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Productivity, water use and climate resilience of alternative cocoa cultivation systems

Dissertation

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Summary

Global demand for cocoa beans is projected to keep rising while future production is likely to be limited by climate variability and change. Over 70% of the global cocoa supply comes from West Africa, a region expected to be greatly affected by climate change and extreme droughts. Cocoa production in West Africa needs to be adapted to more marginal and extreme climatic conditions, mainly drought, to sustain production and avoid further deforestation of the remaining rainforest for its cultivation. In addition to the climate change effect, current yields are low due to management inefficiencies and soil limitations. Empirical data from cocoa agroforestry system studies are limited compared to those of other perennial crops such as coffee. In addition, the promotion of cocoa agroforestry as a sustainable production system is often based on anecdotes and should therefore be investigated further. There is still a huge knowledge gap on which shade tree species improve and sustain productivity, ecosystem functions (such as increase in flora and fauna diversity), and which are suitable for marginal climates with limited water supply. Studies on the effects of climatic variations on cocoa plant productivity across different regions are lacking although there is a general consensus on the requirement of developing climate change adaption options based on a sound scientific basis for the various regions.

As a contribution towards bridging this research gap and help address current and future cocoa production challenges, for this thesis several studies were performed in Ghana, the second largest and best quality cocoa producing nation: Productivity of different cocoa cultivation systems was studied at three regions along a climatic gradient (from 2014 to 2016). Climate resilience of different cocoa cultivation systems was further investigated in the marginal regions through water use experiments over periods of wet, dry and extremely dry.

Overall hypotheses of the thesis were that (i) climatic region does influence cocoa productivity, and (ii) agroforestry increases resilience of cocoa plants to marginal and extreme climatic conditions.

In **chapters 2 and 3** of the thesis, characterizations of yield gaps, soil fertility status and cocoa cultivation systems were conducted through interviews and on-farm inventories of 150 cocoa farmers and their farms along a climate gradient within the cocoa belt of Ghana. The regions which are between 100 to 150km apart were denoted as dry, mid and wet, based on estimated average annual rainfall of 1200, 1400 and 1800mm from north to south of the cocoa belt respectively. These regions are representative of current and future cocoa climatic regions of West Africa. Based on yield gap and soil fertility evaluations, it was found that the study regions were significantly different. Yield levels in the wet region were significantly higher than in the dry region, mainly due to suitable climate and management intensification. Lower yield in the dry region was due to climatic limitation and farmer's adaptation strategies in terms of income diversification and using less external inputs. Cocoa only contributed 50% to farmer's income in the dry region while non-cocoa crops and off-farm income activities contributed 30 and 20%, respectively. For farmers in the mid and wet regions, cocoa income contributed more than 80% to their annual income, indicating higher intensification and specialization. Soil fertility also varied significantly between the regions but overall the fertility status was low. From these findings it was established that different climatic zones will require different cocoa farm management and soil fertility improvement strategies. Closing yield gaps in the dry region requires improvement in pesticide and fungicide use in addition to fertilizer application. In the mid and wet regions, the control of parasitic mistletoe, improved fertilizer use and the use of quality planting materials are recommended for yield gap closure. Shade tree use and management in cocoa agroforestry systems practiced by farmers were further characterized across all climatic regions. This was to evaluate the existing and potential use of shade trees as a measure to adapt cocoa production systems to climate change. The current cocoa agroforestry systems were characterized for the two main systems of "medium" and "low shade". Medium and low shade systems dominated the dry and wet regions, respectively. Cocoa yield under medium shade system was significantly lower in the wet region but there was no difference in the dry and mid regions. It is therefore recommended that, shade tree selection for cocoa agroforestry should be climatic region-specific to minimize trade-offs between the productivity of cocoa farms and other ecosystem services.

In **chapter 4**, a detailed water use experiment was conducted in the dry region to help understand the effect of different cultivation systems on water use and drought resilience. Cocoa and shade tree water uptake (sap flow) was studied with a thermal dissipation method using Granier sensors. Soil water and microclimatic conditions were also monitored from November 2014 – March 2016. This experiment tested cocoa agroforestry as a potential adaptation strategy in sub-optimal and extreme drought conditions. Cocoa in full sun was compared with agroforestry systems: shaded by (i) a leguminous tree species, *Albizia ferruginea* and (ii) *Antiaris toxicaria*, the most common shade tree species in the dry region. The climate and drought events during the study period served us as a proxy for projected future climatic conditions in marginal cocoa cultivation areas of West Africa. The 2015/16 El Niño event resulted in the strongest drought in the region since 1982/83 when a similarly strong event occurred. Soil water was reduced under the shaded systems during drought events. Cocoa plants under *Albiza* and *Antiaris* recorded 100 and 77% mortality, respectively, during the extreme drought period. Cocoa plants under full sun survived and recovered after the drought while those under shade did not. It was then established that during extreme drought, the role of shade trees on cocoa plants became critical as competition for soil water intensified. Water limitation was found to override microclimatic benefits by the studied shade tree species. Cocoa plants under full sun showed a higher level of resilience and acclimatisation capacity to drought than shaded cocoa. These results call for further detail studies, looking above- and below-ground, to critically evaluate the promotion of shade tree use as a climate change adaptation strategy for cocoa cultivation planning especially in West Africa.

Differences in cocoa plant productivity between shaded and full sun systems across the climatic regions were studied in **Chapter 5**. Three treatments of high shade, medium shade and open sun plots were assessed across the three climatic regions. Three cocoa plots of each system with 20 uniformly distributed cocoa plants were monitored monthly for a whole year. The results showed higher cocoa plant yield (harvested pods) under full sun conditions than in the shaded systems in the low rainfall dry region. In the mid and wet regions, no significant differences were observed between the systems. Both cocoa plant productivity and drought resilience are therefore negatively affected by shade trees under a marginal cocoa climate. The use of shade trees as climate change adaptation strategy especially in the mid region where by 2050 marginal climatic conditions are projected, need to be carefully reconsidered. For the dry region, a potential climate change adaptation strategy would be changing from cocoa to crops that are more productive and are faced with lower climatic risk. One example of such a crop may be cashew, which is more resilient to drought than cocoa and also has a high economic value. The development of more drought tolerant cocoa planting materials could also be an option to sustain cocoa production under the projected climate change. In the mid region, where the projected climatic conditions will be similar to those of the current dry region, shade trees with proven complementary soil water use under natural conditions could be integrated with cocoa. Alternatively, a full sun system is recommended through land sparing approach to ensure biodiversity conservation in the cocoa landscape. For the wet region, where water limitations are not expected, well managed cocoa agroforestry systems could be practiced to ensure sustainable yield and biodiversity conservation. Overall, this study provided detailed results on climatic zone-specific cocoa management as well as options to help adapt plant production systems to climate change and extreme drought within the "cocoa landscape".

To my dear wife and best friend, Wallam

My children, Hajar and Rayyan

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Chapter One

Cocoa plant with pods

Cocoa beans on drying mat

Heaped harvested cocoa pods

1 General Introduction

1.1 Global cocoa production and climate change

Amongst the major drivers of global biodiversity loss is agricultural intensification at local and landscape-scale (Clough et al. 2010, Foley et al., 2011). Africa is considered the most vulnerable region to the expected impacts of climate change (van Ittersum et al., 2016: IPCC, 2014). The West Africa sub region together with other countries in the continent are predicted to experience increased water stress and temperature increase which will result in reduced productivity of rain dependent agriculture (IPCC, 2014). This is no doubt a serious concern considering the significant role agriculture plays in sustaining livelihoods and the extended national economic growth of many African countries.

With $150 billion worth of the global chocolate industry (Fairtrade Foundation, 2016), cocoa is amongst the world's most valuable crops and plays significant role in national economies and rural livelihood sustenance. Current annual global cocoa bean production is estimated at 4million tonnes with demand expected to reach 4.5 million tonnes by 2020 (Fairtrade Foundation, 2016).

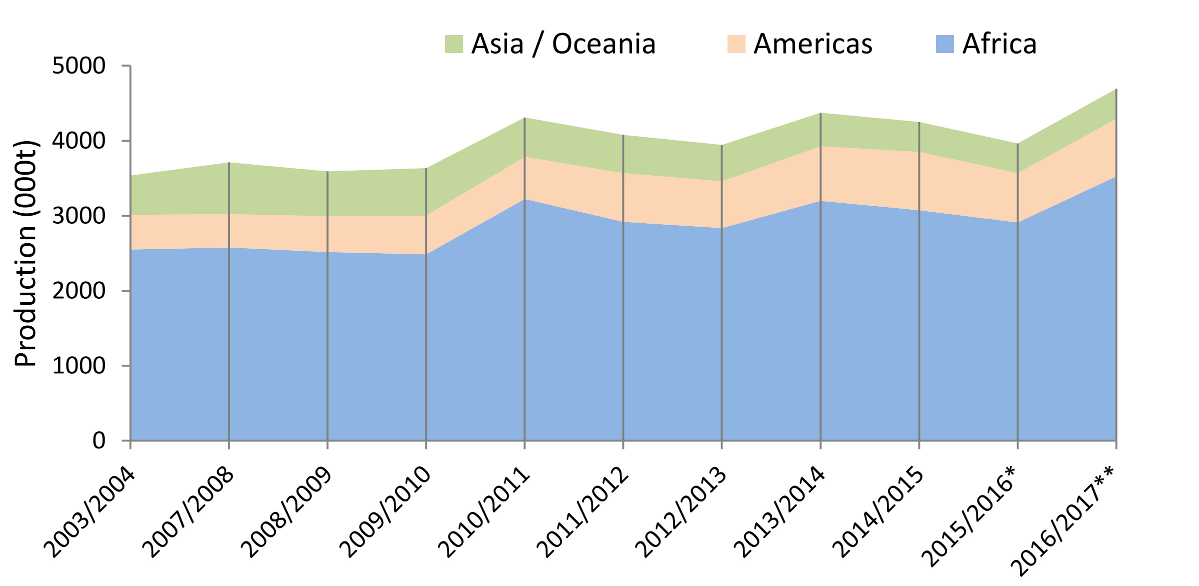

Fig. 1 Global cocoa production by region (ICCO 2017) *Estimate ** Forecast."

West Africa has been the leading global cocoa production region from the early 19th century (Wood & Lass, 1985) to present (Fig. 1). Cocoa in West Africa continues to play multifunctional role of serving as significant foreign exchange earner, supporting rural livelihoods and development (Fountain & Hütz-Adams, 2015). An estimated 2.5 million smallholder farm families in West Africa derive 70-100% of their household annual income from cocoa production (Gockowski *et al.*, 2004). Factors such as limited areas under cultivation, severe pest and diseases infestation and unfavourable political and market condition have resulted in intermittent declines in historical global cocoa production (ECOWAS-SWAC/OECD, 2007). Low yielding tree crop production systems are amongst the major drivers of deforestation in the humid tropics (Zomer *et al.*, 2016). Smallholder cocoa farmers especially in West Africa continue to record low yields of approximately 400 kg ha^{-1} which is less profitable (van Vliet and Giller, 2017). The leading cocoa producing countries of Ivory Coast and Ghana are facing enormous challenges meeting increasing global demand without deforestation (The World Bank, 2017; Vaast and Somarriba, 2014). Although certification is been implemented to ensure sustainable production, cocoa farming has been attributed to the most recent deforestation in the remaining rain forests of Ghana and Ivory Coast (Kroeger *et al.*, 2017). Increasing production through intensification (i.e. use of quality planting materials, higher inputs of labour, fertiliser, pest and disease management) has being proposed as the best option, but this requires soil conservation and knowledge of agroforestry skills to make it sustainable (ECOWAS-SWAC/OECD, 2007).

In addition to the existing production constraints, current and future global cocoa production is further threatened by climate variability and accelerating climate change. Most of the current cultivated areas especially in West Africa are projected to experience marginal climate by 2050 (Schroth *et al.*, 2016a). This is expected to push the production frontiers further to currently forested areas and therefore threatening the remaining few primary forest such as the Congo basin (Schroth *et al.*, 2016a). Cocoa production needs to be adapted to marginal and extreme climatic conditions characterized by intensive and prolonged drought (Abdulai *et al.*, 2017). Cocoa plants has been identified to be sensitive to soil water and climatic conditions (Abdulai et al. 2017; Carr and Lockwood, 2011). Understanding the existing characteristics of cocoa production systems and productivity at different climatic locations within the cocoa belt could help design proper adaptation pathways (Alvarez *et al.*, 2014). A key determinant of farming systems is the variation of agro-ecological zones in which the crops are cultivated (Giller *et al.*, 2011). The proposed use of shade tree cocoa agroforestry as a means of adaption to climate variability and change requires further research (Abdulai *et al.*, 2017). There is a distinct knowledge gap on the understanding of the cocoa plant physiology especially under marginal climatic conditions (De Almeida & Valle, 2007). In fact, very little physiological studies have been conducted in the last three decades (van Vliet and Giller, 2017).

1.2 Cocoa plant botany and productivity

Among the twenty-two species in the genus *Theobroma*, *Theobroma cacao* is the only globally cultivated species (Wood & Lass, 1985). The cultivated cocoa plant (Theobroma cacao L.) belongs to the family Malvaceae and originated from the Amazon region of South America (De Almeida & Valle, 2007). Three main genetic groups of Criollo, Forastero and Trinitario constitute cultivated cocoa varieties worldwide with Forastero being the most popular with an estimated 80% share of global cocoa bean production (De Almeida & Valle, 2007).

Fig. 2 Cocoa plants monitored from flowering to pod formation

Cocoa plant can reach a height of 20-25m when associated with other tree species under forest condition but only 10m under cultivation (van Vliet and Giller, 2017). Roots depth ranges from 0.8-1.5m with soil and nutrients uptake taking place at the top layers where much of the lateral roots are concentrated (van Vliet and Giller, 2017). Mature pods are formed in approximately four months after flowering (Fig. 2). Flowers are mostly pollinated by midge species. Cocoa cauliflorous plant, which means it produces most of the flowers and pods on the trunk (Toxopus, 1985). Pollination gap has been identified as a major limitation to yield as only 0.5 – 5% of flowers are usually pollinated (Wanger, 2014). The main pest and disease for cocoa in West Africa are mirids or capsids (*Sahlbergella singularis* and *Distantiella theobroma*), black pod disease caused by *Phytophthora palmivora* and *Phytophthora megakarya* and mealybugs transmitted cocoa swollen shoot virus (CSSV). Witches broom disease and frosty pod rot are common in the Americas with cocoa pod borer and vascular streak dieback in Asia (van Vliet and Giller, 2017).

1.3 Cocoa agroforestry as a sustainable production system

Agroforestry systems could play a multi-functional role in increasing the resilience of smallholder farmer livelihoods, helping farmers better adapt to climate change and even mitigate the impacts, conserve soil and biodiversity as well as other ecosystem services (Tscharntke *et al.*, 2011). Agroforestry is therefore promoted as an environmentally friendly and sustainable form of cocoa production, especially under vulnerable smallholder farmer conditions (Vaast et al., 2016; Tscharntke et al., 2011). The perceived productive potential of cocoa under diverse shade tree species is inspired by the fact that the species originated from the Amazon region in South America where it grows under multi species forest ecosystems (Wood & Lass, 1985). It has actually been reported that early cultivation by the Mayas was through agroforestry systems (De Almeida & Valle, 2007). Along a shade gradient, the highest yields were obtained from systems with little to no shade (Ahenkorah *et al.*, 1974), but such systems represent higher production risks due to a lack of diversification in livelihood outcomes as well as a higher use of external inputs that maybe too expensive for resource poor smallholder farmers (Tscharntke *et al.*, 2011). In agroforestry systems, high yield quality, minimum external inputs, better climate change adaptation, higher carbon stocks and more ecological services are perceived as great advantages over mono culture systems (Vaast & Somarriba, 2014).

For soils, shade trees in cocoa agroforestry systems are said to increase soil organic carbon and fertility through recycling nutriments from deeper soil horizons and making them available to cocoa plants via litter decomposition (van Vliet and Giller, 2017). There is also potential nitrogen availability improvement when leguminous shade trees are used in cocoa agroforestry system through both litter and root decomposition (Bai et al., 2017; Tscharntke et al., 2011; Beer et al., 1998). Leguminous shade tree species are even thought to have great potential for addressing the soil fertility needs of resource poor smallholder cocoa farmers (Tscharntke *et al.*, 2011). The scale of such positive effects has been found to be quite limited in space in recent studies and hence further investigation required (Blaser *et al.*, 2017; Wartenberg *et al.*, 2017).

A potential problem with shade tree cocoa agroforestry systems is the competition between the cocoa and the shade trees, which could be detrimental under water limited conditions (Abdulai et al., 2017; Beer, 1987). Some shade tree species have been shown to exhibit complementary soil water use characteristics with cocoa by sourcing water from deeper soil horizons while the cocoa depends on the upper soil layers (Niether et al., 2017; Schwendenmann et al., 2010). Positive above ground functions of shade trees in agroforestry systems include weed suppression, the reduction of evapotranspiration to conserve water, extreme temperature buffering for cocoa plants, rainfall interception to prevent run off erosion and the mitigation of some pests and diseases (Andres et al., 2017; Vaast and Somarriba, 2014; Beer, 1987). Cocoa agroforestry provides the best option for biodiversity conservation, as shade trees serve as a feed source and habitat for diverse mammals, birds, insects and amphibian species (Clough *et al.*, 2011). The pollination gap from reduced pollinator diversity in cocoa farms can be bridged through certain agroforestry practices (Toledo-Hernández et al., 2017; Wanger, 2014; Olschewski et al., 2010). Pollination enhancement has been identified as a viable option to significantly increase cocoa yields (Groeneveld *et al.*, 2010). Abundance in cocoa insect pollinators has been found to be associated with multi-species cocoa agroforestry systems (Frimpong *et al.*, 2011). Both climate and farmer management activities, such as intensive pesticide application and reduced shade tree species, have been associated with low pollinator diversity and density on cocoa fields (Forbes & Northfield, 2017; Arnold *et al.*, 2018).

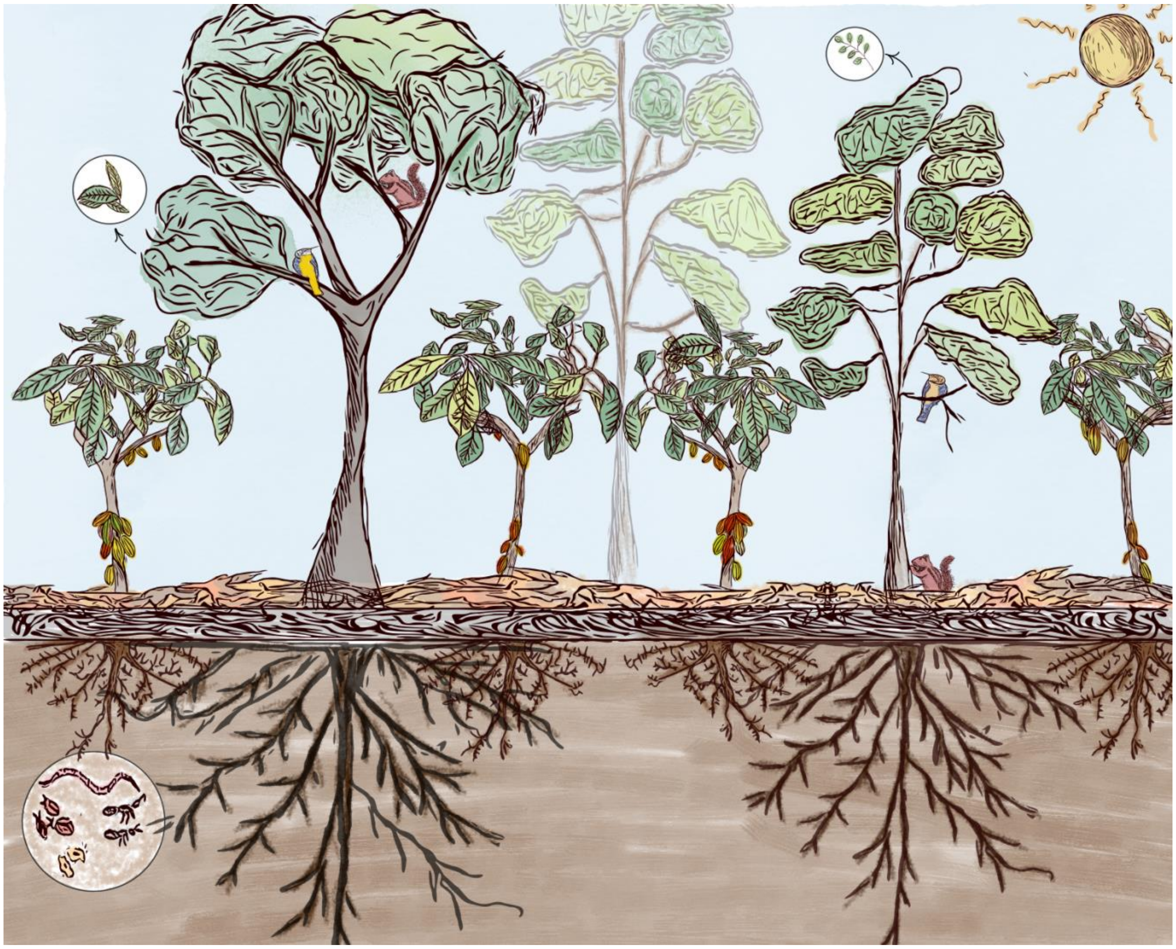

Fig. 3 Schematic view of ideal cocoa agroforestry system with cocoa and shade trees occupying different soil zones, diverse shade tree and animal species

There is a trade-off however between harvested cocoa yield and ecosystem functions when growing cocoa as an agroforestry system (Tscharntke *et al.*, 2011). The affinity toward yield maximization by farmers is high as there is presently no direct monetary benefit for the conservation of biodiversity on farms (Ruf, 2011; Tscharntke *et al.*, 2011). Designing a comprehensive cocoa agroforestry system (Fig. 3) requires in-depth knowledge of above and below ground shade tree species characteristics, such as soil water and nutrient use characteristics. Despite the perceived advantages, agroforestry systems can be management intensive and does result in a higher cost to the farmer (Blaser *et al.*, 2017). Reported biodiversity in cocoa agroforestry is usually lower than the adjacent forest stands but higher than other agricultural land use systems (Asare, 2006). A landscape approach of sparing highly diverse forests and the establishment of natural vegetation strips to serve as corridors has been proposed as an alternative to a multispecies cocoa agroforestry system (Blaser et al., 2017; Ruf, 2011; Wade et al., 2010).

In Ghana and the Ivory Coast, the choice of production system most commonly made by farmers still favours full sun systems in contrast the promoted agroforestry approach (Ruf, 2011). This has been attributed to the introduction of high yielding varieties that are better adapted to full sun conditions (Gockowski *et al.*, 2013). Diverse shade tree species in cocoa agroforestry systems is now common practice in Cameroon (Saj et al., 2017; Gockowski et al., 2004) where high production and biodiversity conservation are reported (Saj et al., 2017a; Asare, 2006).

Empirical data from cocoa agroforestry system studies are limited compared to other perennial tree crops such as coffee. The promotion of cocoa agroforestry as a sustainable farming system is mainly based on anecdotes. There is still a huge knowledge gap on which shade tree species improve and sustain pollinators and fauna biodiversity suitable for marginal climates with limited soil water and fertility. There is still a need for further studies, especially from Africa, the highest production region, to guide the design of ideal cocoa agroforestry systems that will be accepted by farmers.

1.4 Study aims and objectives

The overall aim of this thesis was to study cocoa productivity along climatic gradients, water use and microclimates in different cultivation systems under marginal climatic conditions. The different objectives are addressed in five chapters, which in turn have their own specific objectives. The first sections of the thesis (Chapter 2 and 3) involved a baseline survey and on-farm inventory data collection from 150 farmers and their farms along climatic gradients in Ghana. In Chapter 4, a water use and microclimate monitoring experiment on a farmer's field was conducted within a marginal climatic region for cocoa production. The third section (Chapter 5) involved monthly data collection that was carried out over the course of a year for a cocoa plant productivity assessment between high shade, medium shade and open sun systems along climatic gradients in Ghana. Below are the chapter titles as presented in either published manuscripts, under review or prepared for submission to peer review journal.

1. Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana (Chapter 2)

2. Variations in yield gaps and soil fertility along a climatic gradient in smallholder cocoa systems of Ghana (Chapter 3)

3. Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun (Chapter 4)

4. Cocoa plant productivity under shade tree agroforestry along climatic gradient in Ghana (Chapter 5)

1.5 Materials and methods

This study was carried out within the cocoa growing regions of Ghana along climatic and shade gradients. The study was conducted within the project "Trade-offs and synergies in climate change adaptation and mitigation in coffee and cocoa systems" funded by the BMZ. The University of Goettingen in collaboration with the International Institute of Tropical Agriculture (IITA) implemented the project. Data collection was undertaken in three phases.

Phase I: Cocoa cultivation systems characterization and yield gap study

In phase one, three locations along the climatic gradients categorized as dry, mid and wet regions were selected (Fig. 3). Akumadan and Afrancho communities in the Offinso North district of the Ashanti region were selected for the dry region. This region has experienced change in vegetation type from moist semi-deciduous to forest savanna, which, in part, are due to frequent fires that are influenced by the annual dry Harmattan winds (MOFA, 2017c; Adjei-Nsiah and Kermah, 2012). This region has a mean annual rainfall range of 700-1,200 mm and an average temperature range of 27 to 30°C (MOFA, 2017). The mid region communities were located around five surrounding villages of Goaso in the Asunafo North district of Brong Ahafo region with mean annual rainfall between 1,250 and1,750 mm and mean annual temperatures of around 25°C (MOFA, 2017).

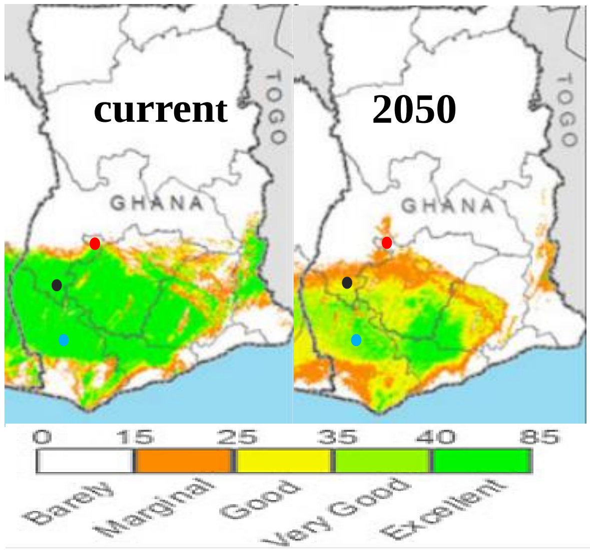

Fig. 3 Study locations with projected current and future climate suitability in Ghana (Läderach et al., 2013, page 848)

The current vegetation is classified as semi-deciduous forest (MOFA, 2017b). Subsequently, the wet region was located further south of the forest belt around five surrounding villages of Asankragua in the Amenfi West district of the Western region of Ghana. The mean annual rainfall is about 1400 in the Northern part and 1700-2000 mm in the South with temperatures ranging between 27 and 30°C (MOFA, 2017c). The vegetation is classified as a moist evergreen forest type (Hall & Swaine, 1976). The soils of the dry and mid regions are Acrisols and Alfisols classified as highly suitable for cocoa cultivation (Anim-Kwapong & Frimpong, 2004). The wet region is dominated by highly weathered and acidic Acrisols, Alfisols and Oxisols and has been classified as unsuitable for cocoa cultivation unless fertilizers are applied. Nonetheless, the region holds patches of remnant forestlands and has supported cocoa expansion for decades and as a result has become the leading production region in Ghana since 1984/85 (Figure 1) (Cocobod, 2017; Anim-Kwapong and Frimpong, 2004). Currently, the dry region is characterized by sub-optimal climatic conditions for cocoa cultivation while the mid and wet regions are considered optimal (Läderach et al., 2013). According to Läderach et al. (2013), the dry region is projected to be climatically unsuitable by 2050, whilst the mid and wet regions become sub-optimal and stay optimal, respectively.

Farmers from the dry and mid regions were randomly selected from the database of the Kuapa Kokoo farmers' cooperative union, which is the largest cocoa farmers union in Ghana and the world's largest producer of Fairtrade certified cocoa beans (Donovan *et al.*, 2016). In the wet region, farmers were selected from the Rainforest Alliance certification database managed by AgroEco-Louis Bolk Institute (AE-LBI) in the Western region of Ghana.

Fig. 4 Farmer interviews, soil sampling and cocoa farm inventory (left to right respectively)

Baseline data on farmer cocoa production and management activities were collected through interviews and on-farm inventories from 50 farmers and their farms per location (Fig. 4). The interviews and on-farm inventories were undertaken from April to September 2014. The interviews concentrated on assessing the impact of drought as perceived by farmers and its effect on cocoa production, income diversification and management activities on cocoa farms. Soil samples for nutrient analysis were also taken during the field inventories. Data was collected on shade tree species diversity, density and mode of regeneration on farmer's fields. The information on the shade tree canopy cover, species diversity and density were used to characterize existing cocoa agroforestry systems practised by farmers (Fig. 5).

Fig. 5 Medium and low shade (left to right) cocoa agroforestry systems identified in Ghana

Phase II: Water use and microclimate experiment

Water availability plays an important role in the productivity of cocoa systems. This study aimed to identify systems with efficient water use and how cocoa responds to water stress and compete with non-cocoa trees for water. The northernmost location with relatively little rainfall, characterized as a marginal cocoa climate region (Läderach *et al.*, 2013), was selected for soil water and microclimate measurements. The experiment was conducted on 10 year old cocoa plants on farmer field. Cocoa plants growing under four randomly distributed individual shade tree species of *Antiaris toxicaria* (Kyenkyen) and *Albizia ferrugenia* (Awiemfosamina) were studied (Fig. 7, Table S2c).

Antiaris toxicaria is the most common shade tree species in farmers' fields in the region after fruit trees (Citrus sinensis and Persea Americana according to Graefe et al. (2017)), whereas *A. ferruginea* is less abundant but recommended as a suitable shade tree species for cocoa cultivation due to its leguminous nature and other beneficial properties (Manu and Tetteh, 1987). The canopy dripline of the shade trees forms the boundary of the shaded plots (Fig. 6). Measurements on the shade systems were capered to adjacent no shade plots of 51m^2. The total plot size of Cocoa-Antiaris and Cocoa-Albizia were 33 and 68 m^2, respectively (Table S2a). The experiment lasted from November 2014 to March 2016. An extreme event characterized by a heat-wave combined with a severe dry season lasting longer than usual occurred as a result of the 2015/16 El Nino event. This allowed for the evaluation of cocoa plant resilience under the different systems.

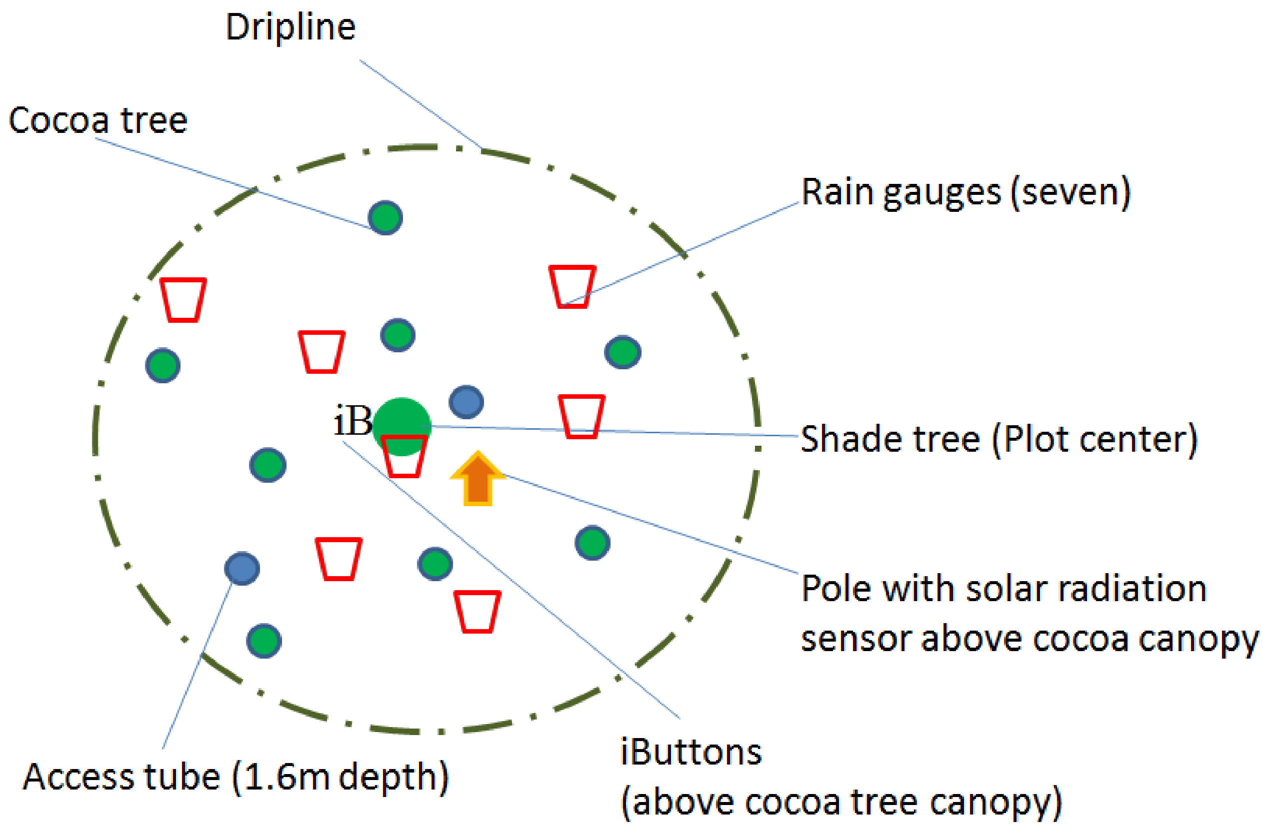

Fig. 6 Schematic view of studied sap flow plot

One soil profile (pit of 1 x 1.6m deep) was dug under each system for further characterization at deeper horizons (Table S2b). General shade and cocoa tree characteristics, such as diameter at breast height (DBH), height, cocoa tree density and the mortality percentage of cocoa trees after the extended drought period were recorded (Table 3). Soil nutrient characteristics for the top 30 cm were measured for all plots (Table S2b). All studied cocoa plants were of the same variety and commonly referred to as "hybrid" and supplied to farmers by the Seed Production Division (SPD) of the Ghana Cocoa Board (COCOBOD).

Table 1. Soil (top 30cm) and plot characteristics of the studied systems (mean with SD in brackets, n = 4). Threshold values for cocoa soil nutrient requirement adapted from Ahenkorah (1981)

Parameter	Cocoa Antiaris	Cocoa Albizia	Full sun cocoa	Thresholds in Ghana
pH	5.60 ±0.05	5.80 ±0.29	5.5 ±0.24	5.6-7.2
Total N (%)	0.11 ±0.02)	0.13 (0.02)	0.11 (0.03)	0.09
C (%)	1.22 (0.15)	1.45 (0.21)	1.29 (0.24)	2.03
Available P (µg /g)	3.13 (0.58)	7.18 (1.41)	3.25 (0.70)	20
K+ (µg /g)	0.09 (0.01)	0.11 (0.03)	0.10 (0.01)	0.25
Mg2+ (µg /g)	1.94 (0.67)	2.74 (0.96)	2.21 (0.55)	1.33
Ca2+ (µg /g)	4.21 (1.08)	6.41 (1.43)	4.74 (1.39)	7.5
Zn2+ (mg / kg)	1.15 (0.48)	1.63 (0.72)	0.83(0.12)	1.33
Cu2+ (mg / kg)	1.34 (0.28)	1.93 (0.75)	1.65 (0.12)	1.33
Fe2+ (mg / kg)	6.29 (1.05)	10.71 (4.68)	6.83 (1.75)	1.33
% Sand	49.5 (5.82)	50.5 (4.90)	46.6 (3.18)	
% Silt	36.8 (6.38)	33.8 (5.60)	37.3 (1.95)	
% Clay	13.7 (0.96)	15.7 (2.41)	16.1 (2.58)	
% OM	2.10 (0.26)	2.50 (0.36)	2.22 (0.42)	
ECEC (cmolc/kg)	6.77 (1.44)	9.68 (1.83)	7.66 (1.79)	
Available K ppm	30.41 (4.58)	38.25 (8.87)	36.81 (5.81)	
		Throughfall (%)		
<10mm rainfall	69.9 (20.3)	63.0 (15.4)	73.8(18.8)	
Total rainfall	75.9 (15.6)	69.9 (14.3)	72.5 (14.0)	
		Plot characteristics		
Plot area m^2	33	68	51	
Shade tree DBH 2014(cm)	25.2	23.8		
Shade tree DBH 2016(cm)	28	26.6		
Cocoa tree DBH 2014(cm)	9.45	9.73	11.16	
Cocoa tree DBH 2016(cm)	10.14	10.31	12.21	
Shade tree height 2014(m)	11.3	11.6		
Cocoa plant density ha^{-1}	1274	1537	1543	
Cocoa tree mortality (%)	77	100	12	

Fig. 7 Studied shade tree species *Antiaris toxicaria* (left) and *Albizia ferrugenia* (right)

Table 2. Soil properties from soil profile, one pit for each studied system

System	Depth (cm)	Texture	Bulk density (g cm^{-3})	Organic carbon (%)	Total nitrogen (%)	ECEC (cmolc kg^{-1})	pH
Cocoa-Antiaris	10	Sandy Loam	1.29	1.35	0.13	11.89	5.8
	50	Sandy Loam	1.65	0.29	0.03	4.82	5.3
	100	Clay Loam	1.62	0.26	0.02	5.19	4.6
	150	Clay Loam		0.14	0.01	3.98	4.2
Cocoa-Albizia	10	Loam	1.21	1.00	0.09	12.77	6.7
	50	Loam	1.63	0.35	0.03	4.76	6.4
	100	Clay Loam	1.67	0.32	0.03	5.37	4.4
	150	Clay Loam		0.29	0.02	5.09	4.2
Full sun cocoa	10	Sandy Loam	1.40	1.00	0.08	12.5	5.9
	50	Sandy Loam	1.73	0.23	0.02	4.71	5.2
	100	Sandy Loam	1.76	0.08	0.01	4.59	5.4
	150	Sandy Clay Loam		0.08	0.01	4.79	4.3

Table 3. Characteristics of and differences between the two studied shade tree species (Oteng-Amoako, 2006; ICRAF, 2016). NB: both are native species.

Characteristics	*Albizia ferruginea*	*Antiaris toxicaria*
Family	- Mimosaceae	- Moraceae
Phenology	- Brevi-deciduous - Strong light demander	- Brevi-deciduous - Light demander
Habitat	- Lowland semi-deciduous and evergreen forest	- Wettest to dry forests of wooded grassland
Soil improvement characteristics	- Roots develop nitrogen-fixing nodules - Highly mycorrhizal dependent - Leaf litter improving surrounding soil quality	- Leaf litter enriches surrounding soil
Economic use	- Timber for construction, furniture, veneer charcoal and medicinal	- Timber and veneer
Crown	- Crown dome-shaped and heavily branched	- Good self-pruning ability
Usage for cocoa	- Cocoa Research Institute of Ghana (CRIG) recommended shade tree species for cocoa	- Most common on farmer field

Data on temperature and relative humidity were recorded at 30 minute intervals with iButton® technology (DS1923 Hygrochron Temperature and Humidity Data Logger). Quantum sensors (SOLEMSPAR-CBE80, Palaiseau, France) calibrated with LI- 250A Light Meter was used to measure solar radiation. Gross rainfall (GR) was measured with a tipping bucket gauge (Model ARG 100; Campbell Scientific Inc., Logan, UT, USA). Solar radiation sensors and tipping bucket rain gauges were connected to a data logger (CR1000 Campbell Scientific Inc.). Throughfall (net-rainfall reaching the soil below the canopy) was measured from February to November 2015 using a combination of standard rain gauges (diameter 11.5 cm) and home-made rain gauges (1l plastic bottles with 14.5 cm diameter funnels). Seven rain gauges per shade plot were installed and 28 rain gauges in the full-sun plots; water content was measured within 24 hours of any rain event. Volumetric soil water content was measured bi-weekly up to a depth of 150 cm at 10 cm intervals with a Diviner 2000 (Sentek Pty Ltd, Australia). Four PVC access tubes were installed in each system.

Thermal dissipation probes after Granier (1987) were applied to continuously measure sap flux density in cocoa and shade trees over the study period. The concept and functioning of the sap flow sensors follows the description of Köhler (2010). Sap flux density was measured for the selected shade trees and two cocoa trees within their canopies. In the full-sun treatment, four cocoa trees were measured. The sensors were inserted into holes drilled at a height of 1.3 m in the shade trees, and 1 m in cocoa trees (Figure 8). Sensors were shielded from incident radiation and thermal influences by reflective foil and covered with plastic foil to protect against rainfall.

Fig. 8 Granier sap flux sensors installed on cocoa and shade trees

The upper probe of the sensors was heated at a constant power of 2.50 mV, which was generated using a solar energy system. Voltage difference between the upper and lower probes of each sensor was measured every 30 seconds, averaged and logged at 30 minute intervals using a data logger with a multiplexer attached (Campbell CR1000, AM 16/32). Recorded voltages were converted into temperature differences, with which sap flux density was calculated according to the empirically derived equation of Granier (1987).

Hourly (g cm^{-2} hr^{-1}) and daily (g cm^{-2} day^{-1}) sap flux densities were calculated for every cocoa and shade tree measured. Daily sap flux data was recorded as the mean of at least three functional sensors. However, there were days in the wet period without data due sensor breakdown resulting in less than three functional sensors. Tree water use rates (l/day) were calculated after the equation of Granier (1987). This used the conductive sap wood area that was determined by microscopic analysis of core samples obtained with incremental borers and collected wood discs from cocoa and shade trees.

Phase III: Cocoa plant productivity along shade and climatic gradients

Following the characterization of the cocoa agroforestry systems, nine plots were selected at each region for a whole year and assessed monthly for cocoa plant productivity. Three shade categories of open sun, medium and high shade was studied. Open sun, medium shade and high shade plots had mean plot shade tree canopy cover percentages of 34, 19 and 9% for the dry, 34, 13 and 9% for the mid, and 32, 12 and 8% for the wet, respectively. Twenty cocoa trees per plot were selected and tagged a (total of 540 cocoa trees) for monthly monitoring. Temperature and relative humidity were also monitored on two open sun and high shade plots per location with iButtons. Management activities such as weeding, fertilizer, pesticide and fungicide applications by farmers on the entire plots were also recorded. The cocoa plant productivity indicators measured were flowering, immature fruits (cherrels), pest and disease infected cherrels and the harvested pods.

1.6 Outline of the thesis

This thesis is subdivided into five studies listed in section 1.3. These chapters are presented as published, submitted or advanced manuscripts to be submitted to peer-review journals.

CHAPTER 2:

Characterization of cocoa production, income diversification and shade tree management along climate gradient in Ghana

In this chapter, existing cocoa production and income diversification between dry, mid and wet regions were compared. Shade trees in cocoa agroforestry systems and their distribution along the climatic gradient was further evaluated. This chapter is published in *Plos One* .

CHAPTER 3:

Variations in yield gaps and soil fertility in smallholder cocoa systems along a climatic gradient in Ghana

In this chapter, yield gap and soil fertility status were assessed between regions denoted as dry, mid and wet, representing a climatic gradient in Ghana. Factors co-determining yield gap and soil organic carbon (SOC) were assessed with three-years of yield data (of 2012/13, 2013/14 and 2014/15) and soil properties analysed from samples taken from the top 30 cm in 150 farms. This chapter is submitted (under review) at *European Journal of Agronomy*: a peer-review journal.

CHAPTER 4:

Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun

Here, the resilience of cocoa under agroforestry and full sun was tested over wet, dry and extremely dry periods. Cocoa in full sun was compared with agroforestry systems: shaded by (i) a leguminous tree species, Albizia ferruginea and (ii) Antiaris toxicaria, the most common shade tree species in the region. This Chapter and a response letter are published in the journal *Global Change Biology*.

CHAPTER 5:

Cocoa plant productivity under different climatic and shade conditions

Cocoa tree productivity in terms of flowering intensity, fruiting (Cherrels count), harvested pod, pest and diseases damaged cherrels and pods was studied between shade systems along climatic gradient. Data was collected once per month for a whole year. Cocoa tree productivity especially harvested pods was highly influenced by climatic regions. This chapter is presented as an advanced manuscript and to be submitted to *Agriculture Ecosystem and Environment* peer-review journal.

Additional publication from work conducted in the framework of this thesis

Additional publication, to which the author of this thesis substantially contributed within the framework of the BMZ funded project “Trade-offs and synergies in climate change adaptation and mitigation in coffee and cocoa systems”:

Evaluating Farmers’ Knowledge of Shade Trees in Different Cocoa Agro-Ecological Zones in Ghana

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Chapter Two

Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana

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2.1 Abstract

Reduced climatic suitability due to climate change in cocoa growing regions of Ghana is expected in the coming decades. This threatens farmers' livelihood and the cocoa sector. Climate change adaptation requires an improved understanding of existing cocoa production systems and farmers' coping strategies. This study characterized current cocoa production, income diversification and shade tree management along a climate gradient within the cocoa belt of Ghana. The objectives were to 1) compare existing production and income diversification between dry, mid and wet climatic regions, and 2) identify shade trees in cocoa agroforestry systems and their distribution along the climatic gradient. Our results showed that current mean cocoa yield level of 288kg $ha^{-1}yr^{-1}$ in the dry region was significantly lower than in the mid and wet regions with mean yields of 712 and 849 kg ha^{-1} yr^{-1}, respectively. In the dry region, farmers diversified their income sources with non-cocoa crops and off-farm activities while farmers at the mid and wet regions mainly depended on cocoa (over 80% of annual income). Two shade systems classified as medium and low shade cocoa agroforestry systems were identified across the studied regions. The medium shade system was more abundant in the dry region and associated to adaptation to marginal climatic conditions. The low shade system showed significantly higher yield in the wet region but no difference was observed between the mid and dry regions. This study highlights the need for optimum shade level recommendation to be climatic region specific.

Keywords Agroforestry**,** Climate change, Cocoa, Income diversification, Marginal climate, Shade trees

2.2 Introduction

Ghana is the second largest global cocoa producer with an estimated US$ 2 billion generated by export revenues in 2013 (WTO, 2014). Cocoa is the main agriculture export product and sustains the livelihood of more than 800,000 small-scale households across the cocoa growing region of the country (Anim-Kwapong and Frimpong, 2004; FAO, 2015). Over two million cocoa farmers across the West African sub-region are vulnerable to climate change (Schroth et al., 2016). Drought is traditionally one of the key climate change effects expected to negatively affect agricultural production (Sheffield and Wood, 2008). The cocoa landscape in Ghana has experienced a latitudinal shift since early 1980s with more than half of current national cocoa production coming from the climatically more suitable areas of the Southwestern region that harbour remnants of the rainforest (Anim-Kwapong and Frimpong, 2004; Noponen et al., 2014). The relatively marginal areas of Northern Ashanti and Brong Ahafo regions used to exhibit good climate suitability and produced more cocoa than the Western region prior to the extreme climate events in 1983/4 that resulted in severe drought and wildfires (Adjei-Nsiah and Kermah, 2012; Anim-Kwapong and Frimpong, 2004). Cote d’Ivoire, the world largest cocoa producer, has also experienced a similar shift with such extreme climate event being a contributing factor to geographic shifts in production areas (Ruf et al., 2015). Such spatial and temporal variations in climatic events allow for the identification of farmers responses to climate change (Ruf et al., 2015; Schroth et al., 2017, 2016). An increase in dry season maximum temperatures together with seasonal droughts are the main projected impacts of climate change within the West African cocoa belt (Asante and Amuakwa-Mensah, 2014; Läderach et al., 2013; Schroth et al., 2016). The variability in current climatic conditions within the cocoa belt of Ghana and Cote d’Ivoire has resulted in different levels of climate suitability (Läderach et al., 2013). Different types of climate change adaptation including incremental, systemic and transformative adaptation would be required at different locations within the cocoa belt of West Africa depending on the projected climatic changes (Schroth et al., 2017). Good to very good cocoa climate suitability is projected to continue shifting cocoa production to the more wet forest regions by 2050 (Läderach et al., 2013; Schroth et al., 2017, 2016). A lack of available forest land for new cocoa farms in the wet regions and the potentially negative effects of climate change are foreseen as being part of the major constraints to sustainable production growth in the coming years (Damnyag et al., 2013; Vaast and Somarriba, 2014).

