests are classified by the number of upper canopy shade trees in the cocoa system but with no indications of size, maturity or type. In Ghana for instance, cocoa farms are categorized as high or heavy shade if there exist about 22–30 forest trees per ha in the

mix; medium shade cocoa farms consist of 15–18 forest trees per ha (Manu and Tetteh 1987; STCP 2002; Ofori-Frimpong et al. 2007; Opoku-Ameyaw et al. 2010) and low shade cocoa farms have 5-6 trees per ha (Ruf 2011). In Côte d'Ivoire Gockowski and Sonwa (2008) described shade levels as no shade, light shade and medium to heavy shade with no description of the percentage of shade cover. In Nigeria, (Oke and Olatiilu 2011) classified shade in cocoa systems as either sparse when a cocoa farm has 40 trees per ha or dense when it has 76 trees per ha. Asare and Asare (2008) reports that through the Sustainable Agriculture Network, the Rainforest Alliance advocates for 70 upper canopy non-cocoa tree species which will provide a shade density of about 40%. CRIG on the other hand recommends up to 18 emergent trees per ha ($\geq$ 12 meter height) amounting to a permanent shade cover of about 30-40% shade (Anim-Kwapong 2006). However, Ashley-Asare and Mason (2011) modified this classification and included canopy cover, tree densities and diameter at breast height (DBH) for these shade classes. They defined canopy cover as 10, 25 and >50% for low, medium and heavy shades respectively, while corresponding tree densities were 28, 35 and 51 shade trees per ha and DBH was 34.3, 61.8 and 50.1 cm. In effect, all the descriptions of shade levels in cocoa growing systems were based on stem count rather than canopy architecture. Hence, it can be argued that classification of traditional cocoa cultivating systems (cocoa agroforests) is not based on the presumed most important character: the occurrence of shade.

1.4 Impact of shade on cocoa production

Shade plays an important role in the life cycle of the cocoa plant. As an understorey rainforest tree, cocoa is sensitive to drought, even though limited quantitative information on field level water relations in mature cocoa exist (Carr and Lockwood 2011). Alvim (1977) reports that regardless of the various varieties under cultivation, all cocoa seedlings (2-3 years old) require some initial shade for growth. Cocoa is a shade loving crop whose leaves have a low light saturation point (LSP) of 400 μ E m^{-2} S^{-1} with a low maximum photosynthetic rate of 7mg dm^{-1} h^{-1} at light saturation (Hutcheon 1981). According to Raja Harun and Hardwick (1988) the photosynthetic rate of the crop decreases if the leaves are over-exposed to light intensities exceeding 60% full sun light, while prolonged exposure to high light intensities damages the photosynthetic mechanism of the leaves. However, it is known that light levels of less than 1800 hours per annum have a depressing effect on production (Asomaning et al. 1971; Gerritsma and Wessel 1996).

Beer et al. (1998) summarized that the major physiological benefits of cocoa from shade trees include the improvement of the micro-climate of the crop through (i) reduced extreme air and soil temperatures (ii) reduced wind speeds, (iii) buffering of humidity and soil moisture availability, and (iv) improvement of soil fertility and erosion control. It also involves the reduction in the quantity and the changed quality of light transmitted and hence avoidance of over-bearing and/or excessive vegetative growth. Shade also reduces nutritional imbalances and dieback. Other authors like De Silva and Tisdell (1990) report that with the proper selection and management of shade tree species in newly established cocoa and coffee farms, the labour and input costs for managing weeds, which can amount to 70% of the total costs during the first 2-3 years of a cocoa plantation (Corven 1993), could be considerably reduced.

Despite these attributes of shade in cocoa, the shade requirements of cocoa have been questioned and investigated with the aim of uncovering whether shade is an innate requirement of the cocoa tree itself or whether it serves a secondary role by maintaining appropriate soil, insect population and other conditions for the cocoa plants, conditions that could potentially be maintained with the

application of suitable chemical inputs like fertilizers, pesticides and weedicides/herbicides (Cunningham and Arnold 1962).

A typical example of such investigations is the widely published work on the first shade and fertilizer trials in Tafo, Ghana in the 1950s, 1960s and 1970s. The results indicated very high yields after shade removal from well-established cocoa on fertilized soils (Cunningham and Arnold 1962; Ahenkorah et al. 1974; Ahenkorah et al. 1987). Similar results were also obtained from experiments carried out by the Imperial College of Tropical Agriculture in Trinidad (Evans and Murray 1953) and the Executive Commission for Planning Cocoa Agriculture (CEPLAC) in Bahia, Brazil (Cabala-Rosaud et al. 1982).

Nonetheless, there have been reports of several deleterious effects that offset the positive aspects of reduced shade. The most prominent of these are the increases in pests and disease damage (Campbell 1984; Entwistle et al. 1985). Higher weed growth and higher nutritive demands of the cocoa plant are also observed (Ahenkorah et al. 1974). Furthermore, it has been reported that young and unshaded cocoa produced a high percentage of small category G beans (Adu-Ampomah et al. 1998).

In effect it is hypothesized that non-shaded cocoa is not economically justified despite the initial production advantage. The inputs required by unshaded cocoa may simply be too expensive for smallholder farmers and are often not available when needed. Under sub-optimal conditions serious dieback diseases and in good environments excessive vegetative growth at the expense of pod production has been observed under no-shade conditions (Wessel and Gerritsma 1997). Hence, even though the production of cocoa pods generally increases if shade is decreased, such changes may bring on other problems (Alvim 1977).

1.5 Climate variability and implications on cocoa production

Despite the high production in recent years, cocoa, like other agricultural crops appears to be exposed to the impact of climate variability, particularly in and around the boundary areas of its cultivation. Alvim (1977) suggested that even though solar radiation and relative humidity affects physiological processes in the cocoa plant, the most critical climatic factors generally considered as suitable for growth are temperature and rainfall.

Wood and Lass (2008) reported that cocoa thrives well in areas where annual rainfall ranges from 1,250–3000 mm. In particular, cocoa is performing well in areas of rainfall beween1500–2000 mm with a dry season of not more than three months with less than 100 mm of precipitation per month. Its temperature requirements vary between 30°-32°C mean maximum and 18°-21ºC mean minimum.

Are and Gwynne Jones (1974) indicated that for optimum production there should not be more than one month when the average daily maximum temperature exceeds 33.5º C. Consequently, changes in temperature and rainfall could impact today's cocoa growing belt in West Africa in general and Ghana in particular. According to Läderach et al. (2013), climate predictions in the West African sub-region have improved in recent times. Brown and Crawford (2008) noted a period of high rainfall between 1930s to the 1950s, which was followed by a period with lower precipitation and frequent droughts for the next thirty years. Consequently, Léonard and Oswald (1996) suggested

that the dry period and high variability impacted negatively on the climatic suitability for cocoa in the 1970s and 1980s.

In their prediction of the future climatic suitability for cocoa farming in Ghana and Cotê d'Ivoire, Läderach et al. (2013) noted that the Global Circulation Models accepted by the UNFCCC have projected an increase in the yearly and monthly minimum and maximum temperatures in the cocoa growing areas in the two countries by up to 2.0 ºC. Similarly, Anim-Kwapong and Frimpong (2008) predicted an increase of 0.6 - 5.4º C in mean annual temperature over the next 70 years in the Moist Evergreen and Moist Semi-Deciduous Forest Zones of Ghana, which encompasses the cocoa growing belt.

Although an increase in temperature is generally projected for West Africa, models tend to be less clear on the impact of climate change on rainfall amounts and patterns. Nevertheless, Anim-Kwapong and Frimpong (2008) predicted for cocoa producing zones of Ghana that mean annual rainfall levels will decline by 2.1% to 20.2% over the next 70 years. According to these researchers cocoa is highly sensitive to changes in climatic conditions – especially increases in the incidence of sunlight, changes in rainfall pattern and temperature fluctuations due to the effects of evapo-transpiration. Longer periods of drought and higher temperatures are causing fluctuations in productivity, and farmers are experiencing losses from tree desiccation and death.

In some degraded areas, attempts to replant cocoa have failed due to seedling mortality as a result of prolonged drought, low soil fertility, an increased incidence of diseases and pests and the use of poor planting materials (Padi et al. 2013). Negative changes like extended periods of rainfall or drought, with its associated high temperatures, have been argued to increase the rate of disease and pest development, as well as modify host resistance, which could lead to changes in the physiology of host-pathogen/pests interaction. According to Anim-Kwapong and Frimpong (2008), the consequence is a shift in the geographical distribution of hosts, pathogens and pests, and crop losses which may impact on farm income, livelihoods, and farm-level strategies. To adapt to the harsh effects of climate variability on cocoa, it has been suggested that cocoa producing countries enact and implement policies that will ensure shade in cocoa systems (Anim-Kwapong and Frimpong 2008). Also, there should be support for farmers to develop diversified and resilient agricultural systems that provide critical ecosystem services (water supply and regulation, habitat for wild plants and animals, genetic diversity, pollination, pest control, climate regulation) (Nellemann 2009). Some research in coffee and cocoa systems have already shown that shade trees play a key role in regulating humidity and temperature fluctuations (Beer et al. 1998) and in reducing the overall vulnerability of these systems (Lin et al. 2008), but there have been limited robust information and experience on how to develop adaptive methods to help protect cocoa and coffee agro-ecosystems from climate change (Adams et al. 2003).

1.6 Description of the study areas

The studies that form this thesis were conducted in the Ashanti and Western regions of Ghana (Figure 4). These areas fall under the Moist Semi-Deciduous (MSSE) and Moist Evergreen (ME) forest zones respectively. The ME and MSSE forests correspond to the *Lophira-Triplochiton* and the *Celtis-Triplochiton* associations (Taylor 1960) respectively, which enable the establishment of high forest vegetation with the characteristic multi-tier vertical stratification. Both areas experience double rainfall maxima characterized by two rainy seasons annually. The major rainfall

season occurs between April and October, peaking in May/June and the minor occurs between August and October, peaking in September.
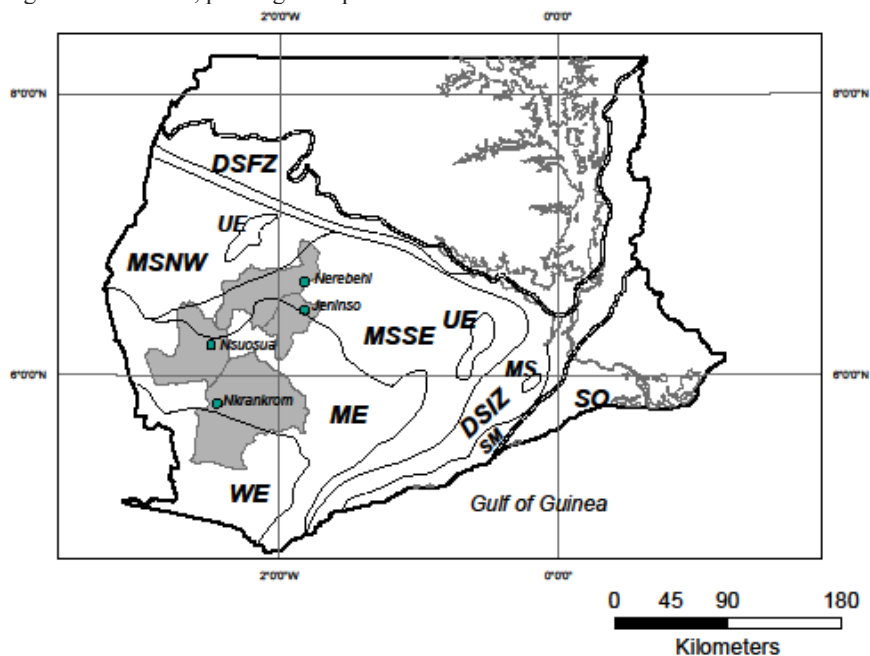
Figure 4: Map of Southern Ghana showing four shaded districts consisting of the study sites (•). Forest type boundaries are shown by broken line (-----). Forest-type abbreviations: WE=Wet Evergreen; UE=Upland Evergreen; ME=Moist Evergreen; MSSE=Moist Semi-deciduous (NW=Northwest subtype; SE=Southeast subtype); DS Dry Semi-deciduous (FZ=Fire Zone subtype; IZ=Inner Zone subtype; SM=Southern Marginal

The studies were conducted in four cocoa growing communities in four administrative districts in the Ashanti and Western regions of Ghana. Sites for the Ashanti Region were situated in Jeninso and Nerebehi located in the Amansie West and Atwima Nwabiagya districts respectively, while sites in the Western region were located in Nkrankrom and Nsuosua in the Wassa Amenfi West and Sefwi Wiawso districts respectively.

The Ashanti Region study sites fall under the Moist Semi-Deciduous Southeast subtype (MSSE) while the Western Region sites fall under the Moist Evergreen (ME) forest zones (Hall and Swaine, 1981). The ME forest zone is characterized by a semi-equatorial climate that has high rainfall (1500-1750 mm) and daily temperatures that range from 22º C to 34º C. High temperatures exist throughout the year, even though March is generally the hottest month. Humidity is high, ranging from 70-90 % for the monthly means. The MSSE forest zone is marked by moderate annual rainfall (1250-1500 mm) with uniformly high temperatures (mean monthly minimum and maximum of 27-31ºC) and high relative humidity.

According to Adu (1992), generally soils of the forest zone are developed from rocks of the Birrimian system (middle Pre-Cambrian). The well-drained soils in the MSSE and ME forests belong to the Forest Ochrosol and Forest Ochrosol-Oxysol Intergrade (ME) Great Soil Group of the Ghanaian soil classification system (Bramner, 1962) and are in general classified as Acrisols in the

FAO-UNESCO Revised Legend (FAO–UNESCO, 1988) and as Ultisols Soil Taxonomy (OSD, 1998). Under natural conditions, these soils contain moderate nutrient concentrations that are tied-up with the organic layer in their top soils.

The Ashanti and Western regions were selected for this research work as they represent old and comparatively new areas of cocoa cultivation in Ghana respectively and together they produce 66% of the total annual production.

1.7 Organization of the thesis

The thesis is organized in six main sections. Section one reviews the literature on cocoa production and how cocoa plantations spread across and the cultivation system in place. This section delves into the definition of shade in cocoa in Ghana and West Africa and the current mode of estimating shade cover across the sub-region. The final parts of the section deal with the impact of shade and the implication of climate variability on cocoa production. The second section deals with the hypothesis and objectives of the four research papers that make up this thesis and the link between these papers. The third section deals with the overview, methods and results of the papers. Section four provides a discussion of the results of the four papers. Section five provides the general conclusions across all papers, followed by section six which provides perspectives on the future work required to further deepen the discourse on the relevance of shade trees in cocoa systems. This is followed by a list of references of the literature cited and final copies of the four research papers.

2. Objectives

2.1 Hypothesis

There seem to be a general contradiction between authors on the role of shade trees in cocoa plantations. While some consider shade trees to provide considerable ecological and economic benefits, especially in cases of low input agriculture, where sustainability rather than maximization of productivity is of major interest (Willey 1975; Beer 1987; Wessel and Gerritsma 1997; Vaast and Somarriba 2014), other authors claim shade has a negative effect on cocoa yields (Cunningham and Arnold 1962; Ahenkorah et al. 1987; Wade et al. 2010).

However, there is no research information under field conditions that focuses on correlating canopy cover and cocoa yield, even though some results can be found on studies with seedlings (Alvim 1977). In an effort to contribute to the knowledge gap in the literature on shade grown cocoa systems, this thesis hypothesize that, "*canopy cover of shade trees in low input (low-to-no fertilizer application) cocoa growing systems can contribute to cocoa yield improvements.*"

This hypothesis is tested through the four research articles included in this thesis, which demonstrate the role shade trees play in smallholder cocoa farms in influencing growth and factors like air temperature and soil nutrients with regards to yield of cocoa in Ghana. The following are specific objectives of each research paper:

1. Determine factors that influence the variations in the structural diversity of shade trees (shade tree species, density and canopy structure) in low input cocoa farms;
2. Assess the influence of shade trees on cocoa yields, temperature and soil nutrients;
3. Assess the effect of varying canopy cover on whole-farm yields;
4. Determine how functionally diverse (timber and cocoa) low input cocoa farms can contribute to connectivity between fragmented forests.

Paper I focuses on identifying the factors that influence variations in tree diversity and density and how this affects canopy cover of shade trees in cocoa farms. This paper addresses the first specific objective and provides insights to the differences in gender related management practice that leads to variations in tree species diversity and canopy cover. It also provides information in the variations in the canopy cover of shade trees and how a simple measurable feature of a tree can predict its canopy area. Paper II addresses the second specific objective and it investigates the effect of canopy cover of shade trees on canopy temperature of cocoa trees, soil nutrients and cocoa yield at the plot level in an on-farm investigation. Paper III addresses the third specific objective and it is similar to paper II except that it looks at the effect of canopy cover at the farm level and as a result puts things in a broader perspective compared to detailed work shown in paper II. Paper IV describes the possibilities of using cocoa agroforests as a strategy to connect fragmented forests in two protected forest reserves and how farmers could be compensated to adopt this strategy. This paper addresses specific objective number four.

The main theme of this thesis dwells on upper canopy cover of shade trees in cocoa, which is defined here as the percentage ground cover measured from the vertical projection of the crown on the ground. The shade cast is a mottle of light and shaded patches as a result of the crown permitting the transmission of some light to the forest/plantation floor. This measurement is difficult in a multi-strata system like a cocoa agroforest, which below the cocoa canopy is a closed

canopy system. In order to estimate shade therefore, a simplistic measure of the canopy cover of shade trees was used as a proxy.

2.2 Measurement of canopy cover

Shade measurement in integrated and closed cocoa farms is a challenge. In this thesis, a simplistic measure of the canopy cover of shade trees has been used as a proxy for shade cover. This was done by estimating the contribution of each shade tree to the entire canopy cover per farm. In order to do this, the diameter of the crown (CD) of shade trees was measured in four different directions across the crown spread from one tip to the other (Blozan 2006), following the cardinal points. The Figures were then averaged. This was to ensure that the variations of the pattern of the crown were captured. The measure for the CD was then used to estimate the crown area (CA) by the following formula:

$$CA = \pi * \left(\frac{CD}{2}\right)^2$$

The total canopy cover (CC) for all the upper canopy trees was expressed as a percentage per hectare to ensure easy comparison between plots or farms using the following formula:

$$CC = \left(\frac{TCA}{Plot\ size}\right)/10000$$

Where *TCA* is the sum total of *CA* of all trees recorded per plot or farm. *TCA* is expressed in m^2 on plot or farm size in ha.