There is a need to increase the adoption of climate smart technologies in cocoa to sustain its production (Noponen et al., 2014; Vaast et al., 2016). Understanding the existing characteristics of cocoa production, perceived climate change and drought effects, income diversification and management of shade trees in cocoa growing systems in different climatic regions within the cocoa belt should be the first step toward the design of promising adaptation pathways (Alvarez et al., 2014). Knowledge of existing cocoa agroforestry systems is important in developing interventions and tools to aid farmers with proper management strategies. A key determinant of farming systems is the variation of agro-ecological zones in which the crops are cultivated (Giller et al., 2011) and hence characterizing cocoa production systems along a climatic gradient becomes justified. Characterization of shade tree species in cocoa growing systems is an important component of the identification of existing systems (Andersen et al., 2007). This could support location and system specific adaptation since agro-ecological zones for cocoa are being altered by changing climatic conditions, especially in areas close to the forest-savannah transition zones (Schroth et al., 2016). In the context of climate change, shaded cocoa systems have been identified as an appropriate strategy for increasing resilience and improving agro-ecosystem functioning at plant, plot and landscape levels (Asare et al., 2014; Bisseleua Daghela et al., 2013; Damnyag et al., 2013; Läderach et al., 2013; Tscharntke et al., 2011; Vaast and Somarriba, 2014; Waldron et al., 2014). Although potential soil water competition between shade and cocoa trees in cocoa agroforestry systems have been noted as a potential limitation under marginal cocoa climate (Abdulai et al., 2018). Lower yields have also been reported for agroforestry systems under relatively lower rainfall locations in the Ashanti region of Ghana (Asare et al., 2017; Blaser et al., 2017), this could be compensated via income diversification. Consequently, the documentation of agroforestry systems distribution between agro-ecological zones is a necessary step towards identifying and optimizing climate change adaptation strategies.

The aim of this study was to characterize cocoa production, perceived climate change effect on cocoa production, income diversification and shade tree management in cocoa growing systems along a climate gradient in Ghana. The studied locations represented areas with projected future (2050) climatic suitability of medium to high, low to medium and low to non-suitable from the wet to the dry region respectively (Läderach et al., 2013). The first objective was to compare the regions in terms of (a) current cocoa production, (b) farmers' perception on the effects of climate change and drought on cocoa production, and (c) cocoa farmers' income diversification.

Ultimately, our second objective was (a) to document the presence of shade tree species and their functions and (b) to characterize the existing cocoa agroforestry systems and their distribution along the climatic gradient. These objectives were based on the assumptions that location along a climate gradient greatly influences cocoa production, cocoa farmer income diversification and type of shade tree management by farmers.

2.3 Materials and methods

Study area

The study was conducted in three regions within the cocoa belt of Ghana along a climatic gradient represented as dry, mid and wet (Fig 1). The dry region was Akumadan and Afrancho communities in the Offinso North district of the Ashanti region. The vegetation here used to be semi-deciduous but has changed to a forest savanna due to frequent fires and extensive agricultural practices (MOFA, 2017a). The region has an extended dry period from November to March, during which wildfires are common and occasionally destroy farms (Amisah et al., 2010). This region is well known for tomato production, and recently also for cassava and maize (MOFA, 2017a). Cashew is a developing tree crop in this region, and may potentially replace cocoa due to increasing pronounced savanna conditions in this region. The mid region comprised selected communities around Goaso in the Asunafo North district of the Brong Ahafo region. The wet region consisted of communities surrounding Asankragua in the Wassa Amenfi West district of the Western region (Fig 1). The mid and wet regions are within the moist semi-deciduous and the moist evergreen vegetation types (Taylor, 1960). In these regions, the dry season lasts from November to February and relative humidity increases towards the south (Anim-Kwapong and Frimpong, 2004).

The gradient is characterized by annual rainfall of 700-1200 mm in the dry region, 1250-1750 mm in the mid region, and 1400-2000 mm in the wet region (MOFA, 2017a, 2017b, 2017c). Mean temperature variation is less pronounced, with 27, 25 and 26 °C from dry to wet respectively.

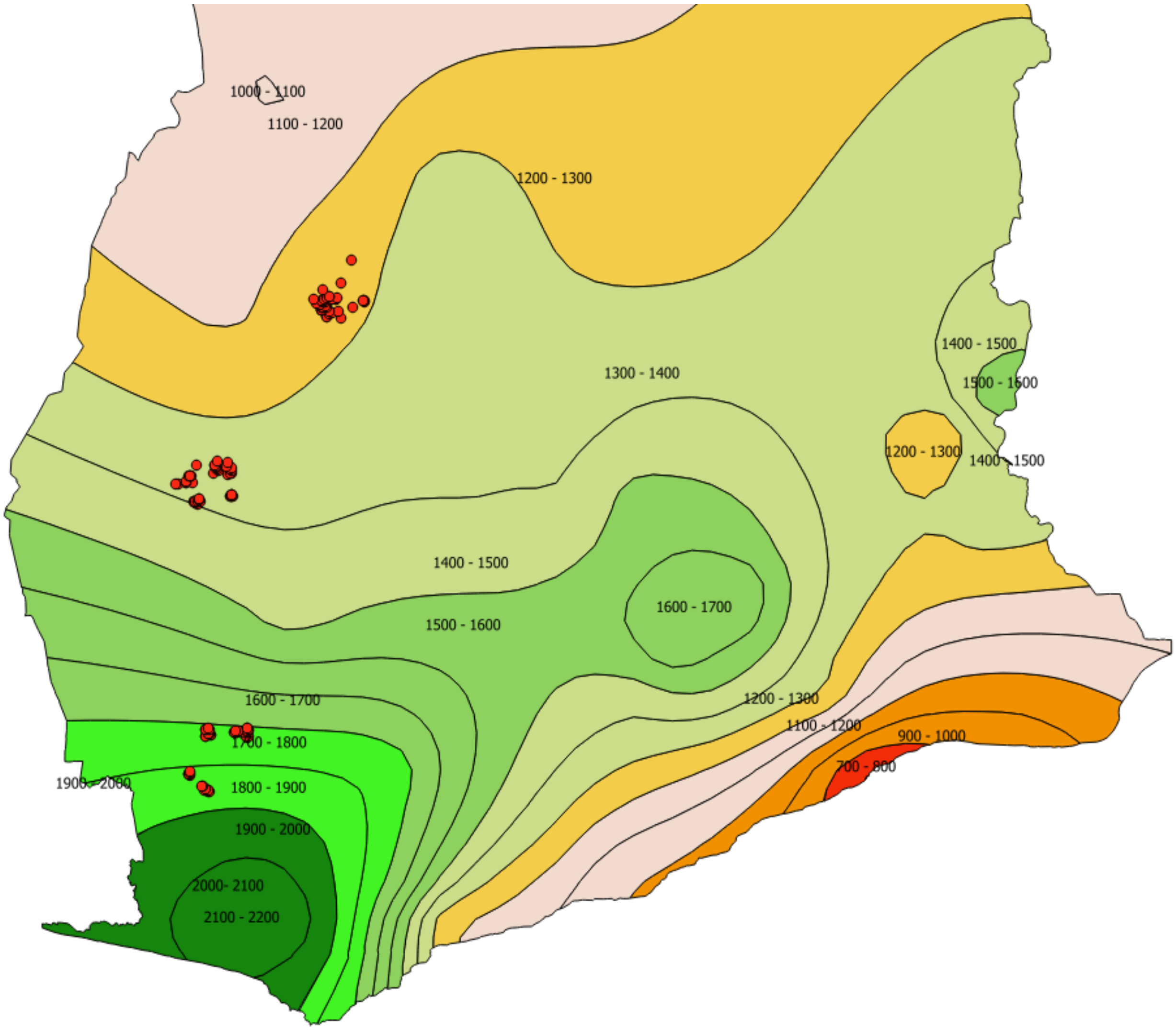

Fig 1 Mean annual rainfall distribution (mm) across Southern Ghana with GPS points of studied sites marked with red dots, representing the dry, mid and wet regions from North to South. Rainfall distribution map of Ghana accessed from (Volta Basin Authority, 2017). Available in public domain

Sampling and data collection

Data collection took place from April to September 2014 with fifty (50) cocoa farmers selected per region for interviews and on-farm inventories. Farmers from the dry and mid regions were randomly selected from a database of the Kuapa Kokoo Farmers'union, which has about 100,000 farmers across Ghana selling Fair Trade certified cocoa. The union combines two administrative districts of Offinso North and South as one cocoa purchasing district referred to as Offinso. A total of 1814 farmers were listed in the Offinso database, but only 261 belonging to Akumadan and Afrancho in the northernmost part were selected for our study. For the mid region, the database consisted of 954 farmers out of which fifty (50) were randomly selected. For the wet region, 50 farmers were randomly selected from 1800 farmers listed in the Rainforest Alliance database managed by Agro-Eco Louis Bolk Institute (LBI).

Farmers were interviewed about household characteristics, perceived climate change and drought effects on cocoa production and income diversification strategies by using a digitized questionnaire on smart phones, which allowed data to be stored in an online database. The questionnaire covered topics such as farmer age, household size, and number of cocoa farms owned by farmers, cocoa farm size, source of planting material and cocoa farm age for both mature and young cocoa farms i.e. cocoa farms above and below 5 years respectively. From the survey, the number of farmers with young cocoa farms were 39, 26 and 35 for the dry, mid and wet regions, respectively, and hence a total of 100 respondents. Information on cocoa farm land use history was obtained to help understand changes in cocoa land availability. Farmers were further asked about quantity of dry cocoa beans (yield) produced in the 2012/13 cocoa season, which was cross-checked with their sales record books. Drought related production constraints, income distribution between cocoa, non-cocoa crops and off-farm income activities were also documented. Cocoa farm management activities such as labor cost, fertilizer, fungicide and pesticide usage were also noted.

On-farm inventories were carried out on mature cocoa farms of each farmer. In instances where a farmer had more than one mature farm, one farm (of interest) was randomly selected for inventory. Data was collected on the number of shade trees, species identity, diameter at breast height (DBH), shade tree canopy cover and mode of regeneration through a complete inventory of the entire farm. DBH was measured with a diameter tape, and canopy area was calculated by measuring the longest and shortest canopy lengths with a 30m tape. The canopy cover estimation was later validated with shade tree canopy and DBH relationships established by Asare and Ræbild (Asare and Ræbild, 2015). Farm size was measured with Garmin GPS equipment. Cocoa tree density, and pest and disease incidence were measured at the cocoa farm center on a fixed area transects of 40 m with cocoa trees selected within 10 m perpendicular distance and at 10m interval as proposed by Nath et al. (Nath et al., 2009). Incidence of black pod (*Phytophthora palmivora and P. megakarya*) and capsids (*Sahlbergella singularis* and *Distantiella theobroma)* was assessed on the cocoa trees within the established transect. Total number of both mature and immature (cherrels) cocoa pods were counted on the cocoa trees within the sampled transect. Black pod and capsid infected pods were harvested and counted. The black pod and capsid incidence per farm were then expressed as the percentage of infected pods to total pods counted per tree.

Data analysis

Statistical analysis to assess variation in cocoa production along the climatic gradient was performed with Statistica software. Descriptive statistics and ANOVA were applied to analyze farm characteristics between regions. This was followed by a k means cluster analysis to identify clusters representing the various cocoa agroforestry systems. Statistical differences with respect to yield, shade parameters, management, pest and diseases were compared between the identified agroforestry systems in each region. Box plots were used to show the differences between the systems across regions. For identification of cocoa agroforestry systems through cluster analysis, a total of 142 of the 150 inventoried cocoa farms (due to removal of 8 outliers) were used with 45, 49 and 48 in the dry, mid and wet locations, respectively. Out of the150 farmers, 39, 26 and 35 also had young cocoa farms (< 5 years) for the dry, mid and wet regions, respectively.

2.4 Results

Cocoa production, income diversification and perceived negative effects of climate change and drought on cocoa production

For the 2012/13 crop season, yield in the dry region was significantly lower than the mid and wet regions with mean cocoa yields of 288, 712 and 849 kg ha^{-1} yr^{-1}, respectively. The age of cocoa farmers decreased from dry to mid and wet regions, with significant difference between the dry and wet regions. This trend was positively correlated with household size, as old farmers had significantly larger family sizes. Differences in cocoa farm age were surprisingly not pronounced across the regions, but farm size was significantly larger in the mid region.

The regions were differentiated by the cocoa farm land use history (Fig 2) with the dry region dominated by farms having been previously used for cocoa, but with a short fallow combined with annual crops such as maize and vegetables in-between cocoa cycles. The mid and wet regions had common characteristics, having been converted from primary and secondary forests. Expectedly, the highest proportion of mature cocoa farms established after deforestation of primary forest was noted in the wet region where the most recent cocoa expansion has occurred.

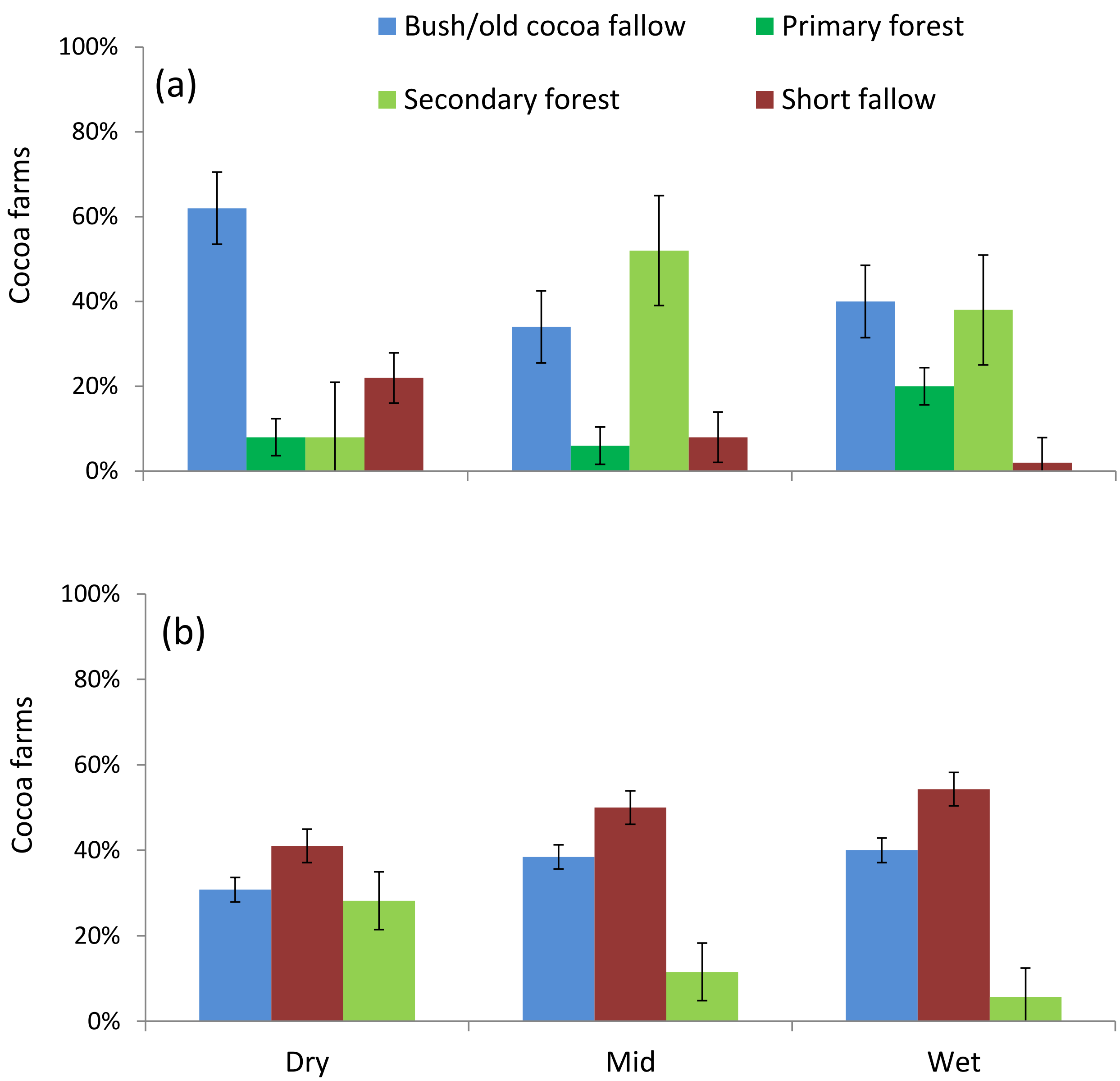

Fig 2 Land use history of (a) mature and (b) young (less than 5 year old) cocoa farms along a climatic gradient from dry to mid and wet regions of Ghana. N=50 per region for mature farms. For young farms, N=39, 26 and 35 for dry, mid and wet regions respectively.

The size of young cocoa farms (< 5 years) was significantly smaller in the wet than the mid and dry regions. The differences in size between young and mature farms per region were not significant. None of the young cocoa farms (Fig 2b) were established on primary forest as all remaining forests are under protection. Planting material was in the form of cocoa seedlings or pods, with the source being either hybrid from the Seed Production Unit (SPU) of the Ghana Cocoa Board (COCOBOD), or from farmers' own selections. The use of the SPU seedlings was less widespread in the wet region (Table 1).

Table 1. Characteristics of cocoa production along a climatic gradient from dry to mid and wet regions in Ghana (Superscript letters denote significant differences between regions at $p \leq 0.05$) and no letters for variables without difference between the regions.

Location	Dry			Mid			Wet		
Mature farms	Mean±SD	Min.	Max.	Mean±SD.	Min.	Max.	Mean±SD	Min.	Max.
Farmer age (yrs)	$64^{a} \pm 19$	32	100	$54^{ab} \pm 14$	26	90	$47^{bc} \pm 11$	25	71
Household members	$11^{a} \pm 8$	1.0	42	$7^{b} \pm 3$	1	21	$8^{b} \pm 3$	1	16
Number of cocoa farms per farmer	2 ±0.4	1.0	3.0	2±0.9	1.0	5.0	3±1.3	1.0	7.0
Cocoa farm size (ha)	$1.7^{a} \pm 2.2$	0.4	16	$5.7^{b} \pm 7$	0.8	40	$2.16^{a} \pm 1.7$	0.3	8.0
Yield (ha^{-1} yr^{-1})	$282^{b} \pm 232$	14	975	$712^{a} \pm 303$	177	1387	$849^{a} \pm 327$	338	1484
Cocoa farm age (yrs)	17 ±11	6	50	21±8	5	40	16.4±8.9	5	48
Young cocoa farms									
Farmer age (yrs)	$64^{a} \pm 21$	32	100	$53^{ab} \pm 12$	27	80	$46^{bc} \pm 10$	25	67
Farm size (ha)	$2.1^{a} \pm 2.8$	0.2	16.0	$2.3^{a} \pm 2.5$	0.4	12.0	$1.0^{b} \pm 0.7$	0.1	3.6
Source of planting material									
Hybrid seedlings (%)	70±40	0.0	100	50±50	0.0	100	40±50	0.0	100
Farmer selected seedlings (%)	30 ±40	0.0	100	50±50	0.0	100	60±50	0.0	100

Farmer's perception of drought effect on cocoa production varied across regions. The perceived effects were a yield decrease, an increase in pests and diseases incidence and decrease in pod and bean quality with fire being an additional burden in the dry region (Fig 3). A yield decrease was the most often perceived effect of drought on cocoa production in all regions, but it was more often stated by farmers as such in the dry and mid regions compared to the wet region. Pests and diseases followed a similar trend but on a much lower scale. A decrease of cocoa quality was also perceived by about 25% of the farmers in the dry and mid regions. Cocoa farmers in the dry region derived their annual income from 50% cocoa sales, 30% non-cocoa crops sales and 20% through off-farm income activities such as trading (Fig 4). Farmers in the mid and wet regions derived approximately 80% of their annual income from cocoa and 10% each for non-cocoa crops and off-farm income activities (Fig 4).

Characterization of existing shade trees and their functions along the climatic gradient

Shade tree density, diversity and percentage shade cover were significantly higher in the dry than in the mid and wet regions (Table 2). The most common shade tree species in the dry and mid regions was avocado (*Persea Americana*) fruit tree, whereas a timber species, *Terminalia superba*, was the most common shade tree species in the wet region (Table 2). In the dry region, apart from *Antiaris toxicaria*, other most common species were two fruit trees, i.e. *P. americana* and *Citrus sinensis. Newbouldia laevis*, mainly used as live stakes for yam (*Dioscorea* spp), was the second most abundant species in the mid and wet regions (Table 2). The Cocoa Research Institute of Ghana (CRIG) has listed eight desirable and ten undesirable shade tree species for cocoa cultivation in Ghana (Asare, 2005). Among the top fifteen most abundant species in the dry and mid region, only two were among those desirable species, i.e. *T. superba* and *Albizia ferruginea* in the dry region, and *T. superba and Milicia excelsa* in the mid region. In the wet region, six desirable and two undesirable CRIG recommended species, were among the top fifteen species. The desirable species included *Alstonia boonei, M. excelsa, Terminalia ivorensis, Entandrophragma angolense, Pycnanthus angolensis* and *T. superba,* whereas *Musanga cecropioides* and *Ceiba pentandra* were undesirable species.

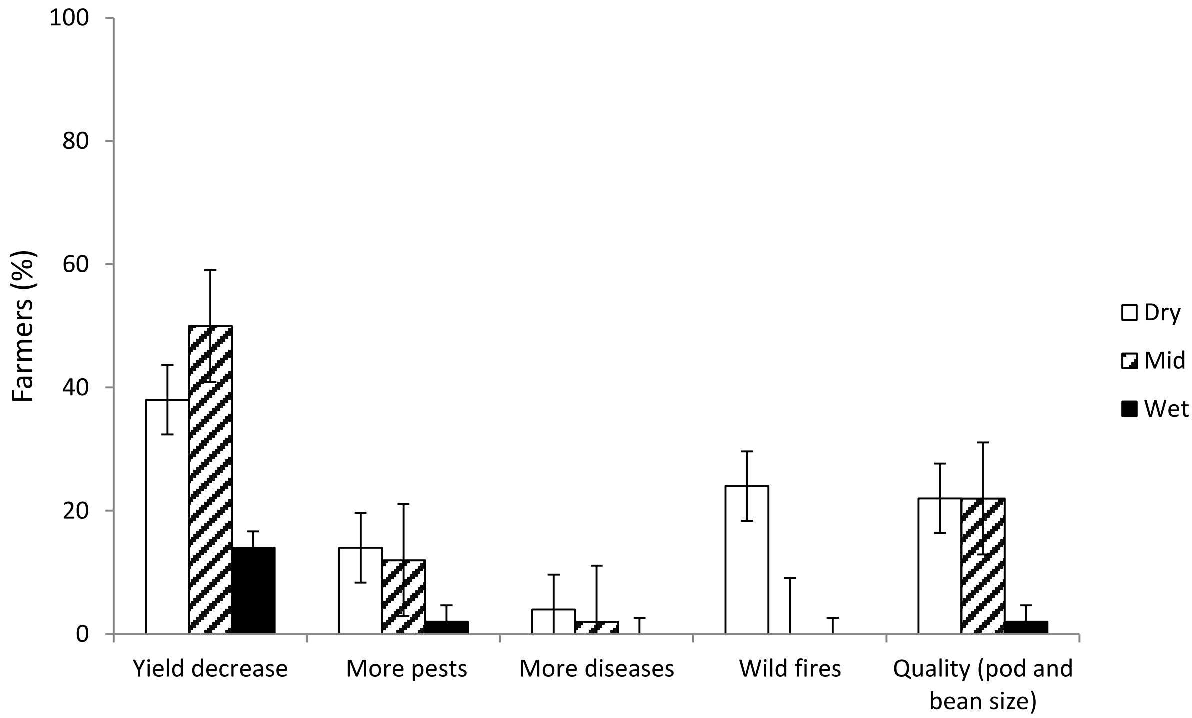

Fig 3 Farmers' (%) perceived effect of drought on cocoa production from dry, mid and wet regions of Ghana

The remaining species in the dry and mid regions were neither among the desirable nor undesirable species (Table 2). The percentage of planted shade trees on farmers' fields decreased from the dry to the wet region (Table 2), but the overall share of planted trees was low, indicating that farmers rely mainly on assisted natural regeneration for maintaining shade trees in cocoa farms.