3. Overview and results of papers

3.1 Tree diversity and canopy cover in cocoa systems in Ghana (Study I)

There exist conflicting recommendations on the required number of trees per unit area cocoa farm, which is supposed to correspond to a certain percentage of shade cover needed for cocoa production. For instance, environmentalists claim that cocoa farms with a diversity of forest tree species numbering 70 per ha can provide a shade cover of ca. 40% (SAN 2005: cf Asare and Asare 2008). This density is roughly equivalent to a shade tree spacing of 12m x 12m. Meanwhile, the Cocoa Research Institute of Ghana (CRIG) recommends up to 18 emergent trees ($\geq$ 12 meter height) per hectare (roughly a 24 m x 24 m spacing) providing permanent shade cover corresponding to approximately 30-40% shade (Anim-Kwapong 2006).

The variation in the recommended number of shade trees can be attributed to differences in the structural diversity of trees in the system i.e., tree species, density, tree characteristics like canopy architecture, diameter at breast height, trunk height as well as age. Variations may arise as a result of farmers' management practices. This can be influenced by the area cultivated and the tree species configurations in the cocoa systems. In Ghana and the rest of West Africa, shade tree recruitment or retaining is part of an anthropogenic process in which the density and structure of trees is as a result of farmers preferences (Asare 2010). However, it is difficult for farmers to plan their farms over the life span of the cocoa trees in terms of the amount of canopy cover needed at any particular stage and age. The objectives of this study were i) to determine the factors that influence the shade tree density, diversity and canopy cover on cocoa farms; and ii) to identify a simple indicator for canopy cover for different tree species in cocoa systems.

In total, 86 farmers (61 men and 25 women) representing 86 farms were selected from the four communities through a systematic sampling process that involved focus group discussions and individual interviews. Farmers were selected by virtue of having shade trees on cocoa farms whose age fall between 8-28 years. Questions on socio-cultural factors included land use type, history of farm, educational background, training experience and whether trees were planted or naturally regenerated.

Furthermore, the selected cocoa farms were at least 100 m apart and delineated such that they did not cross two different management regimes. Farm size was measured with a Garmin Global Positioning System (GPS) by walking along the entire farm perimeter. All shade trees above the cocoa canopy, which were situated within the perimeter of the farm were identified, counted and measured for crown diameter (CD) and diameter at breast height (DBH). In total, 1042 shade trees above the cocoa canopy were recorded on a total area of 127.7 ha. Ninety-six percent of the trees were as a result of natural regeneration and they comprised 90 species from 30 families (see Annex 1 Study I). Forty-nine species appeared in both agro-ecological zones. The most predominant species were *Terminalia superba, T. ivorensis, Newbouldia laevis, Milicia excelsa, Persea americana, Ficus exasperate, Antiaris toxicaria, Amphimas pterocarpoides, Albizia zygia* and *Morinda lucida*. The majority of the trees were timber species in addition to fruit trees such as *Persea americana*, *Cola nitida* and *Ricinodendron heudelotii*.

Results show that men had significantly larger farm sizes compared to women. Number of trees increased with increasing farm size but levelled off at larger farm sizes. The density of trees tended to be high (up to 76 ha^{-1}) on small farm sizes but decreased to low values (less than 5 ha^{-1}) on large

farm sizes. The differences between women and men were again significant, with men having higher tree density than women. Canopy cover of shade trees ranged between 1 – 40 %. There was an inverse relationship between farm size and canopy cover, as relatively large farms had smaller canopy cover from shade trees compared to smaller farms. Crown cover was the sole variable that was not influenced by gender of the farmer.

Men had higher tree species diversity compared to women, and large farms had more tree species compared to smaller farms. Simpsons and Shannon's indices increased with increasing farm size. However, Simpsons measure of evenness was unaffected by farm size and any of the other farmer related parameters. It only varied significantly between locations. There were positive correlations between the DBH and the CA of species investigated (Figure 3 Paper I). Estimated equations for the remaining species are shown in Table 3 of Paper I.

3.2 Influences of shade trees and fertilization on on-farm yields of cocoa in Ghana (Study II)

Cocoa in Ghana and West Africa are grown in complex environments, in which multiple ecological, climatic and agronomic management factors play roles that influence productivity to a large extent (Cunningham and Arnold 1962). However, there is limited – and to some extent contradictory – knowledge on the ameliorating effect of canopy cover of shade trees on cocoa yields and factors like soil nutrients and temperature. While a range of experiments have been conducted on-station (Cunningham and Arnold 1962; Ahenkorah et al. 1974; Ahenkorah et al. 1987) there have been few studies conducted on mature cocoa trees in West Africa under farm conditions that have attempted to measure key growing conditions and to understand the impact of different variables on yield (Isaac et al. 2007; Wade et al. 2010; Koko et al. 2013). The objective of this study therefore was to measure the effect of canopy cover of shade trees on cocoa yields, soil nutrient contents and temperature in two main cocoa growing agro-ecological zones in Ghana in an effort to better understand the conditions affecting production at the farm level.

Thirty-two farms were randomly selected from an initial number of 86, with 8 farms from each community for on-farm experimentation. However, due to natural causes such as death and diseases, the number was reduced to 26 farms with 11 and 15 farms in the Ashanti and Western regions respectively. Age of the cocoa trees ranged between 8 and 28 years. Farms in each region were selected such that they were at least 2 km apart in each community. These farms represent traditional cocoa systems in which cocoa seeds were planted at random on previously cleared forestlands with extremely variable shading, spacing and age. The experimental design was a full factorial design with two factors, shade/no shade and fertilizer/no-fertilizer on 10 m radius circular plots, replicated on the 24 farms (blocks). A shade tree stands in the middle of the shaded plots. These shade trees comprised different species with varying canopy size.

Prior to the start of the experiment, soil samples (0-15 and 0-30 cm in depths) were taken in each plot and analysed in the laboratory of CRIG. Fertilizer was applied in two seasons (2 years), and cocoa yields were monitored continuously through the minor and the major seasons. Temperature in the cocoa canopy was measured in a subsample of the farms by hanging a calibrated Tinytag 2 Plus TGP-4017 above the cocoa canopy in the no shade stands and above the canopy but under the shade trees in the cocoa and shade tree stands .

Figure 5a and b show a Tinytag in an aluminium foiled pot and a farmer mounting the pot in the cocoa canopy

In addition, canopy cover of the shade trees was estimated and expressed as a percentage of the size of the plot and used as a proxy for shade cover per plot.

Results show that cocoa yields varied widely from an average high of 1203 ± 66 kg ha^{-1} y^{-1} in Wassa Amenfi West to 386 ± 60.2 kg ha^{-1} y^{-1} in Amansie West. The average yields across all locations were 219 ± 13.4 kg ha^{-1} y^{-1} for the light crop and 674 ± 50 kg ha^{-1} y^{-1} for the main crop. Plots in Wassa Amenfi West recorded the highest mean yield for the main crop at 1012 ± 62 kg ha^{-1}. This was followed by Antwima Nwabiagya (582 ± 53.7 kg ha^{-1}), Sefwi Wiawso (483 ± 73 kg ha^{-1}) and Amansie West (313 ± 43 kg ha^{-1}) respectively. For the light crop, Antwima Nwabiagya recorded the highest mean yield at (326 ± 18 kg ha^{-1}). This was followed by Sefwi Wiawso (188 ± 30 kg ha^{-1}), Wassa Amenfi West (183 ± 17 kg ha^{-1}) and Amansie West (73 ± 19 kg ha^{-1}).

In the major cocoa season (main crop), there was a highly significant positive effect of fertilizer compared to the unfertilized plots. Fertilizers resulted in an increase of 14.5% in the main crop yields at 953 ± 65.2 kg ha^{-1} ($p<0.0001$) compared to unfertilized plots (832 ± 64.9 kg ha^{-1}). Canopy cover on shaded plots showed a borderline significant positive effect ($p=0.036$) with a significant ($p=0.012$) interaction effect between location and shade. The latter means that the contrast between the non-shaded and the shaded subplots is different in the four investigated locations as represented in Figure 2 of Paper II. There were significant negative effects of shade in Atwima Nwabiagya ($P=0.0382$) and Amansie West ($P=0.0040$), but there was no effect of shade in Wassa Amenfi West ($P=0.7551$) and Sefwi Wiawso ($P=0.4832$). The statistical model includes two different terms describing the shade: The interaction effect of shade and location (yes/no), which shows negative effects of shade in the two locations, and the covariate crown cover, which shows increasing yields with increasing levels of crown cover within the shaded plots. The overall interpretation is that high levels of crown cover increases yields compared to non-shaded plots, except for Amansie West.

On the contrary, there was no systematic relation between the light crop yield and canopy cover of shade trees. However, the interaction between location and fertilization was significant ($p=0.0365$) due to improved yields in fertilized plots in Amansie West.

Effect of canopy cover on soil nutrients
Results showed no significant effects of shade trees on soil nutrients. However, there were differences in nutrient levels between locations (Table 4, Paper II). Soils on plots in Wassa Amenfi West had significantly lower pH levels compared to those in the other locations, with Sefwi

Wiawso recording the highest. There were no significant differences in total soil N between locations. Wassa Amenfi West had the lowest levels of total C. Available P was very low in Amansie West, with the highest values recorded in Sefwi Wiawso. K^+ was high in both Atwima Nwabiagya and Sefwi Wiawso, while Mg^{2+} and Ca^{2+} levels were low in Wassa Amenfi West. Amansie West and Sefwei Wiawso recorded the highest levels in Mg^{2+} and Ca^{2+} respectively. Sefwi Wiawso had the highest levels of Zn^{2+}, while Cu^{2+} levels were low in Wassa Amenfi West. Fe^{2+} was high in Wassa Amenfi West and low in Amansie West.

Effect of canopy cover on temperature

There was a wide temperature variation recorded in the cocoa canopy ranging from 14.7-45.4 ºC across shaded and unshaded plots (Figure 3, Paper II) from January 30 to December 18, 2013. Mean values for the locations were significantly different, but all between 25 and 26 ºC. Maxima daily temperatures were recorded in the main dry season (November-March) while the minima were recorded at the end of the main rainy season (August) and at one occasion in September. There were also significant differences between location for the lowest daily mean temperature, the lowest maximum, the highest minimum and the absolute minimum, but differences were small and within 1-2 ºC (see Paper II Supplementary Table 2). The analyses showed borderline significant effects of shade on the lowest daily mean, the highest minimum and the absolute minimum temperatures. However, differences were always less than 1°C and mostly less than 0.5 °C. Maximum temperatures were not significantly affected by shade.

3.3 On-farm cocoa yields increase with canopy area of shade trees in two regions in Ghana (Study III)

Even though eliminating shade has a productive advantage that boosts yield, a non-shaded cocoa system is not necessarily economically justified. This is because there are reports of negative effects associated with the lack of shade and the continuous use of agro-chemicals in order to maintain productivity (Alvim, 1977).

This study was conducted to examine the effect of canopy cover of shade trees on cocoa yields under farmers' farm conditions over a 4 year period, taking into consideration variables such as management and social factors. Eighty-six farmers representing the same number of cocoa farms (selected in study I) were used in this study. Harvests of dry cocoa beans (kg) were recorded on farms and later in farmers' Cocoa Passbook (CP) for 4 years. Cocoa yield was then expressed as the amount of cocoa beans (kg) produced per annum, divided by the farm size in ha. Socio-economic and management factors, such as land use type, farm history, educational status, training experience, fertilizer application, insecticide use, fungicide application, source of cocoa planting material and whether shade trees were planted or naturally regenerated, were recorded through a questionnaire. During the surveys, application of fertilizer, insecticide or fungicide in a given year was registered as "yes" in the respective record, without recording treatment frequencies or amounts. Canopy cover of shade trees was used as a proxy for shade cover.

In a repeated measurement analysis, results show that with increasing canopy cover on farm, the average yield per ha also increases. The positive influence of fertilizer on cocoa yield, however, is relatively small, especially considering that most cocoa experts promote the use of inorganic fertilizers. With respect to farming history, it was observed that plantations on short fallow/cropped lands had significantly lower yields compared to previously forested and long fallow lands. The two communities in the Western region attained higher average yields compared to the farms in the

Ashanti region. However, variables such as gender, use of fungicide, planting material for cocoa (indicating a hybrid cocoa tree or not), and the land tenure arrangement (history of the land) were not significant in terms of affecting yields.

3.4 Cocoa agroforestry for increasing forest connectivity in a fragmented landscape in Ghana. Agroforestry Systems 88:1143-1156 (Study IV)

Cocoa cultivation that maintains substantial proportions of shade trees in a diverse structure is viewed as a sustainable land-use practice that complements the conservation of biodiversity (Rice and Greenberg 2000b; Schroth et al. 2004). Cocoa cultivation was carried out traditionally under partially cleared forest with remaining trees providing shade to the cocoa trees (Asare 2005; Anglaaere et al. 2011) leaving a biodiversity-rich multi-strata system that also maintains a set of ecosystem services. According to Ruf (2011), in recent times the traditional system of cocoa farming has been changed particularly by migrant farmers who have cultivated cocoa in wide spread forest clearings where little or no shade applies.

It is estimated that about 50-70 % of the total areas of protected forestlands in Ghana have been illegally encroached (England 1993; MSE 2002). In the process, two protected areas [Bia Conservation Area (Reserve A) and Krokosua Hills Forest Reserve (Reserve B)] of biodiversity importance in the Western region of Ghana have been encroached through lumbering for timber, cocoa production and other agricultural land expansions (Oates et al. 2000; Oates 2006). These forest reserves are the last domain for two of the most endangered primates in Africa – the Roloway Guenon (*Cercopithecus diana roloway)* and the white-naped mangabey (*Cercocebus atys lunulatus*) (Oates 2006).

The objective of this study was to develop a strategy for forest connectivity in Reserve A and Reserve B to improve the sustainability of cocoa production and the livelihoods of smallholder cocoa farmers. The study defined forest connectivity in terms of possible gene flow between plant populations and animals' species between the two protected areas. The study employed both biophysical and socio-economic assessments of the study area. The biophysical assessments used satellite images, vegetation pattern maps, and an expert decision support system to delineate suitable sites for the corridor within a GIS framework. The socio-economic assessments used primary data collected from 100 randomly stratified selected farm-households in combination with a representative farm-household classification through focus group discussions. Enterprise budgets of alternative farm production activities were applied to estimate the opportunity costs of cocoa-agroforestry creation and restricting access to food and no-shade cocoa farming as well as non-timber forest product resources in the protected area. Between July and August 2010, farm owners were interviewed on one-on-one meetings to gather all economic data necessary to calculate net revenue. Also expert knowledge from identified community members, government and non-governmental organizations working in the area were used to augment primary and secondary data.

Cost-benefit analysis of the representative farms was done by classifying the primary and secondary data into 6 data categories, namely: farmer demographic and household characteristics, individual farm characteristics, labour and agrochemical application levels, crop yield parameters, GPS and field measurements and farmers' general perception of biodiversity conservation. Farm enterprise budgets from the production and farm management data collected were combined with price data to develop the economic farm optimization model of the farms using the cost-benefit analysis. The resulting representative value was used to quantify the opportunity cost of alternative non-cocoa

farming enterprises. The farms investigated allowed for the comparison of sole production of oil palm (20 farms), rice (20 farms) or cocoa with timber trees (60 farms), along with food or income from managing various staple crops for subsistence, all of which compete for farm resources. The choices of crops were based on focus group discussions and recommendations from key informant interviews including extension specialists. Also, transect walks were done in each of the randomly selected 60 cocoa farms to identify and count number of forest and cocoa trees. The dominant tree species on cocoa farms include *Milicia excelsa, Khaya ivorensis, Entandrophragma angolense, E. cylindricum*, *Terminalia ivorensis*, *T. superba*, *Triplochiton scleroxylon*, *Aningeria robusta*, *Pycnanthus angolensis*, *Masonia spp.*, *Tiegmella heckelii*, *Newbouldia lavis*, *Cocos nucifera*, and *Elaeis guineensis*.

Based on the analysis, the gap between the Bia National Park and the Bia North Forest Reserve and the gap between the south eastern tip of the Bia Resource Reserve (south of the Reserve A) and south western tip of Reserve B were identified as suitable sites for forest corridors. The socio-economic analysis established that no-shade cocoa production is the most profitable with a cost-benefit ratio of 1.26 in the area in comparison with alternatives such as cocoa agroforestry, oil palm and rice (Table 1, Paper IV). The second best enterprise to no shade cocoa is cocoa agroforests, under the assumption that farmers will sell timber after the 20 year production cycle. The scenario analysis showed that cocoa agroforest premiums alone are not attractive enough for farmers to shift from no shade cocoa to cocoa agroforestry. To encourage cocoa agroforestry, cocoa premiums from cocoa agroforests need to be tied with payments for full environmental benefits, including rewards for carbon sequestration and biodiversity conservation.

4. Discussions

4.1 Determination of factors that influence variations in the structural diversity of shade trees (shade tree species, density and canopy structure) in low input cocoa farms (Objective 1)

This study shows that men have larger farm sizes compared to women, a situation that confirms earlier work by Otsuka et al. (2003) who argues that since forest clearance is traditionally a male activity and since cocoa farming predominantly occurs in forest areas, male-led households tend to acquire more forest land through forest clearance compared to women.

In terms of shade tree density, men had a higher tree density per ha compared to women, which can be attributed in part to policies on tree tenure in Ghana. The law on tree tenure as stipulated in the Concession Act, No. 124, 1962, section 16 (4) and the Constitution of the Republic Ghana, entrusts naturally occurring timber trees in the President of the Republic on behalf of the landholding authority. Hence, timber concessions can be given on cocoa farms, thus puting pressure on cocoa farms as reliable sources of valuable timber (Hansen and Treue 2008) to feed the timer industry (Owubah et al. 2001). In spite of the fact that forestry policies require cocoa farmers to be compensated for damage incurred from harvesting of timber by logging companies, officially there is no mechanism for determining compensation (Asare 2006). Hence, possession of valuable trees on cocoa farms require strong institutional backing for protection and negotiating skills in case of compensation but since women tend to be vulnerable in terms of customary rights to protect or negotiate for compensation on such resources they may be inclined to avoid such confrontation by eliminating trees from their farms before they become targets for timber concessionaires.