Primary functions of shade trees varied across regions (Fig 5). Number of fruit tree species decreased from the dry to the wet regions. The use of soil fertility improving shade tree species such as *Gliricidia sepium* was also mainly observed in the dry region. Use of timber and yam stake tree species was quite common, but more predominant in the wet region. Other functions include fuel wood, medicinal value, fodder and building material.

Two types of cocoa agroforestry systems were identified and referred to as medium and low shade cocoa agroforestry systems. Medium shade systems predominated in the dry region, while low shade systems were more predominant in the mid and wet regions (Fig 6). The two systems were significantly different in terms of percentage shade tree canopy cover, shade tree density and species diversity (Table 3). The medium shade system was characterized by a mean shade cover of 31 %, an average diversity of 24 shade tree species ha^{-1}, a density of 56 trees ha^{-1} and basal area of 6.5 m^2 ha^{-1}. The low shade system with lower values of 11% mean shade tree canopy cover, diversity of 12 shade tree species ha^{-1}, density of 21 trees ha^{-1} and basal area of 3.4 m^2 ha^{-1}. There was no significant difference in DBH of the shade trees between systems for all the regions. The low shade system recorded significantly higher cocoa yield than the medium shade system in the wet region. No significant cocoa yield difference was observed between systems in the dry and mid regions (Fig 7).

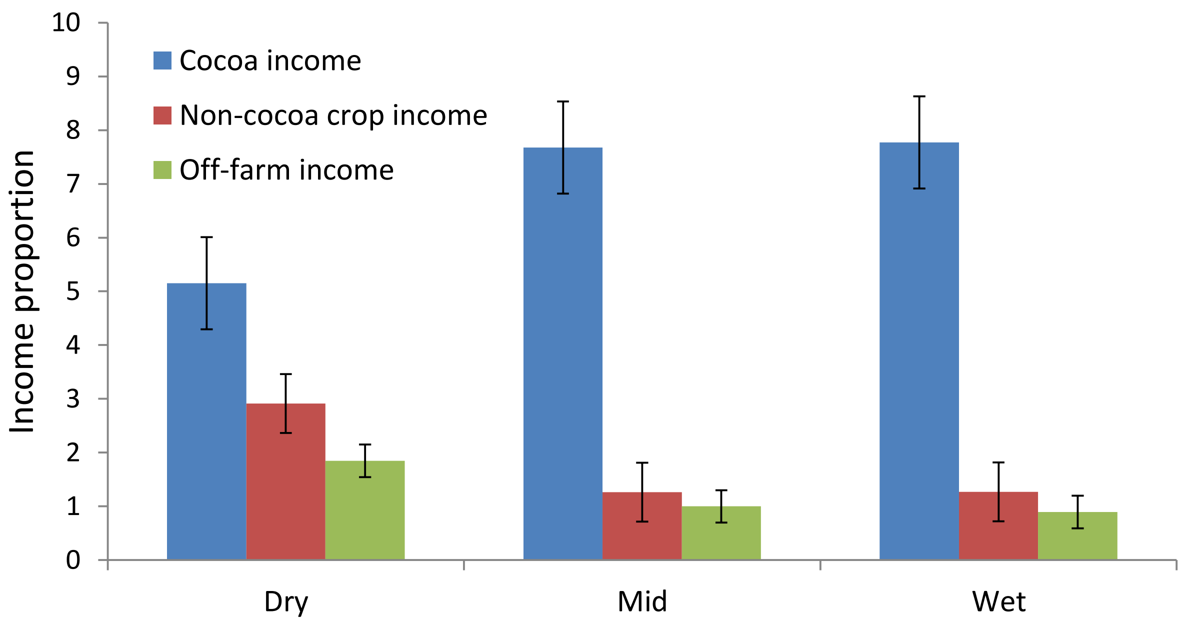

Fig 4 Distribution of cocoa and non-cocoa income proportions among farmers along a climate gradient from dry, mid and wet regions in Ghana

Timber value of shade trees could not be estimated as farmers do not have the right to sell naturally occurring timber trees on their farms. Extra income from mature cocoa farms mainly came from sales of avocado *(P. Americana)*, orange *(C. sinensis)*, banana and plantain (*Musa* spp) and yam (*Dioscorea* spp). These crops were most common in the low shade system while the medium shade system was dominated by quality timber tree species such as *T. superba*, *T. ivorensis*, *M. excelsa*, *A. toxicaria*, *A. ferruginea*, and *A. boonei*.

The low shade system had higher fertilizer input and lower labor costs (mainly associated to weeding costs) than the medium shade system with exception of the mid region where the number of farms under medium shade system were much smaller (only 7 out of 49). Fungicide and pesticide inputs were not significantly different between systems. Farm size was similar except in the wet region, where the medium shade system had a larger mean farm size. No significant differences could be observed between shade systems in the dry and mid regions with respect to black pod disease (*Phytophthora spp.*) incidence, whereas medium shade systems in the wet region displayed a significantly higher incidence of this disease. For capsids (*D. theobroma* and *S. singularis*) no significant difference could be observed between systems in all regions (Table 3).

2.5 Discussion

The study confirms our basic hypothesis that, the climatic gradient significantly influences cocoa production, cocoa farmer income diversification and type of shade trees in cocoa agroforestry systems. Cocoa yields were low in the dry region with only half of farmers income derived from cocoa. However, farmers were adapting through diversification with sales of non-cocoa crops (such as maize, yam, cassava, plantain and vegetables) and off-farm income activities such as trading non-farm produce. In the mid and wet regions, farmers were dependent on cocoa for their incomes due to relatively higher yields under climatically suitable conditions. Perceived effects of climate change, mainly drought on cocoa production included yield decrease, increase in pests and diseases incidence, reduced cocoa pod number, weight and poor bean quality with fire as additional effect at the dry region. Farmers in the dry region kept the most shade trees on their farms, which by extension is an adaptation strategy to the marginal climatic conditions.

Table 2. Occurence (count in 50 farms) of the fifteen most dominant shade tree species and shade characteristics along a climatic gradient from dry to mid and wet cocoa regions in Ghana. N=50 farms per region

Dry	No.	Mid	No.	Wet	No.
1. *Persea Americana*	166	*Persea Americana*	143	*Terminalia superba* *	229
2. *Antiaris toxicaria*	159	*Newbouldia laevis*	134	*Newbouldia laevis*	159
3. *Citrus senensis*	156	*Ficus capensis*	122	*Milicia excelsa* *	104
4. *Albizia zygia*	100	*Terminalia superba* *	103	*Morinda lucida*	78
5. *Terminalia superba* *	99	*Morinda lucida*	99	*Cola nitida*	67
6. *Morinda lucida*	84	*Sterculia tragacantha*	78	*Persea Americana*	54
7. *Holarrhena floribunda*	79	*Ficus exasperate*	68	*Terminalia ivorensis* *	59
8. *Sterculia tragacantha*	75	*Holarrhena floribunda*	66	*Ceiba pentandra* **	44
9. *Ficus exasperate*	72	*Milicia excelsa* *	62	*Musanga cecropioides***	44
10. *Gliricidia sepium*	62	*Citrus sinensis*	61	*Ficus exasperata*	32
11. *Ficus capensis*	51	*Albizia zygia*	49	*Entandrophragma angolense* *	30
12. *Newbouldia laevis*	45	*Antiaris toxicaria*	41	*Rauvolfia vomitoria*	30
13. *Ricinodendron heudelotii*	41	*Ricinodendron heudelotii*	36	*Hannoa klaineana*	28
14. *Cola nitida*	39	*Amphimas pterocarpoides*	36	*Pycnanthus angolensis* *	28
15. *Albizia ferruginea* *	35	*Bombax buonopozense*	33	*Alstonia boonei* *	24
Shade tree density ha^{-1}	49c	Shade tree density ha^{-1}	23a	Shade tree density ha^{-1}	34ab
Species ha^{-1}	22c	Species ha^{-1}	11a	Species ha^{-1}	16ab
Shade cover (%)	27c	Shade cover (%)	13a	Shade cover (%)	18ab
Planted shade trees (%)	27c	Planted shade trees (%)	13b	Planted shade trees (%)	9ab

CRIG recommended desirable* and undesirable** shade tree species. Different letters significantly different

Cocoa production, income diversification and perceived negative effects of climate change and drought on cocoa production

This study confirms the existence of a climate suitability gradient within the cocoa growing regions as demonstrated by Schroth et al.(Schroth et al., 2016). There were significant differences in cocoa productivity as one move from the wet to the dry regions with the wet and mid regions having high cocoa yields compared to the dry region. The high productivity levels in the wet and mid regions can be attributed to higher levels of intensification facilitated by good climatic conditions and higher institutional support through governmental and non-governmental interventions such as the Ghana Cocoa Board (COCOBOD) High Tech program, the Sustainable Tree Crops program by the World Cocoa Foundation and the Rainforest Alliance's Certification program all directed towards productivity increases (Gockowski et al., 2013).

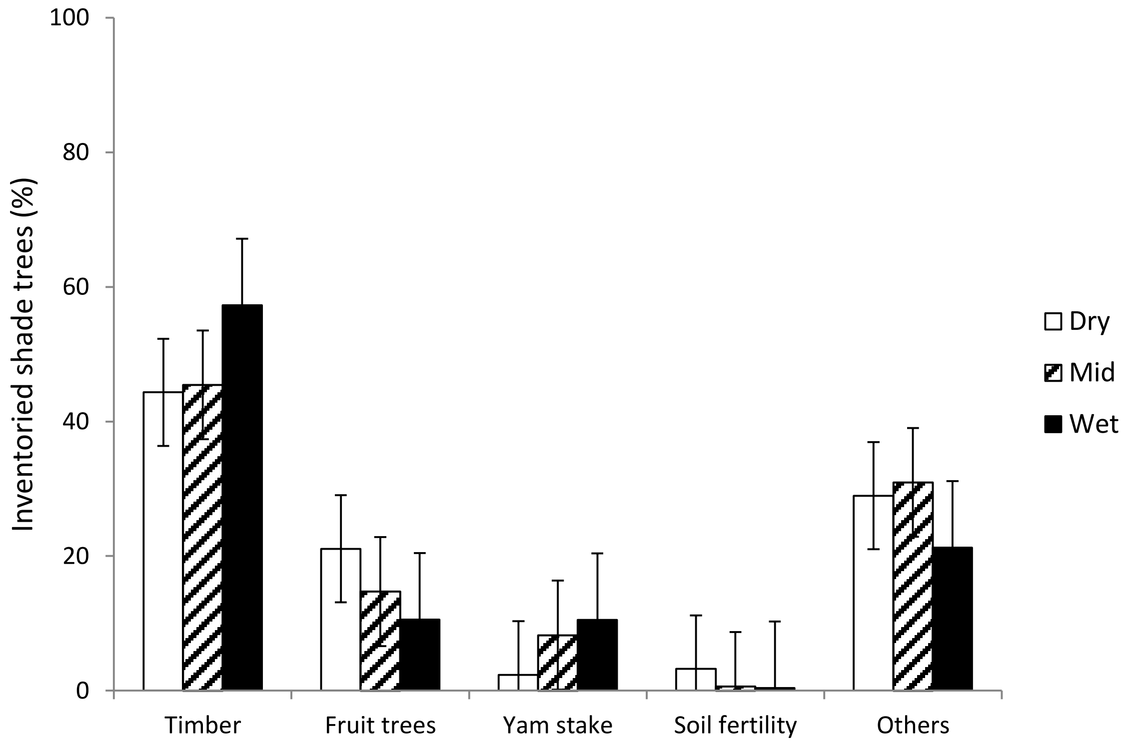

Fig 5 Eco-systemic functions of shade trees along a climatic gradient from dry to mid and wet cocoa regions in Ghana

The dry region is rather marginalized due to environmental constraints that partly may have resulted to the low productivity (Adjei-Nsiah and Kermah, 2012). In addition, the old age of farmers in the region constituted to a major constraint to intensive cocoa production and hence the lower yield (Fountain and Hütz-Adams, 2015). It was observed that even though current cocoa production might not be economically viable for some farmers in the dry region, old farmers continued to "stay in cocoa" (Anim-Kwapong and Frimpong, 2004). The occurrence of relatively large land sizes under newly established cocoa farms in the dry region can be attributed to the encouraging price hikes in cocoa prevailing at the time as ordinarily, farmers are incentivised by increase in cocoa prices (Asante et al., 2016) and will follow their fortunes despite projected climatic limitation (Läderach et al., 2013; Schroth et al., 2017). In this region, young cocoa farms were mostly established after a short fallow and several years of food crops on land that was previously cultivated with cocoa. Farmers also established new farms occasionally on secondary forests. These secondary forests mainly developed from remnants of old cocoa farms abandoned after the 1983/84 ENSO event when most cocoa farms were destroyed by drought and wildfires in the dry region (Adjei-Nsiah and Kermah, 2012) and (Antwi-Agyei et al., 2014). In the wet region, cocoa farm expansion has been attributed to recent deforestation (Ruf, 2011), which is in accordance with the observed predominance of primary and secondary forests as mature cocoa farms land use history. Lack of available forested land has been identified as a major limitation to cocoa production in Ghana and Côte d'Ivoire (Ruf et al., 2015). This could also explain the reported lower number of young cocoa farms in the wet region. However, this has enhanced farmer's act of diversification in terms of how they establish cocoa farms.

The negative effects of drought on cocoa production perceived by farmers in this study and confirmed in literature included but not limited to decreased yields, increase in the incidence of pests and diseases and wildfires (Adjei-Nsiah and Kermah, 2012; Anim-Kwapong and Frimpong, 2004).

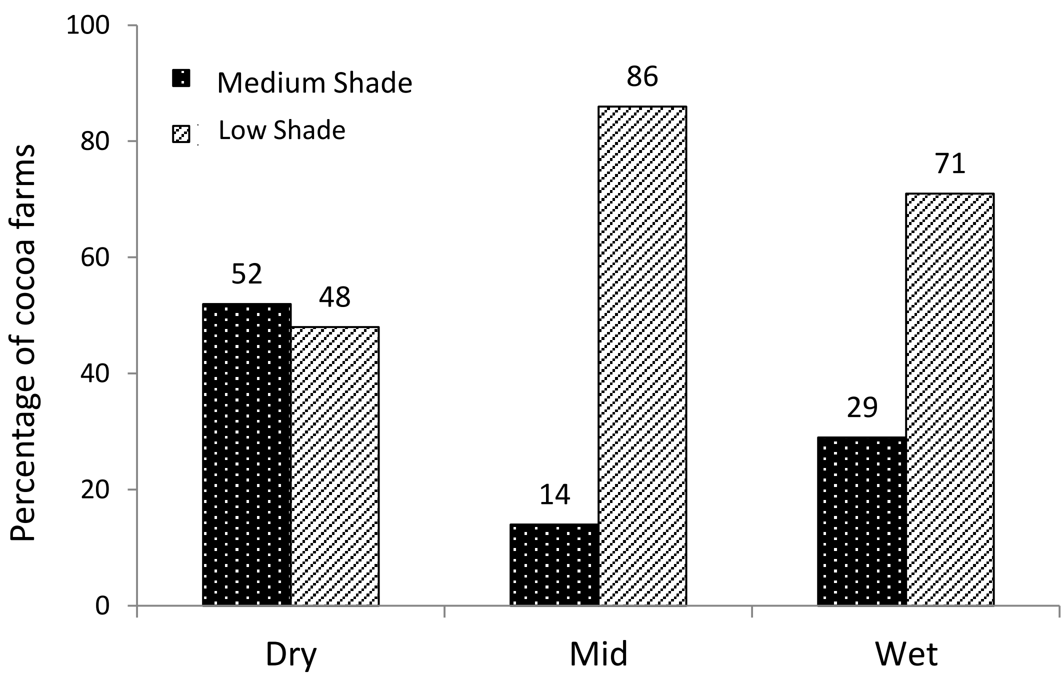

Fig 6 Distribution of medium and low shade cocoa systems along a climatic gradient from dry to mid and wet cocoa regions in Ghana

Farmers could therefore avoid further cocoa planting if they are convinced of projected increase in drought duration and severity. Farmers' knowledge on the influence of climate variability on cocoa production emanates from their experience with past drought events such as the 1983/4 and recently in 2015/16 (Abdulai et al., 2018). Under marginal climatic conditions for cocoa production such as in the dry region, it is expected that farmers will substitute limited cocoa income with income from non-cocoa crops and off-farm activities. This was observed as an adaptation strategy in the dry region, where farmers diversified their income with 50% from cocoa and the rest from non-cocoa crops and off-farm income. Cashew (*Anacardium occidentale)*, which is known to be more drought tolerant and profitable has been identified as a potential alternative tree crop for the region (Schroth et al., 2017)

The situation was different in the mid and wet regions, where farmers were much specialized and made approximately 80% of their annual income from cocoa farming. This could be attributed to farmers having the means of intensifying their cocoa production (Gockowski et al., 2011), due to high yields under optimum climatic conditions for cocoa production.

Shade tree species functions and characterization along a climate gradient

Shade trees have been shown to perform various eco-system functions in cocoa cultivation (Tscharntke et al., 2011). The functions under which all trees species were categorized in this study are indication of their roles in the cocoa farm as perceived by farmers. Much shade tree usage (Table 2) especially fruit trees in the dry region could be attributed to farmers using shade trees to buffer micro climatic conditions and cocoa farm product diversification (Graefe et al., 2017).

Table 3. Comparison of cocoa production systems along a climatic gradient from dry to mid and wet cocoa regions in Ghana (only significant differences at $p<0.05$ between systems are indicated by superscript letters).

Region	Dry		Mid		Wet	
Production system	Medium	Low	Medium	Low	Medium	Low Shade
Number of cocoa farms	24	21	7	42	14	34
Yield (kg ha^{-1} y^{-1})	323^{c} ±282	268^{c} ±265	454^{b} ±290	415^{b} ±275	568^{b} ±289	870^{a} ±556
Farm area (ha^{-1})	1.5±1.0	2.1±3.2	2.9±1.7	6.2±7.1	2.3±1.7	2.1±1.8
Farm age (yrs)	15±10	17±10	18±8	21±8	15±5	17±10
Shade						
Shade cover (%)	32.0^{a}±8.1	14.0^{b}±4.8	27.0^{a}±8.2	11.0^{b}±5.3	30.0^{a}±8.4	12.0^{b}±4.8
Shade tree density (ha^{-1})	57.0^{a}±15.5	25.0^{b}±7.1	49.0^{a}±9.7	19.0^{b}±8.5	58.0^{a}±11.3	22.0^{b}±9.6
Shade tree species (ha^{-1})	25.0^{a}±12.8	14.0^{b}±5.8	20.0^{a}±10.8	9.0^{b}±4.3	24.0^{a}±7.0	12.0^{b}±6.2
DBH (cm)	36.0±27.9	33.0±9.4	39.0±6.7	45.0±13.0	34.0±10.6	36.0±14.1
Management						
Organic fertilizer (kg ha^{-1})	0.0±0.0	0.0±0.0	20.0±55.0	45.0±91.0	40.0±80.5	35.0±135.6
Mineral fertilizer (kg ha^{-1})	5.0±19.0	0.0±0.0	0.0±0.0	25.0±78.8	45.0±83.7	45.0±114.0
Labour cost (USD ha^{-1})	41±55	47±68	56±60	29±37	24±31	43±51
Fungicide (sachets ha^{-1})	68.0±114.6	23.0±35.1	23.0±27.7	22.0±26.0	16.0±14.3	24.0±56.3
Insecticide (l ha^{-1})	6.5±14.2	2.6±2.04	3.3±2.06	2.6±1.9	3.5±2.8	13.0±56.0
Pest and disease incidence						
Black pod (%)	3^{b}±7	5^{b}±11	31^{b}±18	18^{b}±15	33^{a}±19	17^{b}±17
Capsids (%)	47±35	43±31	70±27	60±26	48±30	46±24

This can be referred to as plot level adaptation to marginal climatic conditions, which coincidentally has been recommended for such conditions (Schroth et al., 2017, 2016). Provision of ecosystem services by shade trees such as improving soil fertility with nitrogen fixing species such as *Gliricidia sepium* (Tscharntke et al., 2011) was noted mainly in the dry region (Fig 4).

The analysis of shade trees in cocoa agroforestry systems revealed two main clusters, which were characterized as medium and low shade systems with 30% and 10% canopy cover respectively and consistent with the classification of mid-high and low shade systems identified across West Africa by Gockowski et al (Gockowski et al., 2004) . The medium shade system shade canopy cover is within the Rainforest Alliance and CRIG recommendations for sustainable cocoa production (Asare, 2008). Farmers with medium shade cover generally reported reduced labour costs, which can be due to weed suppression and consequent reduced weeding. The fact that cocoa farm age for medium shade systems is lower than low shade systems across all regions can be partly attributed to farmers experience in changing climatic conditions (Asante et al., 2016), leading to a more positive perception on the effects of shade as adaptation strategy (Graefe et al., 2017). More medium shade system farms in the wet than the mid region can be attributed to farmers' involvement in agroforestry interventions under Rainforest Alliance cocoa certification schemes. Such incentives encouraged farmers to maintain shade trees (Gockowski et al., 2013). The Rainforest Alliance and UTZ certification projects promote shade maintenance and improvement of cocoa farm biological diversity (Asare, 2008). However, the dry and mid regions represented a conventional situation of farmers' use of shade trees as the decision of keeping shade trees were not influenced by certification. Since the climatic conditions are favourable for cocoa in the mid region, farmers did not find it necessary to maintain much shade compared to the dry region.

The two shade systems had different effects on cocoa yields. Medium shade systems had a positive effect on cocoa yields in the dry and mid regions but had a negative effect in the wet region.