On the farm level, shade tree density per hectare decreased with increasing farm size, a relationship that is consistent with findings by Asare (2010). This could possibly be that in order to avoid undue attention from timber extractors that might cause damage to large size farms, these farmers may restrict the number of timber trees on their farms to just a few that they need. Also, a manual published by CRIG that cites many trees species as incompatible with cocoa and for this reason are often eliminated from cocoa farms (Manu and Tetteh 1987). This is further highlighted by the fact that 48% of the recorded trees in this study constituted 12 recommended species by CRIG indicating to a large extent that farmers follow the recommendations by removing non-recommended species from cocoa farms. Over time, the elimination of trees from cocoa systems has contributed to the reduction of tree diversity on farms. Therefore, while the Shannon index is noted to be sensitive to the number of species and thus will likely increase as sampling effort increases, the Simpson index is less sensitive to species richness and sampling effort (Magurran 2004). Hence, it was observed that there was a per farm increase in the number of species that were not related to the farm size in itself. However, larger farms tend to be more diverse in term of tree species. Due to the fact that men had relatively larger farms, there was the likely effect that more species can enter the farms, germinate and grow, resulting in a high diversity on male farms compared to females'. Meanwhile, results of this study show that as farm size increases, both tree density and crown cover decrease.

There were strong positive relationships between CA and DBH even though there were differences in the crown area between different species. As trees grow older, their crowns expand and provide more cover. Hence, if a constant number of shade trees are maintained on a cocoa farm, the canopy cover will vary substantially over the life time of the farm plantation. For example, the canopy area

of *Pycnanthus angolensis* is 131 m^2, which is 10 times the amount provided by 10 individual *Newbouldia laevis* trees whose mean CA is 13 m^2 as shown in this study. Hence, using the DBH to estimate the crown area of trees would be a simple way for farmers and extension workers to assess the canopy cover, provided that the correlation between DBH and CA is known for the species in question. However, it should be remembered that the quality and quantity of light transmitted through different crowns will vary as a result of the degree of opacity or translucency of the crown of that particular species.

4.2 Assessment of the influence of canopy cover on temperature, soil nutrients and cocoa yields at plot level (Objective 2)

Analysis of the data shows varied implications on yield and as a result it reveals the complexity of cocoa yields in agroforestry systems. There was an increase in yield of cocoa with increased canopy cover in the major season on the shaded plots. However, for the two locations in the Ashanti region, non-shaded plots on average had higher yields than the shaded plots, indicating a negative effect of the shade trees on yields. We speculate that this is due to underground competition between cocoa and shade trees for water and/or nutrients. This could reduce yields as a result of the reduced irradiation due to shade from the canopy trees. It is interesting to note that the reduced yields of shaded plots were only found in the Ashanti region, which has lower precipitation than the Western region, and was especially pronounced in Amansie West which also had a relatively low soil P levels. However, the two locations in the Western Region recorded positive net effects on yields on shaded plots. This may be attributed to the improvement of nutrient uptake by cocoa trees under shade trees as documented by Isaac et al. (2007).

Results for the light cropping season indicate that shade appears to have no effect on yield. This may be because the light cropping season coincides with the dry period. Since most of the shade tree species located within the sampled plots are deciduous and pioneers that typically shed leaves in the dry seasons as a strategy to avoid moisture loss from evapotranspiration during the driest months of the year, there is no canopy cover above the cocoa trees. Hence, cocoa trees in shaded and unshaded plots may experience the same light incidence during the light crop season when most trees would be defoliated. However, the data suggest that when all trees have leaves in the wetter months (main crop) there is a positive impact on cocoa yields as represented in Figure 2 in Paper II. In any case, there is a need to fully elucidate the responses of cocoa to shade and competition. In our study, we have ignored the fact that different shade trees may be more or less compatible with the cocoa trees. In order to improve cocoa agroforestry, tree species analysis, should take into consideration guilds and ecological characteristics of the species. Likewise, simple experiments with suspended shade nets above the cocoa canopy could help in separating the effects of below-ground competition from the effects of shade. Finally, extrapolating the studies to the farm scale may help to elucidate whether there is an overall effect of tree density or canopy cover on yields.

In terms of soil nutrient levels, we found no effect of shade cover. This is partly consistent with studies by Isaac et al. (2007) who found no effect of shade on nutrients like N in Ghana. The fact that farmers used little or no fertilizer before fertilizer application on the study plots could account for the mixed and low availability of nutrients in the soils as shown in Table 4 of Paper II. This is corroborated by Appiah et al. (1997) who found that cocoa in Ghana is mainly produced by small-scale farmers under low level of management and within a subsistence economy in which few fertilizers are used. Ogunlade et al. (2009) also report the same situation among Nigerian Cocoa

farmers. Hence, it is no surprise that the baseline soil data showed low levels of nutrients, especially P (Tables 4).

In general, fertilizer application increased yields, with the best result obtained in Wassa Amenfi West, Atwima Nwabiagya and Sefwi Wiawso and an overall increase of 121 kg ha^{-1}. Average pH, N, K^+ and micronutrients were within recommended thresholds for cocoa cultivation at all locations (Ahenkorah 1981), but P, C and Ca^{2+} contents were lower than the critical thresholds. Authors have consistently reported low levels of P in West African cocoa systems (Hartemink 2005; Ogunlade and Aikpokpodion 2006; Aikpokpodion 2010), partly due to the relatively low use of inorganic fertilizers. P was the most limiting nutrient, with levels below the recommended threshold at all locations, but especially at Amansie West. The relatively low yield in Amansie West may partially be a result of the exceptionally low P levels in the soil, which could not be sufficiently ameliorated by the recommended fertilizer application. This highlights the importance of targeted fertilizer recommendations as opposed to the blanket policy that is in place currently.

Considering the effect of canopy cover on temperature, the sampled cocoa canopies experienced maximum temperatures that exceed cocoa's recommended temperature range of 18-21ºC mean minimum and 30-32 ºC mean maximum (Wood and Lass 2008). The maximum temperatures were uniformly above 40 ºC, with the highest temperatures of 43 and 42 ºC found in Nwabiagya and Amansie West respectively. The mean maximum temperature across sites ranged from 31 to 33 ºC in Sefwi Wiaso, which also exceeded the recommended mean maximum. With these findings, it can be argued that shade in cocoa can only play a limited role in ameliorating the effect of higher temperatures as projected for the cocoa growing belt of Ghana by Anim-Kwapong and Frimpong (2008).

4.3 Assessment of the effect of canopy cover of shade trees in low and high input cocoa farms on yields over time (Objective 3)

As a follow up to objective 2, this study recorded on-farm cocoa yields for 4 years on 86 farms. Results showed that the average annual yield across farms over the period studied (618 kg/ha) exceeded the national average of 400 kg (Aneani and Ofori-Frimpong 2013). We surmise that part of this discrepancy is because previous studies relied on extrapolations from research plots and/or farmers' estimates of cocoa bean production (the number of bags produced) and their own farm size. This is known to be problematic as farmers with little information of their farm size tend to over-estimate the size (Hainmueller et al. 2011), which potentially result in underestimation of the yield per hectare. In this study, we determined yield from both farm records and Cocoa Passbooks with an accurate determination of the farm size. Another possible reason for the higher yields as compared to the national average is the significant effect of farmer training on yield. This is highlighted in the Western Region (where yields were the highest), where the government and private sector have focused the bulk of their economic and agronomic resources. This has led to over 50% of the current cocoa beans being produced in this region (Gockowski and Sonwa 2011).

The current study shows that with increasing canopy cover on farm, the average yield per ha increases (Figure 3 Paper III). This supports the assertion in Study II that on a large scale, canopy cover of shade trees can have a positive effect on cocoa yields. This is also in agreement with previous findings in controlled environments (Cunningham and Arnold 1962; Ahenkorah et al. 1987) in Ghana. Those studies noted that applying more fertilizers in full-sun cocoa systems produced high yields compared to shaded systems with same amount of fertilizer resulted in smaller

effect. We hypothesize that even though fertilizer use was widespread amongst respondents (60%) compared to other research results obtained from other parts of the country (Baah et al. 2011; Nunoo et al. 2014), the effects of fertilizers was relatively small. Small scale farmers in Ghana tend to apply low levels of fertilizer and therefore not reaping the benefits that one might assume compared to field trials where dramatic yield increases have been observed (Appiah et al. 1997; Edwin and Masters 2005). However, further research that employs a multi-year and multi-location approach will be important to support this finding as our results contradict what Wade et al. (2010) found in the Eastern Region of Ghana. In their study, higher yielding, more intensively managed farms had significantly lower shade levels as compared to farms that were not very productive and were extensively managed but maintained a multi-strata shade system. The two studies, however, contain a number of differences. Wade and colleagues based their yield and farm size estimates on farmers' information, which may bias the data. Besides, farming practices in the Eastern Region also tend to be different from what is found in the Ashanti and Western Regions. Whereas cocoa has been cultivated for a longer period of time in the Eastern region, opening up the possibility that the soils are significantly degraded, the Western and Ashanti regions present more recent frontiers of cocoa production where management practices have improved and taken advantage of modern technical know-how on cocoa production.

Moreover, there were no significant effects of insecticides and fungicides on yields even though other research have documented the potential yield increases from spraying to prevent losses from pests such as Capsids or diseases such as black pod (Aneani and Ofori-Frimpong 2013). This can possibly be because use of pesticides and fungicides are limited to only a single spraying per year, as offered by the government as against normal recommendations of four sprayings to control Capsid/Myrid and black pod attacks. It is also likely that if the majority of farmers in the area are not controlling pests and diseases, they will persist in the fields, making the efforts of a few farmers counter productive. Hence, it could be speculated that farmers are benefitting from natural maintenance of soil fertility, and pest and disease control by non-chemical means, which according to Beer et al. (1998) is possible in low input, diverse cocoa systems with shade trees.

The results from this research question some of the main assumptions on yield-management relationships that have been driving recommendations and the socio-economic discourse on cocoa for more than a decade. Many variables that are commonly assumed to be important such as gender, use of fungicide, the cocoa seed source and the land tenure arrangement were not significant in affecting yields. However, gender issues have received limited attention with respect to cocoa farming in West Africa. Though Paper I found that gender had a significant impact on farm size with women having smaller farms compared to men. Since we did not find that gender influenced yield, the interpretation must be that women farmers are likely to obtain less income from cocoa farming due to the smaller size of their farms. Land and tree tenure have no effect on yield even though they are commonly cited as factors influencing management decisions on shade tree management. Regarding yields their influence is not significant. Contrary to recommendations on the use of hybrid seedlings for increased productivity, cocoa seed source for farmers' cocoa trees did not significantly impact yield. Therefore the absence of a significant relationship between planting material source and yield highlight the need to have a better understanding of hybrid material adoption and on-farm productivity. There was a considerable variation in yield between different farms. Therefore, a more focused analysis targeting highly productive farms would lead to our understanding on how high yields may be attained under low and high input management systems.

4.4 Determination of how functionally diverse (timber-fruit-cocoa) low input cocoa farms can contribute to fragmented forests connectivity (Objective 4)

The use of spatial technology, especially GIS, helped to creat a commanding and integrated overview and analysis of complex human-dominated and natural landscapes for holistic planning and a multi-criteria decision-making in this study. As a result, this work identified the following critical factors in a decision process to choose suitable sites for corridor development and implementation: level of land use intensification; population density; presence of resources attractive to wildlife; protective legislation and policy instrument; short separating corridors; cropping systems; land use with low monetary value; biodiversity importance; and traditional and cultural practices.

In the end, the analysis indicated two areas most favorable for connecting the Bia Conservation Area (Reserve A) and Krokosua Hills Forest Reserve (Reserve B). These are given as i) the gap between the Bia National Park and the Bia North Forest Reserve, which is referred to as the northern site (Figure 2, Paper IV) covering a distance of 4 km and, ii) the gap between the south eastern tip of the Bia Resource Reserve (south of the Reserve A) and south western tip of Reserve B, which is referred to as the southern site covering a of distance of 5.5 km.

These areas were selected due to high density of rivers and streams connecting the forest blocks. The area is also protected by water resource policy instrument for vegetation along water bodies. This presents a corridor with a central core of pure natural vegetation along water bodies that provides high degree of connectivity between the forest reserves. As a result, this area will act as an extension of the forest reserves that will enhance possible gene flow between the forest reserves. In implementing the corridor, the national land and buffer policies could be used as protective instruments to manage the area. This area is expected to have a minimum width of 200 m beyond which, an area of cocoa agroforests on individual farmlands with high indigenous tree density are maintained.

However, the baseline scenarios show that cocoa agroforest premiums alone will not be attractive enough for farmers to shift from no shade cocoa to cocoa agroforestry. The only incentive to cause this shift to cocoa agroforestry would be when farmers are given cocoa premium and full environmental benefits such as carbon sequestration plus biodiversity benefits. When this is done cocoa agroforestry becomes profitable than no-shade cocoa production. Hence, promoting incentives for environmentally-friendly agriculture could lead to adoption of appropriately designed agroforestry systems like biological corridors. Consequently, this will help in decreasing the use of forest lands for cocoa cultivation (Ruf and Zadi 1998; Owubah et al. 2001).

5. General conclusions

This study has demonstrated that gender plays a significant role in farm size, tree density and diversity in cocoa cultivation. Tree density decreased with farm size, while species diversity was found to increase with farm size. Yet, more trees do not necessarily translate into greater canopy cover as it is dependent on species and tree characteristics. The diameter at breast height (DBH) of species like *Terminalia superba, T. ivorensis Newbouldia laevis, Milicia excelsa, Persea americana, Ficus exasperate, Antiaris toxicaria, Amphimas pterocarpoides, Albizia zygia* and *Morinda lucida*. *Persea americana*, *Cola nitida* and *Ricinodendron heudelotii* provide a good estimate of the canopy cover on a given farm. However, this statement must be applied with caution as the relationship between DBH and CA is extremely species dependent. Also species composition may vary from one locality to the other.

The long standing argument that shade trees limit productivity needs to be reassessed in light of the on-farm research results revealed in this thesis. These findings show that shade tree canopy can have a positive impact on yields depending on the crown area. It is demonstrated in this thesis that canopy cover coupled with modest fertilizer use will give the best results under low input smallholder cocoa cultivation. However, fertilizer application must be targeted, as soil nutrient levels vary from place to place. It is also shown that even though the temperature results confirmed some buffering effects of canopy cover on cocoa farms, canopy cover alone was inadequate in ameliorating the microclimate under cocoa production in the current climatic context. Therefore, more work is required to fully understand this relationship in the context of mature cocoa farms in different locations under multiple age regime scenarios. It must be stated that there is a limitation in the method used to estimate shade cover in this study as we used a simplistic assumption that the crown area projected on the ground would be circular and will provide a solid patch of shade on the ground.

On the issue of fragmented forest connectivity, creating corridors on such complex landscapes with multiple objectives must be carefully negotiated. This should be done by considering all relevant factors for effectiveness. Thus, the success in the corridor delineation in this study makes a strong case for similar applications. However, we acknowledge that the choice of weighting and configuration in practice may be site-specific and for that matter should be sensitive to local policies and natural resource endowment.

The effective management of land use and forest resources would require measures aimed at improving the integrity of the landscape while optimizing farmers' production levels in addition to necessary compensation packages to farmers who adopt environmental stewardship practices. Thus, paying premium prices to farmers for the cocoa produced and substantial off-farm environmental and ecosystem services under agroforestry systems can promote the adoption of sustainable biodiversity-friendly, agricultural practices. The ensuing revenue acrued from the payment of premium could help improve household incomes. Similarly, valuable trees planted within cocoa agroforests could offset any perceived yield losses in the shade-yield relationship compared to full sun-production systems. In effect, promotion of a sustainable climate-smart cocoa agenda that fosters increased productivity, resilience from climate-change and climate-change mitigation require a better understanding of the relationship between canopy cover and cocoa yield as it is realized on smallholders' farms.

6. Future perspectives

National assessment of cocoa yield has relied on farmers' estimates of cocoa bean production (the number of bags produced) and their own farm size. The continuous dependence on such information may give biased results. Hence, government and the private sector should take adequate steps and begin to monitor reliable farm-based yield data, based on accurate farm size measurement and yield data from farmers' fields and Cocoa Passbook.

Given the lack of contemporary data on cocoa age-yield profiles in Ghana, it is recommended that further longitudinal trials with different age-yield profile regimes of cocoa trees on-farm under varying shade management treatments in different agro-ecological zones must be undertaken. This should include varying soil fertility levels and different cultural management practices to provide more robust information on yield under different sets of conditions to improve farmers' practices and confidence.

It is also proposed that interventions in the cocoa value chain be revisited. More research should be invested in developing a simple but efficient way of measuring shade cover applicable to farmers, and in understanding variations in on-farm productivity under low input conditions in multi-strata cocoa agroforestry systems across multiple locations.

In order to find a cost effective corridor between conservation areas, there is a need to determine the most cost-effective corridor route by analyzing the cost and benefits associated with establishing a corridor of different widths – 200 m, 500 m, 1 km and 1.5 km - against the predetermined length of 5 km.