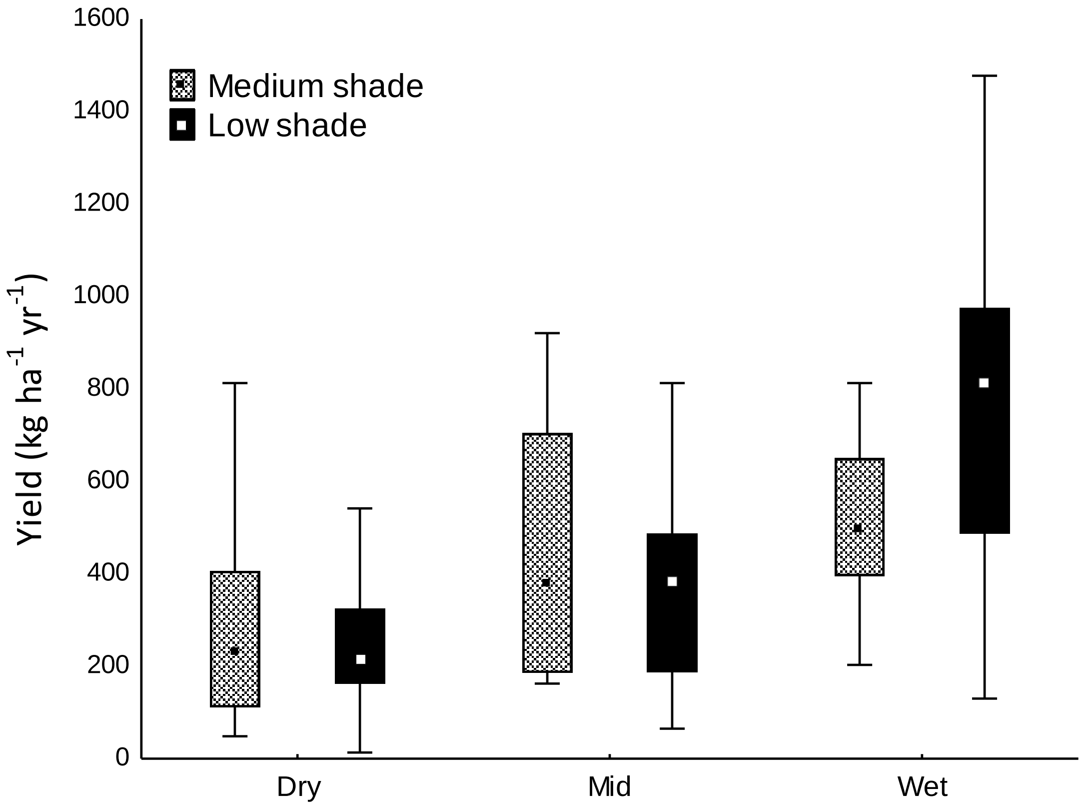

Fig 7 Yield variation between medium and low shade systems along a climatic gradient from dry to mid and wet cocoa regions in Ghana (different letters indicate significant differences at between systems $p<0.05$)

As a result, shade level recommendations for cocoa should therefore consider region specific climatic conditions. The main reason for shade reduction in cocoa farms is the promotion of black pod disease (Beer et al., 1998). This was perceived by farmers as a major constraint in increasing shade levels in cocoa farms in the wet region (Graefe et al., 2017). However, different levels of shade did not influence the incidence of capsids. Therefore, it is expected that farmers will enhance shade usage as a measure of adapting their cocoa farms to climate change.

2.6 Conclusion

Current cocoa production in Ghana is situated over a climate gradient, mostly based on annual rainfall regime. Low yields are already evident in the marginal regions of the cocoa belt in Ghana. Farmers in less climatically suitable areas like the dry regions diversify their income between cocoa, non-cocoa crops and off-farm income activities. Although the marginal areas are projected to be unsuitable for cocoa in the future, farmers continue to grow cocoa. Therefore, there is a need to bridge the information gap on projected climate suitability change awareness between farmers, researchers and other stakeholders. This could guide in developing interventions to ensure timely adaptation to climate change.

The study identified two shade systems, and reveals that medium shade systems are dominant in less climatically suitable dry region than the more suitable mid and wet region. This is an indication of farmers understanding the use of shade to adapt their cocoa farms in marginal climatic conditions. There is also a need to further explore the potential of medium shade systems as resilient and productive cocoa agroforestry system. Shade tree species that are recommended for cocoa in Ghana are not based on climatic regions, therefore limiting their use in climate change adaptation. Species specific studies on shade trees is still required to select appropriate species that will minimize potential negative effects, such as water competition and yield losses from pest and diseases under lower rainfall regimes (Abdulai et al., 2018). Policies should also enhance shade tree ownership through farmers' planting or assisted natural regeneration as an integral component of the cocoa landscapes.

2.7 Acknowledgments

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Chapter Three

Variations in yield gaps and soil fertility along a climatic gradient in smallholder cocoa systems of Ghana

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3.1 Abstract

Increase in cocoa production in West Africa has primarily relied on expansion to forested land as low yields per unit area persist whilst demand keeps growing. To avoid disappearance of forest lands, further area expansion of cocoa in West Africa is limited. The way forward is sustainable intensification, which requires understanding of region-specific soil fertility status, attainable yields and yield limiting factors to guide site-specific crop management. In this study, we first assessed yield gaps (i.e. difference between attainable and average farmer yield) and soil fertility status along a climatic gradient with regions denominated as dry, mid and wet, and representing marginal, moderate and near-optimum cocoa cultivation areas in Ghana. Yield data for three consecutive years (2013-15) and soil properties from the 0-30cm layer were analysed for 150 farms. For each region, we used 90th percentile highest average yield as the attainable yield. Yield gaps were expressed as the percentage of actual yield to attainable yield. Secondly, we evaluated management factors determining the yield gap and soil organic carbon (SOC), a key variable for soil fertility.

Average farmer and attainable yields were 211 and 645 kg ha^{-1}year^{-1} in the dry region, 477 and 1174 kg ha^{-1}year^{-1} in mid region and 999 and 2125 kgha^{-1}year^{-1} in the wet region respectively. Largest yield gaps were found in the dry region (67%) and the smallest in the wet region (53%). Amount of fungicides and pesticides used was a significant factor in explaining the yield gap in the dry region, where the limited usage might be related to the risk adverse attitude of the farmers often exposed to extended droughts. Larger cocoa farms had higher yield gaps in both mid and wet regions, possibly due to insufficient allocation of labour and other inputs. In the mid region, in addition, parasitic mistletoe was a key yield reducing factor. Additionally, farms that were planted with higher proportion of quality planting material from approved source had lower yield gaps in the wet region. The overall soil fertility was low across all regions, as indicated, for example, by the ranges measured for SOC (1.32 – 1.71 %), total nitrogen (0.12 – 0.15%), plant available phosphorous (9.22 – 13.85 ppm) and potassium (0.18 – 0.23 cmolc kg^{-1}). Cocoa farm characteristics such as farm age, planting density, shade cover and basal area of shade trees were not significantly correlated with soil fertility indicators. Our results suggest that sustainable intensification to closing cocoa yield gap needs improvement in integrated pest management, fertilizer management and use of quality planting material. Overall, the role of soil fertility for

sustainable intensification requires further investigation as the current fertility levels are low for developing and sustaining productive cocoa production systems.

Keywords: Attainable yield, Climate suitability, Soil organic carbon, Sustainable intensification, Yield gap

3.2 Introduction

Cocoa production plays a significant role in sustaining both the national economy and rural livelihood of Ghana. Global cocoa demand is projected to be increasing whilst production has been decreasing, with 2015/16 recording 3.972 million tonnes and a deficit of 197,000 tonnes for meeting the demand (ICCO, 2017). Cocoa production in Ghana has declined by more than 30% from 1 million tonnes in 2010/11 to estimated 690,000 tonnes in 2015/16 (Figure 1) (Attenka, 2016; Oppong, 2016). The record production in 2010/11 was achieved through concrete policy interventions and significant price increase by the government in the early 2000s (Fig. 1), which incentivised farmers to establish new farms as well as rehabilitating old ones (Asante et al., 2016; Anim-Kwapong and Frimpong, 2004). Policy interventions included a state sponsored national Cocoa Pests and Diseases Control Programme (CODAPEC), Cocoa High Technology Project (Cocoa HI TECH) as well as the Sustainable Tree Crop program (STCP) funded by the World Cocoa foundation under the cocoa livelihood project (Asare, 2008; Anim-Kwapong and Frimpong, 2004).

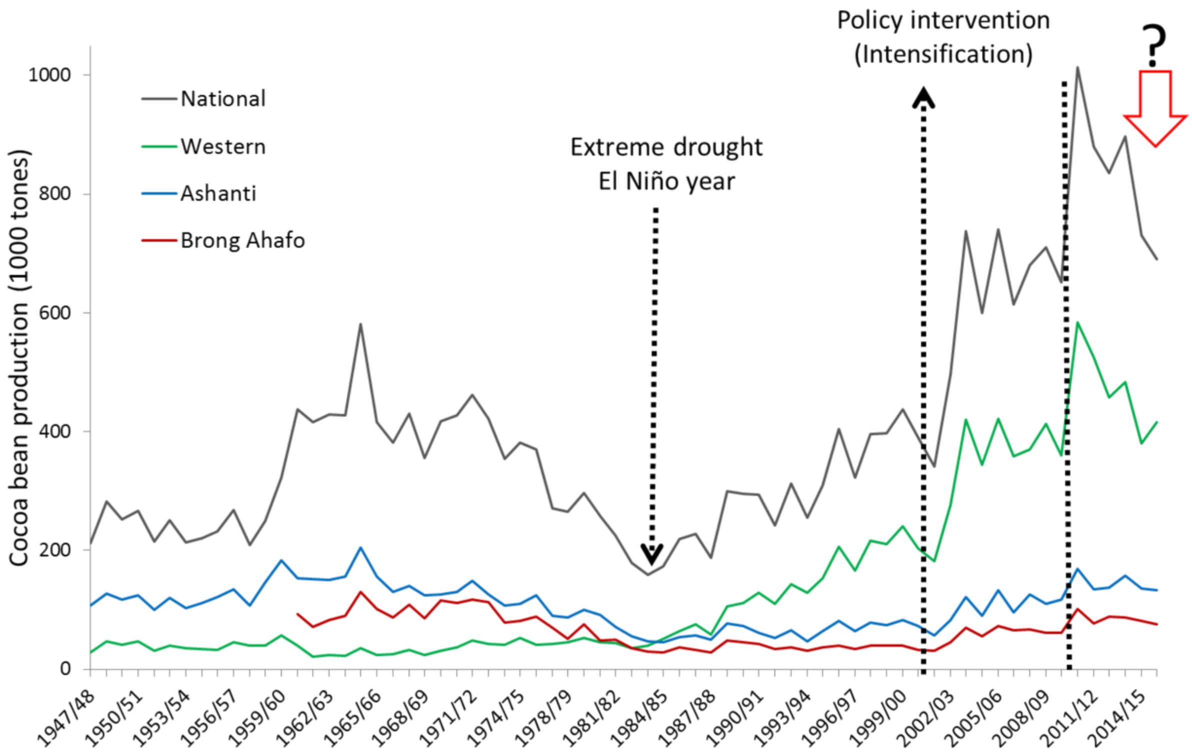

Fig. 1 Annual national and regional cocoa bean production along the selected climatic gradient, Brong Ahafo (dry-mid), Ashanti (mid-dry) and Western (wet) region. The arrows indicate distinct events such as the adverse climatic event in 1983/84 (El Niño) that co-determined shifts of the production regions to the wetter zones; policy interventions (CODAPEC and Cocoa HI TECH program from 2001-2011) leading to intensification of cocoa production; restricted/ ineffective implementation of the policy interventions has resulted in continuous decline in production since 2012 (especially in the western region)

Prevalence of inadequate extension services, low soil fertility, increased pest and disease pressure causing low farm yields are now coming along with increased spatiotemporal variability of weather conditions (Noponen et al., 2014, Anim-Kwapong and Frimpong, 2004). The cocoa growing regions of West Africa are distributed along different climatic zones that require differential innovations for yield improvement and adaptations to climate change (Vaast and Somarriba, 2014; Schroth et al., 2016a). Naturally, farmers have moved to more climatically suitable forested regions in response to change in climatic suitability for cocoa cultivation. This approach is evidenced in both Ghana and Ivory Coast since the 1983/84 El Niño event (Ruf et al., 2015), when shifts in cocoa production from the dry and mid (Ashanti and Brong Ahafo) regions to the wetter Western region took place (Figure 1). With most cocoa related deforestation occurring over the last three decades, there is extreme disappearance of forested land in the wet regions with some areas maintaining only 8% of closed canopy forest cover (Noponen et al., 2014; Ruf, 2011). In such situation with limited land resources, narrowing the gap between actual and attainable yield can be an important means to reduce the pressure on the remaining forests. In addition, such yield improvement has to be sustainable taking into account ecological, economic and social dimensions. Sustainable intensification of cocoa production will involve increasing cocoa production from existing farms without compromising environmental quality and ability to support future productions. This pathway of sustainable intensification production (Garnett et al., 2013; Foley et al., 2011; Godfray et al., 2010) stresses the need for site and season-specific management to ensure high resource use efficiency (Lipper et al., 2014; Noponen et al., 2014; Schroth et al., 2016). Arguably, such approach is knowledge and often resource intensive. Hence site-specific information on soil fertility as well as on actual and attainable farmers yield is a prerequisite for proper guidance of farmers (Ittersum et al., 2013; Cassman, 1999). Considering the existing variations in climatic conditions of the cocoa growing regions in West Africa (Schroth et al., 2016b; Läderach et al., 2013), it is important to pay attention to how climatic factors affect production constraints. Climatic variations and associated risks to crop production have been identified as a major constraint to farmers intensifying their production (Hoffmann et al., 2016).

Sustaining intensive cocoa production without negative environmental impact will require soil fertility improvement as recommended in other cropping systems (Carberry et al., 2013; Cassman, 1999). Soil organic carbon (SOC) which is one indicator of soil fertility has been shown to be negatively influenced by conversion from forest to perennial cropping systems including cocoa plantations (van Straaten et al., 2015; Blaser et al., 2017). Cocoa plantation characteristics such as planting density, farm age and presence of shade trees influence SOC in existing cocoa plantations (van Vliet and Giller, 2016; Tscharntke et al., 2011; Ofori-Frimpong et al., 2010).

Previous studies on cocoa yield gap mainly focused at national scale (Aneani and Ofori-Frimpong, 2013) without accounting for the variations caused by differences in climatic conditions of the producing regions. However, different regions of the cocoa belt in Ghana have been shown to exhibit different yield potentials according to model simulations (Zuidema et al., 2005). Soil fertility assessments have been mainly done at plot level with limited consideration of climatic gradients. To the best of our knowledge, there is no existing work on assessing yield variations and gaps and soil fertility status along a gradient from dry to wet in Ghana as proposed for this study. Although yield gap studies on perennials are limited due to data availability, cocoa yield gap studies are even more limited than those for oil palm and coffee (Bhattarai et al., 2017; Euler et al., 2016; Guilpart et al., 2017; Hoffmann et al., 2017; Lee et al., 2013; Rapidel and Rica, 2017; Wang et al., 2015).

In this study, we hypothesize that 1) Attainable cocoa yields and actual farmer's yields increase from the dry to the wet regions; 2) Yield gaps are smallest in the wet region due to the fact that it is little affected by climate induced risks and largest in the dry region, where climate risks are highest; 3) Soil fertility is lower at the wet than the dry and mid regions due to high rainfall resulting in nutrient leaching and soil acidification.

Consequently, the current study aims to identify variations in yield gaps and soil fertility in smallholder cocoa production systems, as well as in factors determining yield gaps and SOC along a climatic gradient in the cocoa belt of Ghana. The specific objectives of this study were to assess and compare among the different regions: (a) yield gaps and yield variability; (b) the main factors determining yield gaps; (c) soil fertility indicators; and the effect of smallholder cocoa plantation characteristics on SOC.

3.3 Material & Methods

Study sites

The study grouped the current cocoa growing regions of Ghana into dry, mid and wet regions based on current rainfall distribution (Fig. 2). Akumadan and Afrancho towns in the Offinso North district of the Ashanti region were selected to represent the dry region. This region has experienced change in vegetation type from moist semi-deciduous to forest savanna transition due to frequent fire influenced by the annually recurring dry Harmattan winds (MOFA, 2017c; Adjei-Nsiah and Kermah, 2012). This region has mean annual rainfall of 1200 mm (Fig 2) and average temperature range of 27 to 30°C (MOFA, 2017c) which are considered marginal ecological conditions for coca cultivation. The mid region was located in five surrounding villages of Goaso in Asunafo North district of Brong Ahafo region with mean annual rainfall between 1200 and1400 (Fig 2) mm and mean annual temperature of around 25°C (MOFA, 2017).

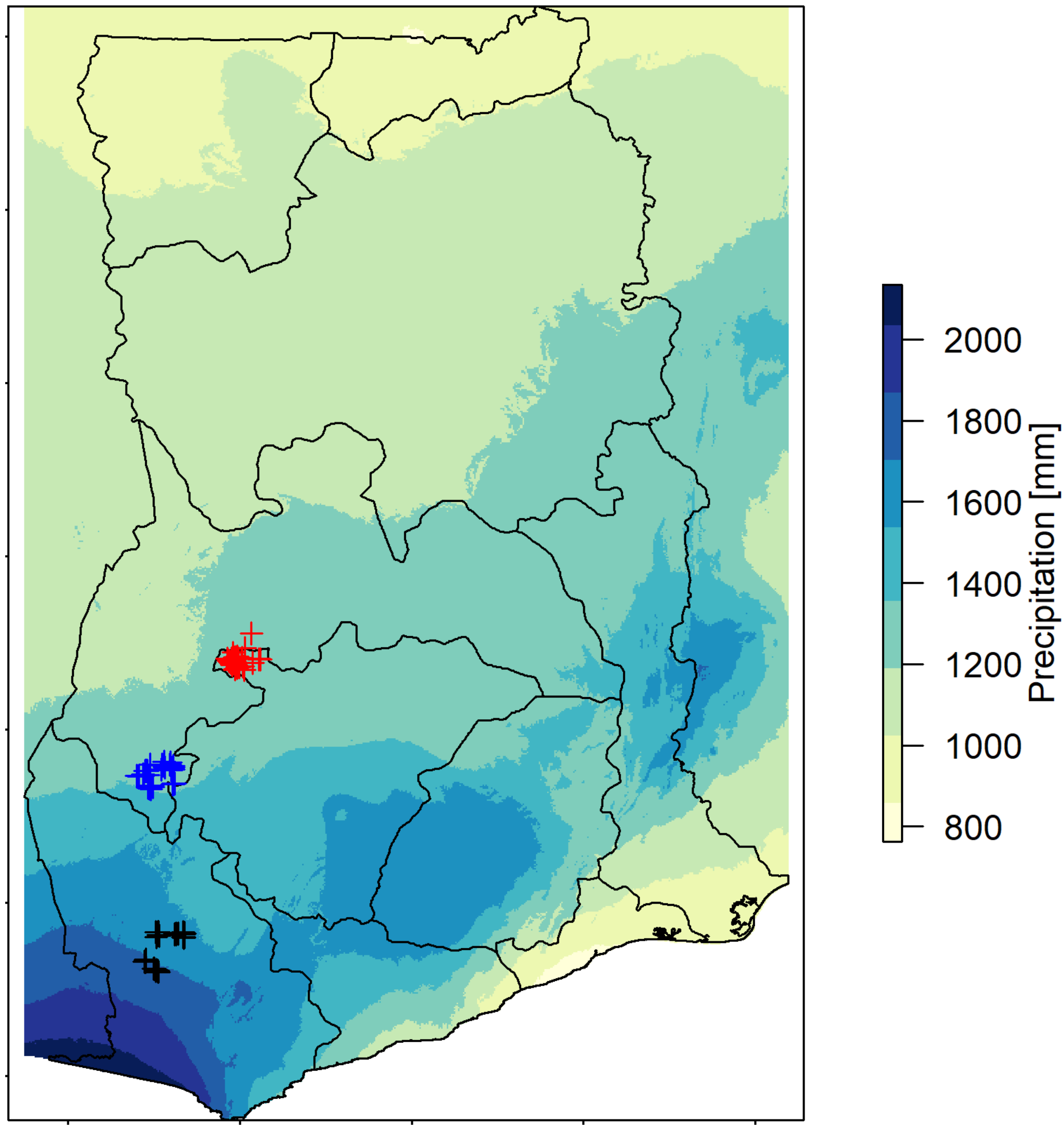

Fig. 2 Total annual rainfall (mm) across the studied regions. Rainfall values derived from WorldClim data ((www.worldclim.org), which represent calculated means of 1950–2000 (Hijmans et al., 2005). Dry, mid and wet regions denoted by red, blue and black colours respectively.

The current vegetation is classified as semi-deciduous forest (MOFA, 2017b). Subsequently, the wet region was located further south of the forest belt around five surrounding villages of Asankragua in the Amenfi West district of the Western region of Ghana. The mean annual rainfall for this region is about 1400 to 2000 mm (Fig 2) with temperatures ranging between 27 and 30°C (MOFA, 2017c). The vegetation is classified as moist evergreen forest type (Hall and Swaine, 1976).

Currently, the dry region is characterized by sub-optimal climatic conditions for cocoa cultivation while the mid and wet regions are considered near-optimal (Läderach et al., 2013). According to Läderach et al., (2013), the dry region is projected to be climatically unsuitable by 2050 whilst the mid and wet regions become sub-optimal and near-optimal, respectively.

The soils of the dry and mid regions are Acrisols and Alfisols classified as highly suitable for cocoa cultivation (Anim-Kwapong and Frimpong, 2004). The wet region is dominated by highly weathered and acidic Acrisols, Alfisols and Oxisols and has been classified as unsuitable for cocoa cultivation unless fertilizers are applied (Anim-Kwapong and Frimpong, 2004). Nonetheless, the region holds patches of remnant forestlands and has supported cocoa expansion for decades and as a result has become the leading production region in Ghana since 1984/85 (Figure 1) (Cocobod, 2017; Anim-Kwapong and Frimpong, 2004).

Data collection

A total of 150 farmers, 50 from each region were selected for conducting farm household surveys between April and September 2014. Farmers from the dry and mid regions were randomly selected from the database of the Kuapa Kokoo farmers' cooperative union, which is the largest cocoa farmers union in Ghana and the world's largest producer of Fairtrade certified cocoa beans (Donovan et al., 2016). In the wet region, farmers were selected from the Rainforest Alliance certification database managed by AgroEco-Louis Bolk Institute (AE-LBI) in the Western region of Ghana. A structured questionnaire and "on-farm survey sheets" digitized on a smartphone was used to collect data using the Mobenzi Researcher ® platform. Interviews were conducted directly in the local "Twi" language which enhanced response. Pretesting of the questionnaire preceded the data collection with translation and back-translation undertaken to verify the understanding of the questions. The questionnaire was centred on cocoa farmer socio-economic household characteristics and cocoa plot management activities for the 2012/13 cocoa season. Yield data for the subsequent 2013/14 and 2014/15 seasons were also collected in June 2016. On-farm inventory involved soil sampling for nutrient balance assessment, measurement of cocoa plant density, enumeration and measurements of shade tree species and percentage shade cover of upper canopy shade trees on cocoa plots. Total cocoa plot size was measured with GPS device by contouring around the plot with Garmin GPS eTrex® 10 as well as around shade tree canopy area with 30 m tape measure following Asare et al (2017). Composite soil samples from five samples taken at uniformly distributed points within the cocoa plots up to 30 cm depth were collected for further analysis. Soil texture and chemical properties were analysed at the laboratory of Soil Research Institute of Ghana (CSIR-SRI). Soil samples were dried at 105° C, sieved through a 2 mm sieve and grounded. Analysis followed standard methods as applied in Blaser et al., (2017).

Assessment of soil fertility status and soil organic carbon

Analysis of variance (ANOVA) was conducted to compare the soil nutrient content between regions. The average regional values were further compared to the threshold/critical values established for cocoa soils (Van Vliet and Giller, 2017; Asare et al., 2016). Cocoa plot characteristics and soil texture were used to determine SOC determining factors per region via multiple regression models using the R software (R core team, 2017). Among factors used in the regression equation in addition to non-correlated soil texture classes were cocoa plot age, cocoa plant density, shade tree canopy cover percentage and shade tree basal area. These factors have been found to influence SOC content of cocoa soils (Ofori-Frimpong et al., 2010; Van Vliet and Giller, 2016). The land use history of the cocoa plots (Fig. 2) were further analysed to help better understand possible relations to the SOC due to its important role for soil fertility and cocoa productivity (Van Straaten et al., 2015).