7. References

Adams RM, Houston LL, McCarl BA, Tiscareño M, Matus J, Weiher RF (2003) The benefits to Mexican agriculture of an El Niño-southern oscillation (ENSO) early warning system. Agricultural and Forest Meteorology 115 (3):183-194

Adu-Ampomah Y, Frimpong EB, Abitey MA, Ofori-Frimpong K, Opoku G, Yeboah SB (1998) Occurrence and distribution of light crop (category G) beans in the main crop season. Technical report. Ghana Cocoa Board, Accra, Ghana

Ahenkorah Y (1981) Influence of environment on growth and production of the cacao tree: soils and nutrition. Paper presented at the International Cocoa Research Conference, Douala, Cameroun, 4-12 Nov 1979

Ahenkorah Y, Akrofi G, Adri A (1974) The end of the first cocoa shade and manurial experiment at the Cocoa Research Institute of Ghana. J Hortic Sci 49:43-51

Ahenkorah Y, Halm B, Appiah M, Akrofi G, Yirenkyi J (1987) Twenty years' results from a shade and fertilizer trial on Amazon cocoa (Theobroma cacao) in Ghana. Experimental Agriculture 23 (01):31-39

Alvim PD (1977) Cacao. In: Alvim PD, Kozlowski TT (eds) Ecophysiology of tropical crops. Academic Press, New York, pp 279-313

Aneani F, Ofori-Frimpong K (2013) An Analysis of Yield Gap and Some Factors of Cocoa (Theobroma cacao) Yields in Ghana. Sustainable Agriculture Research 2 (4):p117

Anglaaere LC, Cobbina J, Sinclair FL, McDonald MA (2011) The effect of land use systems on tree diversity: farmer preference and species composition of cocoa-based agroecosystems in Ghana. Agroforestry Systems 81 (3):249-265

Anim-Kwapong GJ (2006) Potential of planted and natural tree fallows for rehabilitation of degraded cocoa farmlands in Ghana. Paper presented at the conference on extending cacao for biodiversity conservation, Kumasi, Ghana, 14-18 August 2006

Anim-Kwapong GJ, Frimpong EB (2008) Climate change on cocoa production. In: Ghana climate change impacts, vulnerability and adaptation assessments. Environmental Protection Agency, Accra, Ghana, pp 263-314

Appiah M, Sackey S, Ofori-Frimpong K, Afrifa A (1997) The consequences of cocoa production on soil fertility in Ghana: a review. Ghana Journal of Agricultural science 30 (2):183-190

Are LA, Gwynne Jones D (1974) Cacao in West Africa. Oxford University Press,

Asamoah M, Baah F Improving research-farmer linkages: The role of CRIG. In: 4th International Seminar on Cocoa-Pests and Diseases (INCOPED), Accra, 2003. pp 19-21

Asante-Poku A, Angelucci F (2013) Analysis of incentives and disincentives for cocoa in Ghana. MAFAP SPAAA http://www fao org/fileadmin/templates/mafap/documents/technical_notes/GHANA/GHANA_Technical_N ote_COCOA _EN_Apr2013 pdf

Asare R (2005) Cocoa agroforests in West Africa. A look at activities on preferred trees in the farming systems Forest and landscape Denmark working papers (6-2005)

Asare R (2006) Learning about neighbour trees in cocoa growing systems – a manual for farmer trainers. Forest & Landscape Development and Environment Series (4-2006)

Asare R, Afari-Sefa V, Gyamfi I, Okafor C, Mva Mva J (2010) Cocoa seed multiplication: An assessment of seed gardens in Cameroon, Ghana and Nigeria. STCP Working Paper Series, 11.

Asare R, Asare RA (2008) A participatory approach for tree diversification in cocoa farms: Ghanaian farmers' experience. STCP Working Paper. International Institute of Tropical Agriculture, Accra, Ghana.

Asare RA (2010) Cocoa establishment and shade management in Ghana's Ashanti region: Understanding the main factors driving farmers' decision processes and practices. Yale University,

Asare RA (2014) Understanding and defining climate-smart cocoa: Extension, inputs, yields and farming practices. . Nature Conservation Research Centre and Forest Trends. Climate-Smart Cocoa Working Group, Accra, Ghana

Ashitey E (2012) Cocoa Report Annual. Global Agricultural Information Network, GAIN Report Number GH1202, USDA

Ashley-Asare R, Mason JJ (2011) Cocoa Carbon Initiative: Assessing the Feasibility of Climate-Smart Cocoa in Ghana. Nature Conservation Research Center. Forest Trends - The Katoomba Incubator,

Asomaning E, Kwakwa R, Hutcheon W (1971) Physiological studies on an Amazon shade and fertilizer trial at the Cocoa Research Institute of Ghana. Ghanaian Journal of Agricultural Sciences 4:47-64

Baah F, Anchirinah V, Amon-Armah F (2011) Soil fertility management practices of cocoa farmers in the Eastern Region of Ghana. Agriculture and Biology Journal of North America:2151-7517

Beer J (1987) Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agroforestry Systems 5 (1):3-13

Beer J, Muschler R, Kass D, Somarriba E (1998) Shade management in coffee and cacao plantations. In: Directions in Tropical Agroforestry Research. Springer, pp 139-164

Bidzanga N (2005) Farmers' ecological and agronomic knowledge about the management of multistrata cocoa systems in Southern Cameroon. PhD thesis. School of Agricultural and Forest Sciences. University of Wales,

Blozan W (2006) Tree measuring guidelines of the eastern native tree society. Bulletin of the Eastern Native Tree Society 1 (1):3-10

Brooks J, Croppenstedt A, Aggrey-Fynn E (2007) Distortions to agricultural incentives in Ghana. World Bank's Development Research Group:5-6

Brown O, Crawford A (2008) Assessing the security implications of climate change for West Africa. Country case studies of Ghana and Burkina Faso. A report by International Institute for Sustainable Development Manitoba pp:1-66

Cabala-Rosaud P, Santana C, de Miranda E (1982) Response of" catongo" cacao to levels of fertilizers in Southern Bahia, Brazil. Revista Theobroma (Brazil)

Campbell C (1984) The influence of overhead shade and fertilizers on the Homoptera of mature Upper-Amazon cocoa trees in Ghana. Bulletin of Entomological Research 74 (01):163-174

CanatusAnthonio D, Darkoa Aikins E (2009) Reforming Ghana´ s cocoa sector: an evaluation of private participation in marketing.

Carr M, Lockwood G (2011) The water relations and irrigation requirements of cocoa (Theobroma cacao L.): a review. Experimental Agriculture 47 (04):653-676

Chuhan-Pole P, Angwafo M (2011) Yes, Africa Can: Success Stories from a Dynamic Continent. World Bank Publications,

Corven JM (1993) Asociación de cultivos en cacao: aspectos económicos. Sombras y Cultivos Asociados con Cacao:11-18

CSCWG (2011) The Case and Pathway towards a Climate-Smart Cocoa Future for Ghana. Technical report. Climate-Smart Cocoa Working Group. Nature Conservation Research Centre and Forest Trends, Accra, Ghana

Cunningham R, Arnold P (1962) The shade and fertiliser requirements of cacao (*Theobroma cacao*) in Ghana. Journal of the Science of Food and Agriculture 13 (4):213-221

Daymond A, Hadley P (2004) The effects of temperature and light integral on early vegetative growth and chlorophyll fluorescence of four contrasting genotypes of cacao (Theobroma cacao). Annals of Applied Biology 145 (3):257-262

De Silva N, Tisdell C (1990) Evaluating techniques for weed control in coffee in Papua New Guinea. International Tree Crops Journal 6 (1):31-49

DiFalco S, Perrings C (2003) Crop genetic diversity, productivity and stability of agroecosystems. A theoretical and empirical investigation. Scottish Journal of Political Economy 50 (2):207-216

Duguma B, Gockowski J, Bakala J (2001) Smallholder cacao (*Theobroma cacao* Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. Agroforestry Systems 51:177-188

Edwin J, Masters W (2005) Genetic improvement and cocoa yields in Ghana. Experimental Agriculture 41 (04):491-503

England P (1993) Forest protection and the rights of cocoa farmers in Western Ghana. Journal of African Law 37 (02):164-176

Entwistle P, Wood G, Lass R (1985) Insects and cocoa. Cocoa, Forth Edition:366-443

Evans H, Murray D (1953) A shade and fertilizer experiment on young cacao. Report on Cacao Research, 1945-51:67-76.

FAO (2004) National Forest Inventory Field Manual Template. FAO Working Paper 94/E. Food and Agriculture Organization, Rome, Italy

FAO (2013) Climate-Smart Agriculture Sourcebook. Food and Agriculture Organization of the United Nations, Rome-Italy

Gerritsma W, Wessel M (1996) Calculated yield trends of cocoa in different countries.

Gockowski J, Sonwa D (2008) Biodiversity and smallholder cocoa production systems in West Africa. Sustainable Tree Crops Program (STCP) Working Paper Series 6

Gockowski J, Sonwa D (2011) Cocoa intensification scenarios and their predicted impact on CO_2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. Environmental Management 48 (2):307-321

Gockowski J, Tchata M, Hietet JP, Fouda G, Moneye JJ (2006) The value of biodiversity in the Beti Cocoa Agroforests of Southern Cameroon. Paper presented at the International Society of Tropical Foresters conference on conservation and the agricultural frontier, Yale University School of Forestry and Environmental Studies, New Haven, CT, 7 April 2006

Gockowski J, Weise S, Sonwa D, Tchatat M, Ngobo M (2004) Conservation because it pays: shaded cocoa agroforests in West Africa. National Academy of Sciences in Washington DC on February 10 (2004):29

GoG (2011) Ghana's Second National Communication to the UNFCCC. Environmental Protection Agency, Accra, Ghana

GoG (2014) Emission reductions program idea note. Ghana's emission reduction program for the cocoa forest mosaic landscape. Forest Carbon Partnership Facility, Carbon Fund. Republic of Ghana, Accra, Ghana

Greenberg R, Bichier P, Angon AC (2000) The conservation value for birds of cacao plantations with diverse planted shade in Tabasco, Mexico. Animal Conservation 3:105-112

Hainmueller J, Hiscox M, Tampe M (2011) Sustainable Development for Cocoa Farmers in Ghana. MIT and Harvard University http://www responsibleagroinvestment org/rai/sites/responsibleagroinvestment org/files/Ghana Cocoa Baseline Report_Jan 2011