Table 1 Descriptive statistics of variables collected at dry, mid, and wet regions. Different letters indicate significant difference in the means (SD) between the regions at $p \leq 0.05$ significance

	Dry	Mid	Wet
Socioeconomics			
Farmer age (years)	$64(19)^a$	$54(14)^b$	$47(11)^b$
Household size	$11(8)^a$	$7(3)^b$	$8(3)^b$
Training (days/yr)	$4(5)^a$	$2(3)^{ab}$	$6(6)^{ac}$
Labour cost (GHS/ha/year)	$166(230)^a$	$131(164)^a$	$148(183)^a$
Cocoa income (%)	$50(30)^a$	$80(20)^b$	$80(20)^b$
Non-cocoa income (%)	$50(30)^a$	$20(10)^b$	$20(10)^b$
Management			
Fungicide (sachets/ha)	$43(85)^a$	$22(26)^a$	$21(47)^a$
Insecticide applied (liters/ha)	$4.5(10.0)^a$	$2.7(1.9)^a$	$9.9(46.2)^a$
Organic fert. (kg/ha)	$0(0)^a$	$39(86)^b$	$71(121)^b$
Inorganic fert. (kg/ha)	$2(13)^a$	$20(73)^b$	$42(103)^b$
Stand properties			
Plot size (ha)	$1.0(1.0)^a$	$1.7(1.1)^b$	$1.0(0.7)^a$
Cocoa plot age (years)	$17(11)^a$	$21(8)^a$	$16(9)^a$
Cocoa plant DBH (cm)	$9.4(2.6)^a$	$9.9(2.4)^a$	$12.1(2.5)^b$
Cocoa plant density (trees/ha)	$1576(534)^a$	$1620(461)^a$	$1738(395)^a$
Shade cover (%)	$27(16)^a$	$13(8)^b$	$18(11)^b$
shade trees density (trees/ha)	$49(33)^a$	$23(14)^b$	$34(24)^b$
Shade trees diversity (trees/ha)	$22.4(15.2)^a$	$10.8(6.5)^b$	$15.5(8.0)^b$
Shade tree basal area (m^2)	$4.2(3.6)^a$	$7.0(5.7)^b$	$4.1(5.7)^a$
Mistletoe incidence (%)	$13.8(25.6)^a$	$14.6(18)^a$	$18.4(18)^a$
Proportion of hybrid and non-hybrid (farmer selected) cocoa plants per plot			
Hybrid	$7.3(3.5)^a$	$3.4(4)^b$	$2.7(3.9)^b$
Non-hybrid	$2.7(3.5)^a$	$6.7(4)^b$	$7.5(4.0)^b$
Soil texture (0-30 cm depth)			
Sand (%)	$58.90(11.32)^a$	$41.55(8.97)^b$	$31.81(9.09)^c$
Clay (%)	$12.31(4.95)^a$	$12.74(4.18)^a$	$12.42(4.52)^a$
Silt (%)	$28.79(11.36)^a$	$45.71(9.38)^b$	$55.77(8.53)^c$

Assessment of yield gaps and yield determining factors

Generally, Lobell (2009) and van Ittersum et al (2013) differentiate three methods to define attainable crop yield. The standard approach commonly employed to assess yield attainable under potential and water-limited growth conditions in yield gap studies is the use of crop modelling. This has, for instance, the advantage to separate and quantify the influence of different yield determining factors on potential yield (defined by irradiation, temperature and crop characteristics neither limited by water nor nutrients nor any other yield reducing factors such as pests and diseases) and yield attainable under rainfed conditions (considering water as a limiting factor) (see, e.g. Van Ittersum et al., 2013). However, with few exceptions, crop models for tropical perennials do not exist. For cocoa, Zuidema et al. (2005) developed one such model, but it is still far from being sufficiently tested; hence we cannot apply it with confidence. The second approach for assessing attainable yield is through well designed field trials, where in potential growth trials ample of water and nutrients are provided at all times and biotic stresses are minimised as much as possible to estimate potential yield, or, to estimate water-limited yields when performing such trials under actual water balance conditions. However, for cocoa such field trial data are not available for most of the regions we were interested in. The third approach, which we applied in the absence of sufficient field trial data, was to use maximum yields recorded on farms. This method is well established and has the advantage that recorded yields have indeed been shown to be attainable by farmers with good practices (Hoffmann et al., 2017; Wang et al., 2015; Kassie et al., 2014). Yet, in reality such yields might be clearly below potential yields.

In this study, we used three year average yield from the 10% best performing farms as attainable yield. Using average yield data over (at least) three consecutive years is necessary to balance the inter-annual variability and carry over effects in perennials (Hoffmann et al., 2017). Cocoa yields referred to the quantity of annual dried cocoa beans harvested per cocoa farm area as reported by farmers and verified with their sale books. Yield gap (YG) was estimated as the difference between attainable yield (AY) and actual farmers yield (FY) (again determined by three year yield average (2013-2015), at each climatic region based on the approach of maximum farmer yield determined from survey (Van Ittersum et al., 2013: Lobell et al., 2009). Yield gap was further expressed as percentage of farmer yield to attainable yield (Hoffmann et al., 2017). The attainable yield was estimated as the average yield of best performing farmers (90^{th} Percentile) which gives realistic estimate of economically achievable yield (Hoffmann et al., 2017). Yield gap determining factors were identified and estimated per region by multiple linear regression models. All variables considered to be yield gap determining factors were grouped into three categories: management, stand and soil properties (Table 1). Correlation analysis was performed for all the variables (Supplementary table – also contains equation for the multiple regression model). For highly related variables (variables with correlation coefficient higher than 0.5), the most causal variable was selected and incorporated in the model. All variables were further scaled to ensure standardization of the different variables in the model. For the management variables, no significant correlations were observed. Among the plantation properties, plot size was significantly correlated to shade tree basal area while shade tree density, diversity and shade cover were also significantly correlated to each other across all regions. Plot size and shade cover were used to represent these variables in the model based on the correlation results. Soil pH, soil carbon, K and clay content were the selected soil variables for the model following the correlation test. Yield gap was used as dependent variable, to test the factors contribution in determining the yield gap of each region at p-value < 0.05 of significance level.

3. 4 Results

Yield gap and variability across climatic regions

The three year mean annual cocoa yield from 2013 to 2015 significantly increased along the climatic gradient from the climatically less suitable dry region to more suitable wet region (Fig. 3). The dry region showed significantly lower average farmer yield (FY) of 211 kg ha^{-1} yr^{-1} and attainable yield (AY) of 645 kg ha^{-1} yr^{-1} followed by the mid region with FY of 477 kg ha^{-1} $yr^{-1}$and AY of 1174 kg ha^{-1} yr^{-1}. The wet region recorded the highest average FY of 999 kg ha^{-1} yr^{-1} and AY of 2125 kg ha^{-1} yr^{-1}. This resulted in absolute YG values of 1126, 697 and 434 kg ha^{-1} yr^{-1} for wet, mid and dry regions, respectively. Relative yield gap (in percentage) is derived from the ratio FY to AY per region in order to compare its variations between climatic regions. The highest relative YG was recorded for the dry region with 67%, but not significantly different from the mid region with 59%. The wet region with 53% yield gap was significantly different from the dry region (Fig.4).

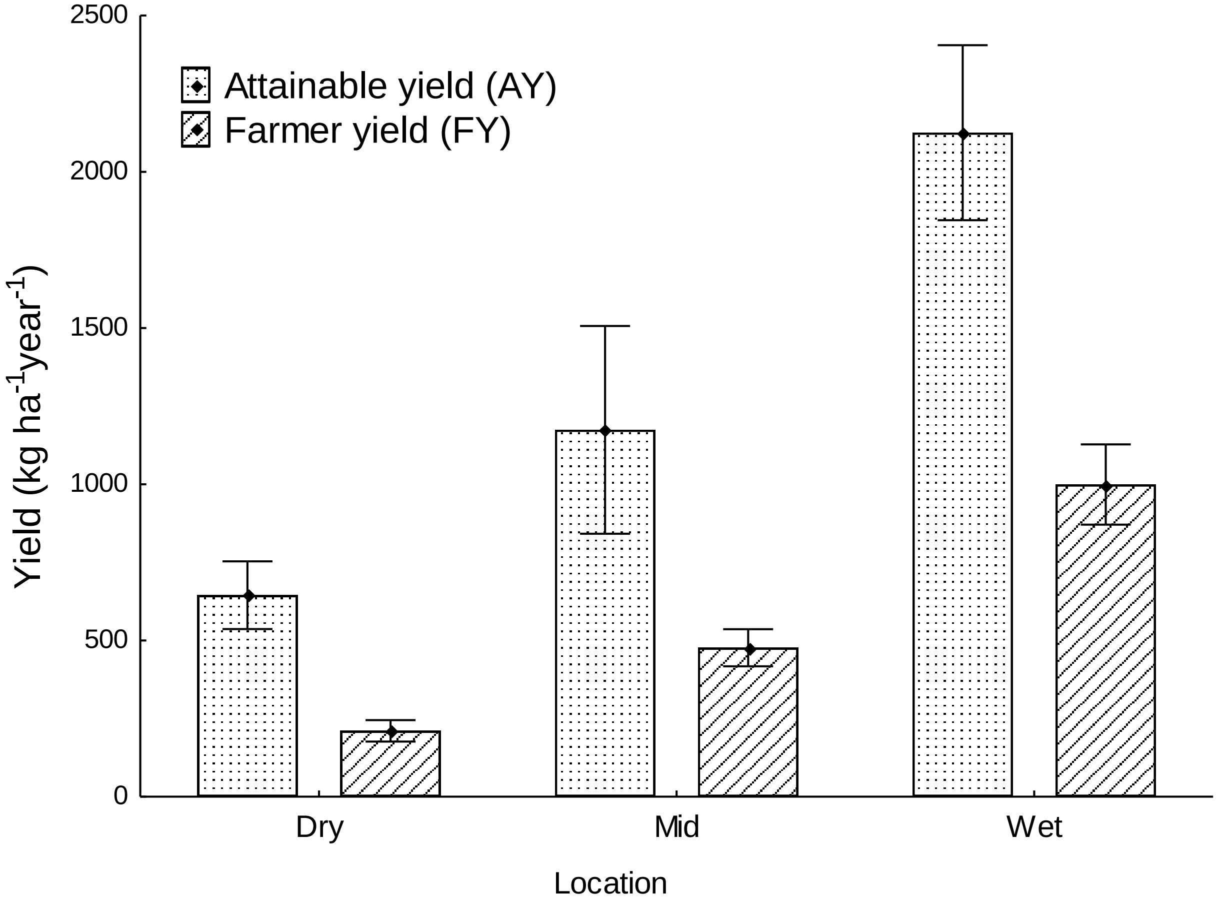

Fig. 3 Attainable yield (AY) and average farmer yield (FY) along a climatic gradient in Ghana. The attainable yield is the 90th percentile of farmer yield per region. Average farmer yield (FY) defined as the mean yield of the sampled 50 plots, and the attainable yield (AY) determined by the 90th percentile for the sampled 50 plots per each region. Columns represent the mean and whiskers indicate 95% confidence intervals.

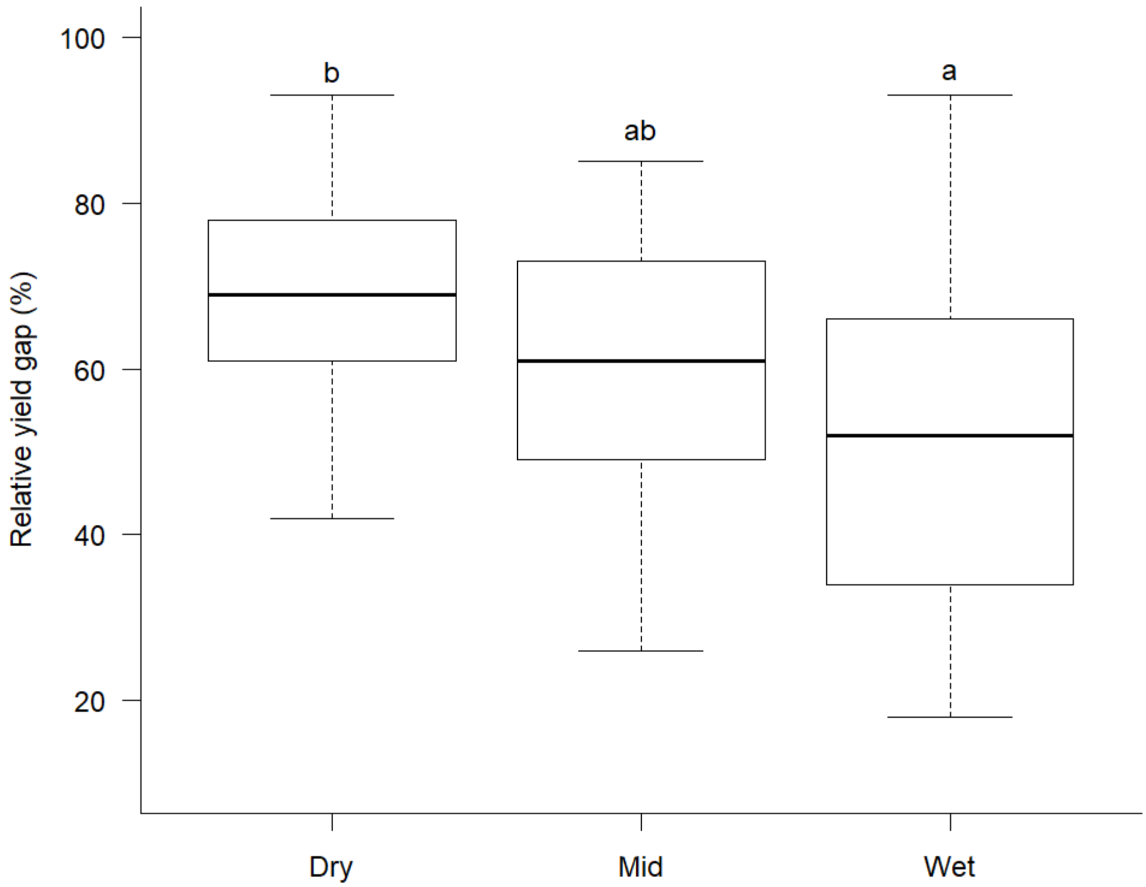

Fig. 4 Variation in relative yield gap (YG) between the studied regions. YG expressed as average farmers yield (FY) percentage of attainable yield (AY), Attainable yield defined as the 90th percentile of farmer yield per region (n = 50 per region).

Yield gap determining factors across the regions

In the dry region, fungicide and pesticide application significantly reduced the yield gap (Fig. 5a). However, this relationship was biased based on an outlier, which was double checked with the farmer and was proven to be a true yield value. Soil pH and clay content had marginal effect on yield gap (p-value =0.076 and 0.061, respectively) (Table 2). In the mid region, factors that significantly determined yield gap were farm size and occurrence of mistletoe (*Tapinanthus bagwensis*) all of which positively correlated with the yield gap (Fig. 5b). For the wet region, yield gap increased with increasing farm size and decreased with increasing proportion of hybrid planting material on the farm (Fig. 5c). Cocoa farm age, SOC and K content had marginal effects on the yield gap in the wet region (Table 2).

Table 2 Yield gap determining factors

Region	Dry		Mid		Wet	
			P-values			
Cocoa plant density (trees/ha)	0.128		0.699		0.493	
Plot age (years)	0.537		0.076	.	0.051	.
Plot size (ha)	0.526		0.002	**	3.57E-05	***
Shade cover (%)	0.560		0.347		0.502	
Soil pH	0.076	.	0.701		0.777	
Soil carbon %	0.678		0.402		0.075	.
Potassium (cmol/kg)			0.581		0.094	.
Clay content (%)	0.061	.	0.616		0.910	
Cocoa tree DBH (cm)	0.840		0.891		0.308	
Mistletoe (%)	0.526		0.014	*	0.159	
Pesticide (ltr/ha)	0.029	*	0.743		0.793	
Fungicide (sachets/ha)	0.006	**	0.583		0.453	
Hybrid seedlings (%)	0.475		0.252		0.016	**

Significant levels: p at 0.001= ‘***’, 0.01= ‘**’, 0.05 =‘*’, 0.1 =‘.’

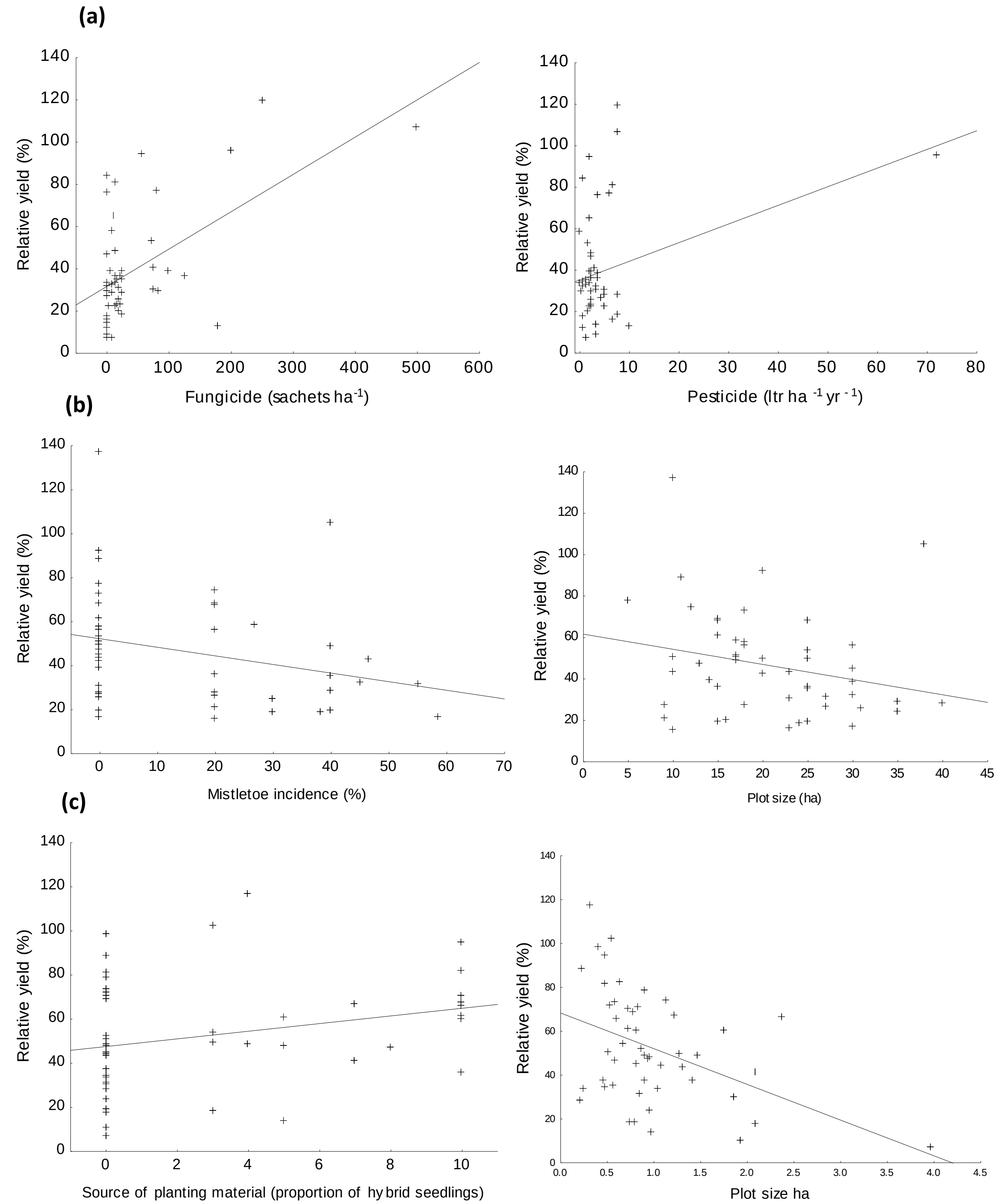

Fig.5 Significant yield gap determinant factors for the dry (a) mid (b) and wet (c) regions. Relative yield is the farmer yield percentage of attainable yield. NB: the relationship for pesticide usage and yield gap was strongly influenced by an outlier; this value was double checked and confirmed with the farmer. Points above 100% contributed to the attainable yields.

Soil fertility status

There were significant differences between some soil nutrient parameters among the three regions (Table 3). The highly weathered Ferralsols of the wet region had significantly lower pH compared to the dry and mid regions. Soil organic carbon (SOC) and total N were significantly lower in the dry region compared to the mid and wet regions, but all regional values were below the established threshold values of 2%, 0.2% and 3.5%, respectively (Table 3) as recently proposed by Van Vliet and Giller (2017) and Asare et al. (2016). The wet region soils also had significantly lower calcium (Ca) content than those in the mid and dry regions. Soil magnesium (Mg) content decreased significantly from the dry to the wet region while no difference in soil potassium (K) was observed between the regions. Extractable P determined by Bray I extraction metod was significantly higher in the mid region than in the wet region but not different from the dry region, with all regions recording P values below the threshold value of 20 ppm. The soil cation exchange capacity (CEC) was only significantly higher in the mid region than in the wet region, but all regions were within the threshold values of 3-15 cmolc/kg (Van Vliet and Giller, 2017; Asare et al., 2016). Base saturation was much above the threshold values of 35% for all regions but the wet region had significantly lower levels (Table 3).

Table 3 Mean and standard deviation (SD; in brackets) of soil nutrient characteristics between the studied regions. Different letter indicating significant difference between the regions

Soils	Dry	Mid	Wet	Threshold*
pH	6.9(0.40)^{a}	6.8(0.47)^{a}	5.3(0.31)^{b}	5.6–7.2
Soil organic C%	1.32(0.45)^{a}	1.64(0.53)^{b}	1.71(0.41)^{b}	2.03
Total N%	0.12(0.03)^{a}	0.14(0.05)^{b}	0.15(0.04)^{b}	0.2
Soil OM%	2.3(0.8)^{a}	2.8(0.9)^{b}	2.9(0.7)^{b}	≥3%
Ca (cmolc/kg)	8.46(4.34)^{a}	10.23(7.15)^{a}	3.93(2.34)^{b}	7.5
Mg (cmolc/kg)	2.34(1.14)^{a}	3.16(1.89)^{b}	1.56(0.92)^{c}	2.0
K (cmolc/kg)	0.23(0.09)^{a}	0.22(0.10)^{a}	0.18(0.09)^{a}	0.25
P (ppmP)	11.11(5.14)^{ab}	13.74(8.88)^{b}	8.72(3.60)^{a}	20
C.E.C (cmolc/kg)	11.22(5.12)^{a}	13.85(8.84)^{ab}	9.22(3.56)^{ac}	3-15.
% Base Sat.	98.81(1.06)^{a}	98.78(1.47)^{a}	93.67(3.56)^{b}	< 35

*Soil nutrient threshold values for cocoa cultivation (Van Vliet and Giller, 2017), (Asare et al., 2016)

Soil organic carbon was shown to be determined by soil texture, i.e. mainly by the content of sand and clay. Clay content had positive effect on SOC in the dry and wet regions while the reverse was true for sand (Table 3). In the mid region, only clay content was a significant factor determining SOC with a negative effect. All cocoa plantation characteristics including shade cover, farm age, cocoa plant density and shade tree basal area did not have any significant effect on SOC across the regions.

Table 4 Main factors determining soil organic carbon across the regions. N=50 per region

Dry	Unit	Sum Sq	Mean Sq	F value	Pr(>F)		t value
Sand	%	3.710	3.710	41.043	1.03E-07	***	-4.747
Clay	%	1.610	1.610	17.813	0.000128	***	4.057
Shade cover	%	0.015	0.015	0.170	0.681928		-0.513
Cocoa plot age	years	0.027	0.027	0.297	0.588567		0.447
Cocoa plant density	trees ha^{-1}	0.251	0.251	2.773	0.103287		-1.403
Shade tree basal area	(m^2)	0.228	0.228	2.523	0.119688		1.588
Mid							
Sand	%	0.140	0.140	0.540	0.46644		0.291
Clay	%	1.640	1.640	6.345	0.01557	*	-2.489
Shade cover	%	0.267	0.266	1.031	0.31555		0.948
Cocoa plot age	years	0.001	0.001	0.004	0.95149		-0.28
Cocoa plant density	trees ha^{-1}	0.477	0.477	1.848	0.18114		-1.495
Shade tree basal area	(m^2)	0.129	0.129	0.499	0.48369		0.706
Wet							
Sand	%	1.426	1.426	9.620	0.003394	**	-2.635
Clay	%	0.170	0.170	1.145	0.290492		0.531
Shade cover	%	0.103	0.102	0.691	0.410269		0.684
Cocoa plot age	years	0.025	0.025	0.168	0.683777		0.315
Cocoa plant density	trees ha^{-1}	0.061	0.061	0.411	0.524998		0.638
Shade tree basal area	(m^2)	0.000	0.000	0.000	0.991279		-0.011

*Significant levels: '***'= 0.001, '**' =0.01 '*' =0.05*

3.5 Discussion

The study showed that noticeable variations in yield and yield gaps exist between and within the different climatic regions due to heterogeneous soil fertility of the cocoa producing regions in Ghana. The proposed hypothesis of higher yield in the more climatically suitable wet region and higher relative yield gap in the climatically marginal dry region were confirmed, but absolute yield gaps followed the opposite trend. Soil fertility indeed also varied between regions, but no significant effect of cocoa plot characteristics and management on SOC was recorded. Significantly higher organic carbon at the mid and wet regions than in the dry region could be attributed to the land use history of the cocoa plots as most plots were established on primary and secondary forest (Abdulai et al, 2018b). Overall soil fertility status was low across all regions but regions will require different nutrient recommendations and application rates due to high variations with climate being a major factor contributing to the differences in soil fertility (Snoeck et al., 2010). Soil organic carbon status was mainly determined by soil texture, when management only had a limited effect.