Hall JB, Swaine MD (1981) Distribution and ecology of vascular plants in a tropical rain forest. Forest vegetation in Ghana. Dr W. Junk Publishers.,

Hansen CP, Treue T (2008) Assessing illegal logging in Ghana. International Forestry Review 10

(4):573-590

Hartemink AE (2005) Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. Advances in agronomy 86:227-253

Hill P (1963) The migrant cocoa-farmers of southern Ghana: a study in rural capitalism. In: Last M (ed) Classics in African Anthropology. James Curry Publishers, Oxford,

Hutcheon W (1981) The swollen shoot research project at the Cocoa Research Institute of Ghana. Section V Physiological Studies Tafo, Ghana:67-115

ICCO (2014) Production of cocoa beans. ICCO Quarterly Bulletin of Cocoa Statistics: Cocoa year 2013/14 Published:28-11-2014, vol XL, No. 4. International cocoa Organization

Isaac M, Timmer V, Quashie-Sam S (2007) Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis. Nutrient cycling in agroecosystems 78 (2):155-165

Koko LK, Snoeck D, Lekadou TT, Assiri AA (2013) Cacao-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. Agroforestry systems 87 (5):1043-1052

Kolavalli S, Vigneri M (2011) Cocoa in Ghana: Shaping the success of an economy. Yes, Africa can: success stories from a dynamic continent 201

Léonard E, Oswald M (1996) Une agriculture forestière sans forêt: changements agro-écologiques et innovations paysannes en Côte d'Ivoire. Natures, sciences, sociétés 4 (3):202-216

Lin BB, Perfecto I, Vandermeer J (2008) Synergies between agricultural intensification and climate change could create surprising vulnerabilities for crops. BioScience 58 (9):847-854

Läderach P, Martinez-Valle A, Schroth G, Castro N (2013) Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. Climatic change 119 (3-4):841-854

Magurran AE (2004) Measuring biological diversity. African Journal of Aquatic Science 29 (2):285-286

Manu M, Tetteh EK (1987) A guide to cocoa cultivation. Cocoa Research Institute of Ghana (CRIG), Tafo

MLNR (2012) Ghana Investment plan. Climate Investment Funds Forest Investment Program. Ministry of Lands and Natural Resources, Accra, Ghana

MSE (2002) National Biodiversity Strategy Action Plan. Ministry of Environment and Science,, Accra, Ghana

Nellemann C (2009) The Environmental Food Crisis: The Environment's Role in Averting Future Food Crises: a UNEP Rapid Response Assessment. UNEP/Earthprint,

Nunoo I, Frimpong BN, Frimpong FK (2014) Fertilizer use among cocoa farmers in Ghana: the case of Sefwi Wiawso District. International Journal of Environment 3 (1):22-31

Oates J (2006) Primate conservation in the forests of western Ghana: field survey results, 2005–2006. Report to the Wildlife Division. Forestry Commission, Ghana

Oates JF, Abedi- Lartey M, McGraw WS, Struhsaker TT, Whitesides GH (2000) Extinction of a West African red colobus monkey. Conservation Biology 14 (5):1526-1532

Obiri BD, Bright GA, McDonald MA, Anglaaere LC, Cobbina J (2007) Financial analysis of shaded cocoa in Ghana. Agroforestry systems 71 (2):139-149

Ofori-Frimpong K, Asase A, Mason J, Danku L Shaded versus unshaded cocoa: implications on litter fall, decomposition, soil fertility and cocoa pod development. In: symposium on multistrata agroforestry systems with perennial crops, CATIE Turrialba, Costa Rica, 2007. pp 17-21

Ogunlade M, Aikpokpodion P (2006) Available Phosphorus and some micro-nutrient contents of cocoa soils in three cocoa growing ecological zones of Nigeria. Paper presented at the

Proceedings of 15th International Cocoa Research Conference,

Ogunlade M, Oluyole K, Aikpokpodion P (2009) An evaluation of the level of fertilizer utilization for cocoa production in Nigeria. Journal of Human Ecology 25 (3):175-178

Oke D, Olatiilu A (2011) Carbon storage in agroecosystems: a case study of the cocoa based agroforestry in Ogbese Forest Reserve, Ekiti State, Nigeria. Journal of Environmental Protection 2 (08):1069

Opoku-Ameyaw K, Baah F, Gyedu-Akoto E, Anchirinah V, Dzahini-Obiatey H, Cudjoe A, Acquay S, Opoku S (2010) Cocoa Manual—A Source Book for Sustainable Cocoa Production. Cocoa Research Institute of Ghana, Tafo

Osei-Bonsu K, Ameyaw-Oduro C, Tetteh J Traditional cocoa agroforestry: 1. Species encountered in the cocoa ecosystem of a typical cocoa growing region District in Ghana. In: Proceedings of the 14th International Cocoa Research Conference, COPAL, Lagos, Nigeria, 2005. pp 531-538

Otsuka K, Quisumbing AR, Payongayong E, Aidoo J (2003) Land tenure and the management of land and trees: the case of customary land tenure areas of Ghana. Environment and Development Economics 8 (01):77-104

Owubah CE, Le Master DC, Bowker JM, Lee JG (2001) Forest tenure systems and sustainable forest management: the case of Ghana. Forest Ecology and Management 149 (1):253-264

Padi B, Owusu G (1998) Towards an integrated pest management for sustainable cocoa production in Ghana. Cocoa Research Institute of Ghana:11

Padi FK, Adu- Gyamfi P, Akpertey A, Arthur A, Ofori A (2013) Differential response of cocoa (Theobroma cacao) families to field establishment stress. Plant Breeding 132 (2):229-236

Raja Harun R, Hardwick K The effects of prolonged exposure to different light intensities on the photosynthesis of cocoa leaves. In: Proceedings of the 10th International Cocoa Research Conference, Santo Domingo, Dominican Republic, 1988. pp 205-209

Rice RA, Greenberg R (2000) Cacao cultivation and the conservation of biological diversity. AMBIO: A Journal of the Human Environment 29 (3):167-173

Rolim SG, Chiarello AG (2004) Slow death of Atlantic forest trees in cocoa agroforestry in southeastern Brazil. Biodiversity & Conservation 13 (14):2679-2694

Ruf F, Zadi H (1998) Cocoa: from deforestation to reforestation. Paper from workshop held in Panama. Paper presented at the International Conference on Shade Grown Cacao, Panama, 3/30-4/2, 1998

Ruf FO (2011) The myth of complex cocoa agroforests: the case of Ghana. Human Ecology 39 (3):373-388

SAN (2005) Additional criteria and indicators for cocoa production. Sustainable Agriculture Network, Rainforest Alliance. http://www.rainforest-alliance.org/programs/agriculture/certified-crops/standards_2005.html. Accessed September 10, 2007 2007

Schroth G, da Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac A-MN (eds) (2004) Agroforestry and biodiversity conservation in tropical landscapes. Island Press, Washington

Siebert SF (2002) From shade- to sun-grown perennial crops in Sulawesi, Indonesia: implications for biodiversity conservation and soil fertility. Biodiversity and Conservation 11:1889-1902

Sonwa D, Weise SF, Tchatat M, Nkongmeneck B, Adesina AA, Ndoye O, Gockowski J (2001) The role of cocoa agroforestry in community and farm forestry in southern Cameroon. vol Paper 25g(i). Rural Development Forestry Network, London

Sonwa DJ, Nkongmeneck BA, Weise SF, Tchatat M, Adesina AA, Janssens MJ (2007) Diversity of plants in cocoa agroforests in the humid forest zone of Southern Cameroon. Biodiversity and Conservation 16 (8):2385-2400

STCP (2002) Production systems and biodiversity impacts: cocoa belt survey 2001/2002 Ghana. Sustainable Tree Crops Program, International Institute of Tropical Agriculture, Accra Ghana

Taylor CJ (1960) Synecology and silviculture in Ghana. Synecology and silviculture in Ghana

Vigneri M (2007) Drivers of cocoa production growth in Ghana. ODI Project Briefing 4

Vigneri M, Santos P (2007) Ghana and the cocoa marketing dilemma: What has liberalization without price competition achieved. ODI project briefing (3)

Vaast P, Somarriba E (2014) Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agroforestry Systems 88 (6):947-956

Wade AS, Asase A, Hadley P, Mason J, Ofori-Frimpong K, Preece D, Spring N, Norris K (2010) Management strategies for maximizing carbon storage and tree species diversity in cocoa-growing landscapes. Agriculture, Ecosystems & Environment 138 (3):324-334

Wessel W, Gerritsma W (1997) Re-thinking the shade policy for cocoa growing in West Africa.

Willey R (1975) The use of shade in coffee, cocoa and tea. In: Horticultural Abstracts. 12: 791-798

Wood GAR, Lass R (2008) Cocoa. John Wiley & Sons,

Zapfack L, Engwald S, Sonke B, Achoundong G, Madong BA (2002) The impact of land conversion on plant biodiversity in the forest zone of Cameroon. Biodiversity and Conservation 11 (11):2047-2061

LIST OF PAPERS

Asare, R. & Ræbild, A.: Tree diversity and canopy cover in cocoa systems in Ghana. Manuscript.

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