Yield gap and variability across climatic regions

The results demonstrated significant differences in current cocoa yields between the studied regions thereby confirming the existence of a climate suitability gradient as projected by Läderach et al. (2013). The low attainable yield of 645 ha^{-1} yr^{-1} in the dry region in conjunction with the projected climatic suitability decline for cocoa suggests that farmers need to explore the cultivation and possible shift to other crops, in line with Schroth et al., (2017) labelling the region as a "transformational climate change adaptation zone". The low farmer's yields and high percentage yield gap in the dry region can be attributed to the lack of intensification as a risk management strategy due to the existing marginal climatic conditions and associated drought and fire risks in this region (Abdulai et al. 2017a; Asante et al., 2016; Adjei-Nsiah and Kermah, 2012). Farmers' decision for low intensification and crop management efforts might be influenced by the existing climatic risks as revealed in other studies (Menapace et al., 2013; Cooper and Coe, 2011). This risk pattern has resulted in the region to be dominated by old age cocoa farmers as the economic return is unattractive to the younger generation. As a result, cocoa production in the dry region is likely to transit into short rotation annual crops and drought tolerant tree crops (such as cashew) which are less vulnerable to current and projected future climatic risks (Asante et al., 2016; Adjei-Nsiah and Kermah, 2012). Cocoa being a perennial tree crop is difficult to adapt to climatically risky conditions, unlike annual crops where crop management activities could be much better aligned with season-specific practices to reduce risk in conjunction with seasonal weather forecasts (Hoffmann et al., 2018). Assuming that improved seasonal weather forecasts and El Niño information will become available to reliably predict drought, at least pruning and replacement of high water demanding shade trees species could be adopted, as well as fertilizer management. Average farmer yields and attainable yields in the mid and wet regions recorded for this study are higher compared to the yield levels previously reported for Ghana (Aneani and Ofori-Frimpong, 2013; Anim-Kwapong and Frimpong, 2004). In addition to the more suitable climatic conditions, farmers in these two regions have intensified their production and management activities than those in the dry region. The climatic effect on productivity in the wet region is further minimized by the fact that farmers have low percentage yield gap due to the absence of water limitation that can hinder intensification. Although the yield gap is an indication of existing challenges faced by farmers, it concurrently indicates the scope for productivity increase (Wang et al., 2015). Ghana has shown that it is possible to attain higher yield as the country recorded a cocoa bean production of over 1 million tonnes in 2010/11 (Fig. 1). The variations in the average farmer yield and attainable yield between the climatic regions is therefore an indication that region-specific production improvement interventions are required.

Yield gap determining factors across the regions

To explore existing opportunities after yield gap analysis, it is important to understand the determinant factors to guide intervention aiming at closing the gap. Due to high climatic risks of increased drought frequency and severity causing lower yield, increase in pest and diseases, frequent fire and high mortality of cocoa plants in the dry region (Adjei-Nsiah and Kermah, 2012; Anim-Kwapong and Frimpong, 2004), farmers have resorted to co-planting of fruit trees such as avocado (*Persea americana*) and orange (*Citrus cinensis)* in a diversification strategy for risk management (Graefe et al., 2017) (Abdulai et al., 2018b). The most significant determining factors for yield gap in this region were fungicide and pesticide usages, resulting in higher yields (Fig. 5a). Pesticide and fungicide applications have being identified as crucial for cocoa production in Ghana as black pod diseases (*Phytophthora palmivora* and *megakarya*) and mirids (*Sahlbergella singularis*) infestation could lead to complete crop failure (Aneani and Ofori-Frimpong, 2013; Anim-Kwapong and Frimpong, 2004). Their application is the most important cultural practice under low intensive system as cocoa yield could reach over 2000 kg $ha^{-1}yr^{-1}$ with pest and disease control without fertilizer under experimental conditions (Ahenkorah et al., 1974).

In the mid region, mistletoe (*Tapinanthus bangwensis*), a parasitic plant which is commonly severe in older plantations was among the most significant yield gap determinant factors. This confirms reports by other authors in the West African region (Kumi and Daymond, 2015; Smith Dumont et al., 2014). According to Ahenkorah et al, (1974), lack of shade on cocoa trees enhances mistletoe prevalence and considering that the mid region had the lowest shade cover (13%), such effect is not surprising. Farm size was another significant factor for both the mid and wet regions. Farm size has being observed to negatively influence smallholder farmer's productivity for both cocoa and oil palm (Euler et al., 2016; Aneani and Ofori-Frimpong, 2013). This could be attributed to inefficient management under bigger farms as farmers mainly depend on household labour and are usually unable to afford sufficient inputs (Aneani and Ofori-Frimpong, 2013)

The wet region is the most intensified considering the highest attainable yields which therefore reduce the yield gap factors from management to quality of planting materials. Quality planning material refers to hybrid cocoa seedlings or seed sourced from the seed production unit of the Ghana COCOBOD. Increase proportion of hybrid cocoa trees per farm resulted in significantly positive impact on cocoa yield.

Soil fertility status and effect of smallholder cocoa cultivation on soil organic carbon

Although the soil nutrient parameters did not show significant effects as yield gap determining factors, they cannot be overlooked in any effort of addressing yield gap as their effect on cocoa yield is well established (Van Vliet and Giller, 2017).

The soil analysis results highlight variation in soil fertility across the different climatic regions for cocoa cultivation in Ghana. Soil pH, Ca, Mg, K, P, and CEC were the lowest in the wet region. This can be attributed to heavy rainfall and associated soil weathering and nutrient leaching in the region (Snoeck et al., 2010). In spite of this, the wet region is still the highest cocoa yielding region as the high rainfall results in high growth and biomass accumulation resulting in high nitrogen availability and SOC (Snoeck et al., 2010). The plantation history can also have an effect on the organic carbon as the farms in the dry region were mainly established on bush/old cocoa and short fallow lands with less initial organic carbon (Abdulai et al, 2018b). Higher SOC in the wet region is therefore not surprising as the farms were mainly established on primary and secondary forests with higher initial organic carbon content (van Straaten et al., 2015). It has been documented that farmers in this region apply pesticide and fertilizer frequently (Ruf, 2007), which can be contributing factors to the high yield even though the soil conditions might not be ideal. The dry and mid regions have been noted to possess favourable soil conditions for cocoa cultivation (Anim-Kwapong and Frimpong, 2004), but unlike the mid region with higher yield, the dry regions had very low yield and might be rather limited by reduced rainfall. The high yield in the mid region is therefore a combination of favourable soils and optimum rainfall (1400 – 1500mm) conditions (Snoeck et al., 2010).

Soil organic carbon was low across all the regions and can be attributed to the effect of land use change from forest to cocoa as most land use change studies including those for cocoa have found negative effect on SOC (Van Vliet and Giller, 2016; Don et al., 2011; Guo and Gifford., 2002). This suggests that smallholder cocoa farming systems might not be environmentally sustainable as it could not maintain SOC levels at moderate levels of 2-3%). The cocoa plant densities across all the regions were higher than the recommended density of 1111 tree/ha from the Cocoa Research Institute (CRIG). This can be a contributing factor to the low SOC contents as Ofori-Frimpong et al. (2010) observed negative effect of cocoa plant density on SOC. Shade trees were expected to increase the soil organic matter with resultant effect on SOC over time (Tscharntke et al., 2011). This could not be confirmed as we could not establish any significant effect of cocoa plant age, shade cover and shade tree basal area on SOC across all the regions. A follow up study specifically on soil fertility at higher spatial resolution along gradients from shade to non-shade within plots would be desirable. Interestingly, the lack of shade tree effect on SOC has also been documented by Ofori-Frimpong et al., (2010) and Blaser et al., (2017) in their studies in Ghana. The importance of soil texture to SOC reported by Li and Pang (2014) was confirmed. In the dry region, both sand and clay were significant SOC determining factors with negative and positive effects respectively. In the mid region, only clay content was significant but with a negative effect. For the wet region, sand showed negative significant effect as determining factor of SOC. This could be the effect of high leaching influenced by rainfall condition and less organic aggregation in sandy soils (Van Straaten et al., 2015). Underlying the importance of ‘sustainable aspect’ of sustainable intensification, the role of SOC in maintaining adequate cropping systems and as sink to mitigate GHG emission requires more attention than currently in cocoa production. This might even offer new dimensions, especially when SOC of these perennial systems are compared with alternative cropping systems, in particular cereal based annual systems, cocoa might be a better option for climate smart farming.

3.6 Conclusion

This study highlights the large variations in yield and yield gaps in cocoa producing regions of Ghana that have contrasting climatic conditions. Large yield gaps across the regions showed a low degree of sustainable intensification and should be perceived as an opportunity to increase and sustain national cocoa production by site-specific and possibly season-specific management. Overall, there was variation in soil fertility along the climatic gradient. Soil organic carbon contents under smallholder cocoa farming systems were low. Low yield in the dry region could be attributed to either farmer not able to afford the cost of pesticide and fungicides or not willing to invest under such climatically marginal conditions. In addition to large farms recording higher yield gap, the yield gap determining factors were parasitic mistletoe for the mid and type of planting material for the wet regions. The different climatic regions within the cocoa belt therefore require different crop and soil management strategies tailored to local conditions. The underlying factors to close the existing yield gap based on the identified site-specific determining factors are improved crop management, high quality planting material and improved soil nutrition mainly N, P and K (Snoeck et al., 2010; Afrifa et al., 2009). National production would benefit from taking up these site-specific production recommendations which to ensure sustainable intensification of cocoa production in Ghana. National interventions for closing the current cocoa yield gap should be climatic region and soil-specific.

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Chapter Four

Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun

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4.1 Abstract

Cocoa agroforestry is perceived as potential adaptation strategy to sub-optimal or adverse environmental conditions such as drought. We tested this strategy over wet, dry and extremely dry periods comparing cocoa in full sun with agroforestry systems: shaded by (i) a leguminous tree species, *Albizia ferruginea* and (ii) *Antiaris toxicaria*, the most common shade tree species in the region. We monitored micro-climate, sap flux density, throughfall and soil water content from November 2014 to March 2016 at the forest-savannah transition zone of Ghana with climate and drought events during the study period serving as proxy for projected future climatic conditions in marginal cocoa cultivation areas of West Africa. Combined transpiration of cocoa and shade trees was significantly higher than cocoa in full sun during wet and dry periods. During wet period, transpiration rate of cocoa plants shaded by *A. ferruginea* was significantly lower than cocoa under *A. toxicaria* and full sun. During the extreme drought of 2015/16, all cocoa plants under *A. ferruginea* died. Cocoa plants under *A. toxicaria* suffered 77% mortality and massive stress with significantly reduced sap flux density of 115 $gcm^{-2}d^{-1}$ whereas cocoa in full sun maintained higher sap flux density of 170 $gcm^{-2}d^{-1}$. Moreover, cocoa sap flux recovery after the extreme drought was significantly higher in full sun (163 $gcm^{-2}d^{-1}$) than under *A. toxicaria* (37 g cm^{-2} d^{-1}). Soil water content in full sun was higher than in shaded systems suggesting that cocoa mortality in the shaded systems was linked to strong competition for soil water. The present results have major implications for cocoa cultivation under climate change. Promoting shade cocoa agroforestry as drought resilient system especially under climate change needs to be carefully reconsidered as shade tree species such as the recommended leguminous *A. ferruginea* constitute major risk to cocoa functioning under extended severe drought.

Key words: Agroforestry, extreme heat and drought, shade tree species, sap flux density, soil water deficit, *Theobroma cocoa L*, transpiration rate

4.2 Introduction

Cocoa is a major global commodity and according to the International Cocoa Organization (ICCO), annual global production in 2016 stood at 3,971 thousand tonnes resulting in 197,000 tonnes deficit in global demand (ICCO, 2017). Up to 95% of the global cocoa production comes from smallholder farms, and global cocoa demand is expected to increase from 4.1 million in 2016 to 4.7 million tonnes by 2020 (Carr & Lockwood, 2011; World Cocoa Foundation, 2014; ICCO, 2016). Such economic outlook offers good perspectives for improving the livelihood of smallholders, including the estimated two million farmers in the cocoa growing regions of West Africa (Schroth *et al.*, 2016a), a high percentage of which are suffering from severe poverty, defined as per capita income of less than 1$ per day (Lambert, 2014; Fountain & Hütz-Adams, 2015). Increasing income from cocoa is therefore a major pathway for smallholders to escape poverty in the region. However, farmers livelihoods are highly threatened by the vulnerability of their agricultural production systems to increases in the frequency and severity of extreme weather such as heat-waves and drought (Sheffield & Wood, 2008; Coumou & Rahmstorf, 2012; Thornton et al., 2014;Sultan & Gaetani, 2016). El Niño Southern Oscillation (ENSO) phenomenon plays an important role in global cocoa production as historical records show strongly reduced cocoa production during El Niño years (ICCO, 2016). The Harmattan season in West Africa characterized by continental northerly winds carrying dry dust from the Sahara desert following the Monsoon season is significantly intensified during El Niño years (Lyngsie *et al.*, 2011). This results in extended dry spells, low air humidity, high evaporative demand of the atmosphere and high maximum daily temperatures over much of West Africa (Wang *et al.*, 2014). Although studies on the projected frequencies of such extreme events are limited for West Africa (Niang et al., 2014), their relation with El Niño events are well established. Since El Niño events are projected to be amplified by climate change (Cai *et al.*, 2014), we expect such extreme drought events to become more frequent. Apart from such extreme events, almost half of the cocoa growing areas of West Africa are projected to become climatically marginal according to climate change projections as reported by Schroth et al. (2016). The duration and severity of the Harmattan is crucial for cocoa production in the region, as increase in water stress significantly reduces cocoa plant performance (Carr & Lockwood, 2011). During 2015/16 production cycle, Côte d'Ivoire and Ghana, the major global cocoa producers, experienced the lowest production of the past decade due to a prolonged dry season (ICCO, 2016). In fact, the

2015/16 El Niño event resulted in the strongest drought in these countries since the 1982/83 ENSO event. Historical response of cocoa production areas in West Africa to the 1982/83 El Niño event was mainly a cocoa migration into more humid regions, i.e. new forest frontiers (Ruf *et al.*, 2015). Such response is currently not feasible anymore as forest land is limited and deforestation related to cocoa farming under strict control due to international commitments to prevent deforestation to reduce global warming and loss of biodiversity (Damnyag *et al.*, 2013; Ruf *et al.*, 2015; Asante *et al.*, 2016). Cocoa production therefore needs to become more resilient to more frequent occurrence of extreme weather, expected to be aggravated by climate change (Fischer & Knutti, 2015). Cocoa plant (*Theobroma cacao L*) is considered a drought-sensitive crop with water limitations having direct negative effect on leaf physiology, fruit and bean size (Carr & Lockwood, 2011). Marginal climatic conditions for cocoa, characterized by high temperatures during the Harmattan season are being experienced in the Forest-savanna transition zones of the cocoa belts across West Africa (Schroth *et al.*, 2016a). Ghana is already experiencing a reduction in rainfall within the forest zones where cocoa is mainly grown (Owusu & Waylen, 2009). Schroth *et al.* (2016b) have employed a statistical niche model, using Maximum entropy (Maxent) approach, to characterize cocoa climate suitability across West Africa. Climatically suitable areas for cocoa in Côte d'Ivoire, Ghana and across West Africa are shrinking and projected to become restricted to the wet and previously forested regions by 2050 as moisture availability and thermal suitability thresholds are likely to be exceeded in large parts of current cultivation areas due to climate change (Läderach *et al.*, 2013; Schroth *et al.*, 2016b).

To date, however, relatively little quantitative information is available for relating climate suitability to concrete measurements on how different cocoa systems perform under contrasting (micro-) climatic conditions. It has been proposed that under severe adverse climatic events such as pronounced drought and/or heat periods, agroforestry systems combining shade trees with cocoa (or coffee) possess high climate resilience. Consequently, the agroforestry systems have been proposed as an adaptation strategy (Lin, 2007; Schwendenmann *et al.*, 2010; Tscharntke *et al.*, 2011; Vaast & Somarriba, 2014; Padovan *et al.*, 2015; Schroth *et al.*, 2016b). These studies explain that shade trees contribute to climate resilience by taking up water from different soil depths than the crop in the under-storey resulting in complementary water resource use. In addition, they demonstrate that shade buffers the shaded crop from high temperature and solar radiation, thereby providing a more favourable micro-climate than in full sun. Finally, it has also been demonstrated that shade trees increase soil organic matter in the long term and consequently improve plant water availability through an enhanced water holding capacity of the soil in some agroforestry systems such as cocoa in Indonesia (Schwendenmann *et al.*, 2010), coffee in Costa Rica (Cannavo *et al.*, 2011) and rubber systems in China (Wu *et al.*, 2016a & b). The perceived long term benefits of shade trees sustaining soil fertility and having positive effect on cocoa plant growth and yield on smallholder plots have been shown to be limited (Blaser *et al.*, 2017). Even under a well-managed cocoa agroforestry system, balanced fertilizer and soil nutrient management is required to avoid soil nutrient depletion (Bai *et al.*, 2017).

However, despite the promotion of agroforestry as adaptation strategy for cocoa production under climate change, quantitative studies on the response of mature cocoa plants to drought under sub-optimal to marginal climate conditions are lacking for the different cultivation systems (Carr & Lockwood, 2011). The work of Schwendenmann *et al.* (2010) aimed to partly close this knowledge gap by assessing soil water availability and sap flux densities of cocoa plants under leguminous *Gliricidia sepium* shade trees in a throughfall reduction experiment to simulate extreme drought associated with strong El Niño years in Sulawesi, Indonesia. A major limitation of this study was the lack of comparison between agroforestry and full sun systems, the latter being increasingly the dominant practice in the major production regions of West Africa.

Consequently, in this paper we aimed to evaluate the basic hypothesis that shade indeed improves cocoa tree resilience to climate variability and change, particularly in drought-prone conditions. It is based on the following sub-hypotheses: (1) extreme climatic conditions (drought and heat) are buffered by the more favourable micro-climate generated by shade trees, and (2) higher water uptake in shaded system is due to (i) complementary soil water use in shaded system during drought situations and (ii) reduced water loss due to shade, particularly surface evaporation and run-off and thus enhanced soil moisture conservation. Therefore, we monitored micro-climate, soil moisture change and water use characteristics of cocoa and two associated shade tree species for three cocoa cultivation systems: (a) under a recommended leguminous tree (*Albizia ferruginea*), (b) under the most common shade tree in the study region (*Antiaris toxicaria*), and, for comparison, (c) under full sun conditions, over periods of wet (rainy season), dry (2014/15 normal Harmattan) and extremely dry (i.e. severe Harmattan as a result of 2015/16 El Niño event) at the forest transition to savanna zone in Ghana.

The occurrence of a very severe drought due to the El Niño event in 2015/16 provided the opportunity to gain deeper understanding of cocoa plant response to extreme drought. The marginal climatic conditions of the study site (Läderach *et al.*, 2013) are projected for almost half of the cocoa cultivation areas in West Africa by 2050 according to climate change and suitability projections reported by Schroth *et al. (*2016a). Therefore, this study aimed to provide crucial quantitative information on cocoa plant response to drought stress under shaded and full-sun systems in order to guide long term planning of cocoa adaptation strategies to climate change in those areas.

4.3 Materials and methods

Study site

The experiment was conducted in a 10-year-old cocoa (*Theobroma cacao L*) plantation near Akumadan, Offinso North District of Ashanti region, Ghana (1°59'37.211"W 7°19'51.69"N) at an elevation of 298 m a.s.l. The area has a bi-modal rainfall pattern with mean annual rainfall varying between 700 and 1200 mm and mean annual temperature of 27˚C based on climatic records for the period 1951-2000 (Owusu & Waylen, 2009). Over the past 30 years, much of the vegetation in this region changed from moist semi-deciduous to a more dry Savanna transition forest zone resulting in change from cocoa to maize as the dominant crop (Adjei-Nsiah & Kermah, 2012). The soils of the region are classified as Forest Ochrosols based on Ghana system of classification or Acrisols in the FAO system (Anim-Kwapong & Frimpong, 2004). These soils at the studied plots were deep, moderately well drained and of sandy loam to sandy clay loam texture. The soils under full sun and *A. toxicaria* trees were sandy loam while those under the *A. ferruginea* were loam - in the top 50cm. The deeper horizons (50-150 cm) were clay loam for the two shaded systems, and sandy clay loam for the full sun (Table S2b). Soil nutrient characteristics for the top 30cm were measured by sampling four different points within each plot to form a composite (Table S2a). Measured bulk density for the soils under *A. toxicaria* , *A. ferruginea* and full sun were 1.29, 1.21 and 1.40 g/cm^3 at 10cm, 1.65, 1.63 and 1.73 at 50cm and 1.62, 1.67 and 1.76 at 100cm depth of one soil profile established for each system in August 2015 (TableS2b).

Experimental design, plant and plot characteristics

The experimental period lasted from November 2014 to March 2016. Three cocoa systems were studied: (i) cocoa shaded by *A. toxicaria* (hereafter referred to as Cocoa-Antiaris), (ii) cocoa shaded by *A. ferruginea* (hereafter referred to as Cocoa-Albizia) and (iii) cocoa without shade trees (cocoa full sun). The two shade tree species were selected based on the fact that *A. toxicaria* is the most common shade tree species on farmers' fields in this region after fruit trees (*Citrus sinensis* and *Persea Americana* according to Graefe *et al.*, 2017), whereas *A. ferruginea* is less abundant, but recommended as suitable shade tree species for cocoa cultivation due to its leguminous nature and other properties (Manu and Tetteh, 1987). Each shaded system was studied with four replicates. Four randomly distributed individuals of the two shade tree species (*A. toxicaria* and *A. ferruginea*) were selected on a farmer field, under which measurement plots were established using the canopy dripline as the boundary. For the current cocoa agroforestry systems practised by farmers, this was the best possible way of studying the direct shade tree effect on cocoa plant since shade trees are not spatially arranged; furthermore, this is also the best way considering technical constraints of working with sap flow sensors. This was compared to an adjacent area of no shade (full sun cocoa system) with an area of 51 m^2. Total plot size of Cocoa-Antiaris and Cocoa-Albizia were 33 and 68 m^2, respectively (Table 2a). The plot size of the Cocoa-Antiaris was approximately half the other systems due to *A. toxicaria* having smaller canopy area compared to the wider canopy area of *A. ferruginea.* Both tree species are brevi-deciduous with distinguished characteristics (Table S2c). Characteristics such as diameter at breast height (DBH), height of cocoa and shade trees, cocoa tree density of each system, and finally percentage mortality of cocoa trees after the extended drought period were recorded. Soil nutrient characteristics for the top 30cm were measured (Table S2 a & b). All studied cocoa plants were of the same variety – commonly referred to as "hybrid" and supplied to farmers by the Seed Production Division (SPD) of the Ghana Cocoa Board (COCOBOD). The method of planting was direct seeding, which is the most common practice by cocoa farmers in Ghana. Pesticides and fungicides were applied to all plants during the same period since the entire farm was treated as one unit. There was no fertilizer application during the study period and weed growth was minimal, as the cocoa canopy had already closed, suppressing weeds growth. There were no understorey plants and the few weeds were controlled through herbicide application rather than the usually machete weeding to avoid damaging the cables and equipment.

Microclimate and soil water content

Air temperature and relative humidity were recorded at 30 min intervals with iButton® (DS1923 - Hygrochron Temperature and Humidity Data Logger). One iButton was installed below the canopy of each shade tree above the cocoa canopy. Three iButtons were installed in open sun on a platform that was mounted for a tipping bucket rain gauge. The iButtons were shielded with aluminium foils to avoid direct impact of solar radiation on the recordings. Quantum sensors (SOLEMSPAR-CBE80, Palaiseau, France) calibrated with LI-250A Light Meter was used to measure solar radiation. Gross rainfall (GR) was measured with a tipping bucket gauge (Model ARG 100, Campbell Scientific Inc., Logan, UT, USA) (Figure 1b). Solar radiation sensors measuring every 30s and tipping bucket rain gauge were connected to a data logger (CR1000 Campbell Scientific Inc., Logan, UT, USA) storing mean values for every 30min interval throughout the studied period with the exception of few days between sensor malfunction and replacement. Vapour pressure deficit (VPD, measured in kPa) was calculated from temperature and relative humidity recordings according to Allen *et al.* (1998). Throughfall, which refers to net-rainfall reaching the soil below the canopy, was measured from February to November 2015 using a combination of standard rain gauges (diameter 11.5cm) and home-made rain gauges (1l plastic bottles with 14.5cm diameter funnels). Seven rain gauges for two shade systems were installed in each of the four replicate shade plots per system and 28 rain gauges in the full sun plots; water content was measured within 24 hours of any rain event. Volumetric soil water content was measured bi-weekly up to a depth of 150cm at 10cm intervals with a Diviner 2000 (Sentek Pty Ltd, Australia). Four access tubes (PVC tube) were installed in each system. Diviner measurements were later calibrated using actual water content that was measured following the standard procedure (Sentek Pty Ltd, 2000).

Sap flux density and daily plant water uptake

Thermal dissipation probes after Granier (1987) were applied to continuously measure sap flux density in cocoa and shade trees over the study period. Two cocoa trees were selected under each shade tree, with four replicates per treatment (four shade trees per species). In the full sun treatment, four cocoa trees were measured. Each tree was equipped with a pair of sensors with a length of 20 mm. The sensors were inserted into holes drilled at a height of 1.3m in the shade trees, and 1m in cocoa trees (Figure 1a). Sensors were shielded from incident radiation and thermal influences by reflective foil and covered with plastic foil to protect against rainfall. The upper probe of the sensors was heated with a constant power of 2.50mV, which was generated using a solar energy system. Voltage difference between the upper and lower probes of each sensor was measured every 30s, averaged and logged at 30 min interval using a datalogger with attached multiplexer (Campbell CR1000, AM 16/32). Recorded voltages were converted into temperature differences, with which sap flux density was calculated according to the empirically derived equation of Granier (1987). Hourly (g cm^{-2} h^{-1}) and daily (g cm^{-2} day^{-1}) sap flux densities were calculated for each measured cocoa and shade trees. Daily sap flux data was recorded as the mean of at least three functional sensors. However, there were days in the wet period without data due sensor breakdown resulting in less than three functional sensors. Tree water use rates (L d^{-1}) were calculated after the equation of Granier (1987) using conductive sap wood area that was determined by microscopic analysis of core samples obtained with incremental borers and collected wood discs from cocoa and shade trees.

Fig.1 Pictures illustrate various measurements/devices employed to assess water dynamics in the investigated cocoa systems: (a) sap flux sensors installed on shade and cocoa trees protected with foil and plastic sheets and homemade rain gauges (bottom right) made of 14.5cm diameter funnels and 1liter plastic bottles, (b) tipping bucket rain gauge installed above cocoa canopy at a height of 6m and (c) soil water measurement with Diviner 2000 probe. The stick is introduced to pre-installed PVC tubes. Gravimetric water content can be read out every 10 cm down to 150 cm depth. The Diviner readings were calibrated against actual soil water content via soil sampling in dry and wet seasons.

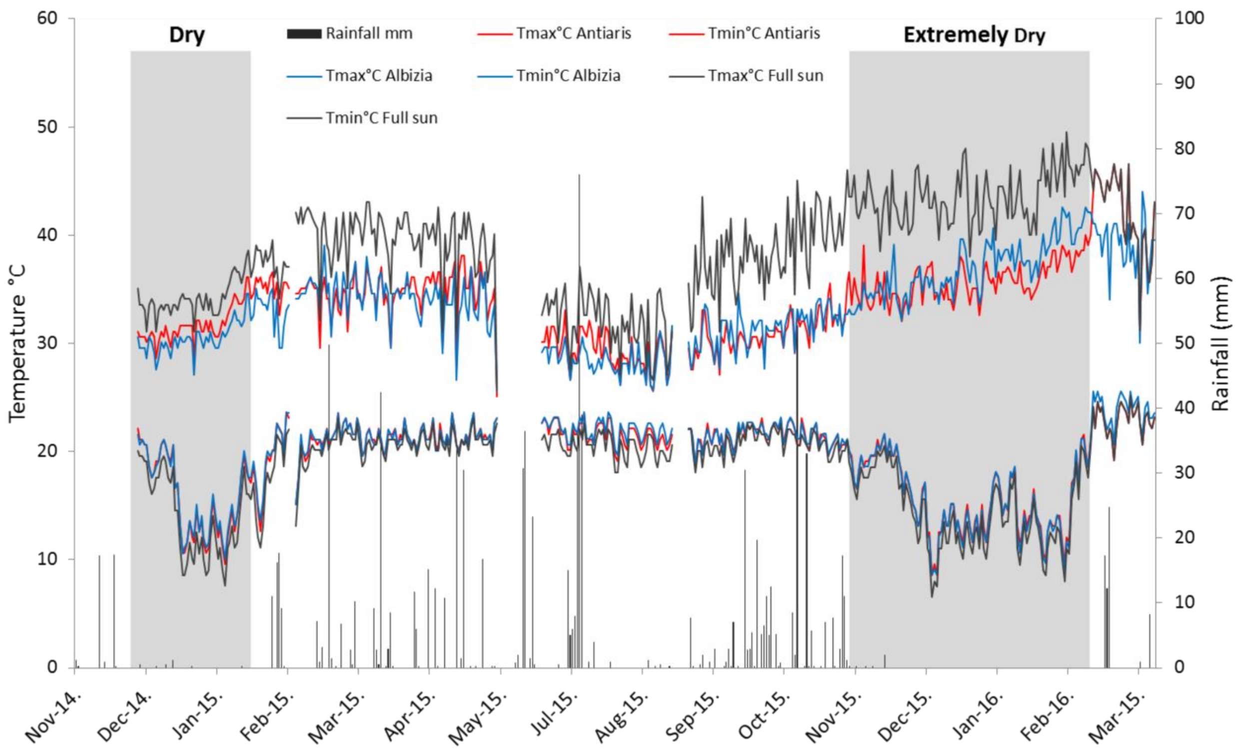

Fig. 2 Daily rainfall, Tmin and Tmax over the course of the studied periods with dry periods shaded. Lines show the mean daily Tmin and Tmax measured for each system (cocoa full sun, cocoa-Albizia, and cocoa-Antiaris). Rainfall is shown as bars. The dry and extremely dry periods were defined as all days within the Harmattan months of the region with daily Tmean of 23˚C and < 5mm rainfall per month and Tmean of 26˚C and days of no rainfall, respectively. No temperature data was available during May-June 2015 due to sensor breakdown.

Sap flux measurements were transformed into transpiration in mm per day for both cocoa and shade trees as well as combined cocoa and shade tree transpiration at plot level following the approach of Cannavo *et al.* (2011).

Data analyses

In order to assess the influence of different seasons on the parameters that were measured, the study period was categorized into four climatic periods: wet1 (November 2014, February – mid-November 2015), dry (from mid-December 2014 – January 2015 and mid-November – mid December 2015), extremely dry (from mid-December to February 2015/16) and Wet2 (March 2016). In order to evaluate the cocoa systems resilience, it is important to investigate systems performance not only before and during a shock event, but also after the shock event (Folke et al., 2002). Hence, we defined the pre-extreme drought period as Wet1 and the post-extreme drought period as Wet2. The dry and extremely dry periods were defined as days within the Harmattan months of the region with mean daily temperature (Tmean) of 23˚C and < 5mm rainfall per month, and Tmean of 26˚C and days of no rainfall, respectively.

The length of the periods was defined by the number of days within the period. The extremely dry period was also characterized by a delay in onset of rains usually taking place by mid-February (Fig. 2). Daily mean values for air temperature, solar radiation and VPD were calculated for each treatment (cocoa-Antiaris, cocoa-Albizia and cocoa full sun). Mean seasonal water use, sap flux density and transpiration rate for each system was calculated by averaging the daily values of all individual measured days over the entire periods per unit area. Analyses of means of individual daily measurements within the studied systems were preceded by Levene's test of normality at $p<0.05$ significance level. The system and seasonal effects were analysed for each period using factorial analysis of variance followed by Tukey's HSD post hoc test. The relationship between above-canopy rainfall and throughfall was also determined for each system. Significant effects were determined at $P<0.05$. Statistical analyses were carried out using STATISTICA version 12 (StatSoft Inc., Tulsa, OK, USA).

4.4 Results

Microclimatic and throughfall variations

Mean temperatures (Tmean) within the systems showed no significant differences across the seasons, except for wet2, and were approximately 26, 23, 25 and 28°C for the wet1, dry, extremely dry and wet2 periods, respectively (Table S3). Differences of up to 7˚C in daily maximum temperature (Tmax) were recorded between the full sun and shaded systems (Table 3). Significant differences in Tmax between the full sun and the two shaded systems were observed at all periods but no significant differences in Tmin were observed with exception of the dry period where the full sun was 2˚C lower (Table S3). Not surprisingly, the extremely dry period showed highest amplitudes between daily minimum (Tmin) and maximum temperatures (Tmax) (Fig 1) that were of 22˚C (15-37), 23˚C (15-38) and 30˚C (14-44) for Cocoa-Antiaris, Cocoa-Albizia and full sun, respectively. Solar radiation, measured at cocoa canopy height, was significantly higher for cocoa under full sun than with shade trees irrespective of the period. Indeed, it was 47% and 44% higher than for Cocoa-Antiaris, and 67% and 60% than for Cocoa-

Albizia during the wet and dry periods, respectively (Table 3). During the extremely dry and wet2 period, solar radiation measurements in full sun had to be discarded due to sensor malfunction. It is worth noting that a reduction in solar radiation by 2.3 kW m^{-2} was recorded between the wet to dry periods caused by the dust filled atmospheric conditions associated with the Harmattan season. On the other hand, there was a significant increase in solar radiation during the extremely dry period within the shaded systems (Table S3). In full sun, VPD generally showed significantly higher values than for shaded systems within the wet1, dry and extremely dry periods. During the wet2 periods, there was no significant difference between full sun and cocoa-Antiaris as the A. toxicaria had lost its leaves. Across the periods, cocoa-Albizia and full sun showed significantly higher mean daily VPD values at the extremely dry period with 1.87 and 2.35kPa compared to the wet1 with 0.84 and 1.04kPa, respectively. Cocoa-Antiaris system showed progressive and significant increases in VPD from the wet1 (0.86kPa) to dry (1.18kPa), extremely dry period (1.94kPa), and reduction in wet2 (1.7 kPa). Cocoa-Albizia system had the lowest VPD among the three systems (Table S3).

Throughfall expressed as percentage of gross rainfall (irrespective of rainfall intensity) was 75.9, 69.4 and 76.4% for cocoa-Antiaris, cocoa-Albizia and full sun cocoa systems, respectively (Table S2a). Daily rainfall of low intensity ($\leq$ 10 mm d^{-1}) resulted in lower throughfall than mean overall throughfall with values of 69.9, 63.0 and 73.8% for the cocoa-Antiaris, cocoa-Albizia and full sun, respectively. Throughfall was highly correlated to gross rainfall for all the systems with coefficients of determination (R^2) of 0.91 for the shade systems and 0.92 for the full sun system, respectively (Table S2a).

Variation in sap flux density during different seasons

Sap flux was significantly correlated with VPD, solar radiation and temperature irrespective of the period (Table S4). VPD always had a stronger effect on sap flux than radiation with exception of cocoa plants under *A. ferruginea* during the wet periods when the solar radiation and VPD were very low. Cocoa plants under the *A. toxicaria* and full sun systems showed reduction in sap flux density from the wet1 to dry periods while cocoa under *A. ferruginea* and the two shade tree species increased their sap flux density. During the extremely dry period, however, cocoa under *A. ferruginea* died and cocoa under *A. toxicaria* suffered severe stress and drastic reduction in sap flux rates, while cocoa under full sun maintained relatively high sap flux rate although with some reduction compared to the wet1 and dry periods (Fig. 3b). During the post-extreme drought wet2 period, cocoa under full sun maintained the flux density whiles those surviving under *A. toxicaria* showed further significant reduction.

Hourly sap flux density reduction in cocoa plants within the systems was more pronounced under extremely dry periods compared to wet1 and dry periods (Fig. 3b). For cocoa plants under cocoa-Antiaris and cocoa full sun, this resulted in significant reduction in daily sap flux density between the wet1 and extremely dry periods with values of 221 – 115 and 212 – 170g cm^2 d^{-1}, respectively (Table 2). In wet2, sap flux density for cocoa plants under cocoa-Antiaris reduced significantly further from extremely dry (115 – 37 g cm^2 d^{-1}) while cocoa full sun sustained its flux (Table 1). Cocoa plants under cocoa-Albizia experienced the lowest sap flux rate (Fig. 3b) with 28% and 25% lower daily mean sap flux density compared to cocoa under cocoa-Antiaris and full sun respectively, during the wet1 period when *A. ferruginea* had a dense canopy with only 33% of the incident solar radiation reaching the cocoa plants.

Regarding the two shade tree species, *A. ferruginea* showed a stronger increase in sap flux (Fig. 3a) resulting in water use of over 10 l d^{-1} from the wet1 to the dry period compared to *A. toxicaria* with slight sap flux density increase (Fig. 3a) and water use of over 1.5 l d^{-1} (Table 1). *A. toxicaria* experienced strong reduction in sap flux in response to the extremely dry periods (Fig.3a). Due to sensor breakdown, sap flux for *A. ferruginea* during the extremely dry and wet2 period could not be measured. However, *A. ferruginea* did survive this period with presence of leaves and canopy conditions resulting in the lowest Tmax observed compared to the two other systems and solar radiation values 66% lower than the ones of the cocoa-Antiaris system (Table S3).

There were distinct trends according to various climatic periods in sap flux density as illustrated by daily maximum sap flux density over the entire period (Fig.4). During the wet1 period, cocoa plants and shade trees maintained their sap flux densities. Maximum sap flux density increased over the dry period until the latter stage when it declined. Both cocoa plants and shade trees experienced continuous reduction in sap flux over the extremely dry period. Such reduction was much pronounced in *A. toxicaria* trees and cocoa under cocoa-Antiaris system than the full sun system (Fig.4). Sap flux density recovery at wet2 after the extremely dry period (March, 2016) could only be observed in *A. toxicaria* trees and cocoa plants under full sun but not cocoa plants under cocoa-Antiaris (Fig.4).

Variations in transpiration rate, water use and soil water content

Significantly reduced transpiration rate was observed in cocoa under shade trees during the extremely dry period (Table 1). In Cocoa-Albizia system, the combined cocoa and shade tree transpiration rate significantly increased from wet1 to dry period (Fig.5).

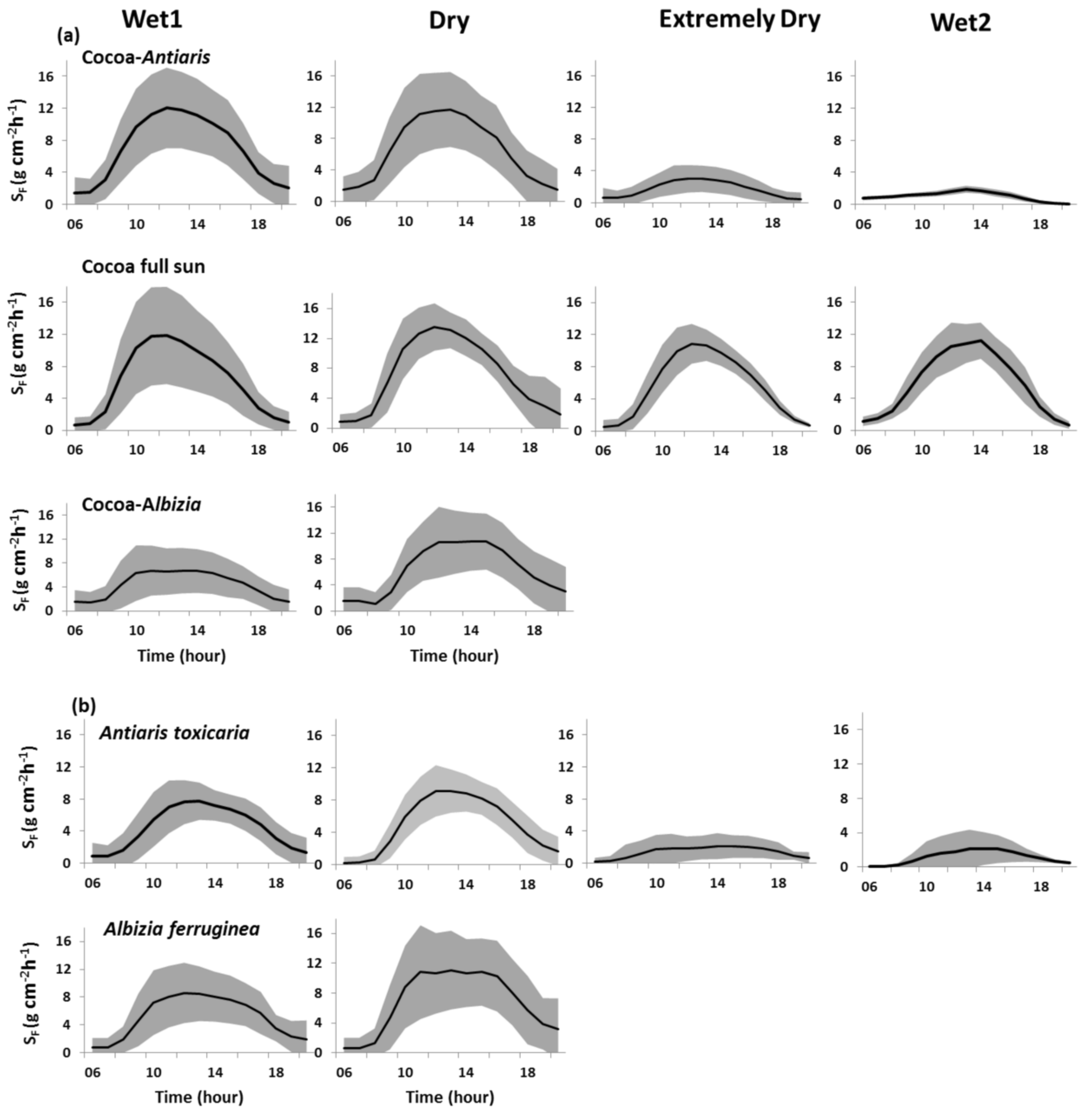

Fig. 3 Daily course of mean hourly sap flux density (g cm^{-2} h^{-1}) over the wet1 (far left), dry, extremely dry and wet2 (far right) periods of (a) cocoa under shade of *A. toxicaria* (Cocoa-Antiaris), Cocoa in full sun, and cocoa under shade of *A. ferruginea* (Cocoa-Albizia) and (b) shade trees (*A. toxicaria* and *A. ferruginea)*. Mean hourly sap flux were calculated for each shade tree species (n=4) and for cocoa trees (n=6) under each shade system and for cocoa trees in full sun (n=4) (Grey areas represent standard deviation, line is mean of sap flux density).

The shaded systems had significantly higher combined cocoa plant and shade tree transpiration rate than full sun system during wet1 and dry periods. During wet1 periods, combined transpiration rate of Cocoa-Antiaris and Cocoa-Albizia systems were 27 and 28% higher than cocoa full sun. For the dry period, the Cocoa-Albizia systems recorded the highest transpiration with 36% higher, and the Cocoa-Antiaris (reduced to) 17% higher than cocoa full sun. This pattern changed during the extremely dry periods with cocoa in full sun transpiring 26% more than the combined transpiration of *A. toxicaria* trees and surviving cocoa plants (Table 1). This gap further increased to 37% during the post extreme dry wet2 period. Cocoa plants under Cocoa-Albizia system had significantly lower transpiration rate (1.3 mm d^{-1}) and daily tree water use rate (11.7 l $t^{-1}d^{-1}$) compared to cocoa under Cocoa-Antiaris and full sun during the wet1 period. Cocoa plants under Cocoa-Antiaris also had significantly lower transpiration rate (1.7 mm d^{-1}) than full sun cocoa (2.4 mm d^{-1}) (Table 1). During the dry period, there was no significant difference between cocoa plants under the shaded systems as transpiration rate of cocoa trees under Cocoa-Albizia increased to 1.4 mm d^{-1} while that of Cocoa-Antiaris decreased to 1.6 mm d^{-1}. Transpiration rate of the cocoa plants under full sun remained significantly higher at 2.3 mm d^{-1}.

During the extremely dry period, cocoa plants under Cocoa-Antiaris and full sun recorded significant reduction in transpiration rate with values of 0.9 and 1.9 mm d^{-1}, respectively (Fig. 5 and Table 1). Cocoa full sun maintained transpiration rate at 1.9 mm d^{-1} during the wet2 while cocoa under Cocoa-Antiaris reduced significantly further to 0.3 mm d^{-1}. Overall, transpiration rate of cocoa plants in full sun were 29, 30, 53 and 84% higher than cocoa plants under Cocoa-Antiaris during the wet1, dry, extremely dry and wet2 periods, respectively. This transpiration difference was even higher compared to Cocoa-Albizia with 46 and 39% during the wet1 and dry period, respectively. For shade trees, *A. toxicaria* and *A. ferruginea* showed no significant difference in transpiration rate during the wet1 periods with 1.5 and 1.6 mm d^{-1}, respectively (Table 1). During the dry period, *A. ferruginea* showed a significant increase in transpiration rate (2.4 mm d^{-1}) and was significantly higher than the one recorded (1.6 mm d^{-1}) for *A. toxicaria* (Table 1).

Table 1 Seasonal variations in daily sap flux density (g cm^{-2} d^{-1}), daily tree water use rate (l d^{-1}), and transpiration rate (mm d^{-1}) between cocoa full sun and the two shaded systems Cocoa-Albizia, and Cocoa-Antiaris. Lower case letters: significant difference between seasons for each system; Upper case letters: differences between systems within a season at $p<0.05$. Daily tree water use rate in litres was calculated as the product of daily sap flux and conductive sapwood area. Transpiration rate estimated from sap flux density and sapwood basal area based on approach of Cannavo *et al.* (2011). N= days with active sap flux measurements within the studied periods.

	Antiaris	Albizia	Cocoa-Antiaris	Cocoa-Albizia	Cocoa-full sun	Antiaris	Albizia	Cocoa-Antiaris	Cocoa-Albizia	Cocoa-full sun	Antiaris	Cocoa-Antiaris	Cocoa -full sun	Antiaris	Cocoa-Antiaris	Cocoa-full sun
Days	210	238	276	151	181	81	64	81	65	81	80	80	80	21	22	22
								Daily tree water use rate (l d^{-1})								
Tree mean	$11.9^{a,A}$	$16.3^{a,B}$	$20.4^{a,C}$	$11.7^{a,AD}$	$19.3^{a,CE}$	$13.4^{a,A}$	$25.6^{b,B}$	$18.7^{a,C}$	$13.2^{a,AD}$	$17.3^{a,CE}$	$3.9^{b,A}$	$12.3^{b,B}$	$13.9^{b,B}$	$3.0^{b,A}$	$4.0^{c,A}$	$15.8^{b,B}$
SD	4.1	6.3	7.3	5.5	4.9	4.2	10.5	5.3	3.9	3.6	2.5	7.7	3.0	2.5	0.8	4.4
								Daily sap flux density (g cm^{2} d^{-1})								
Tree mean	$144^{a,A}$	$161^{a,A}$	$221^{a,B}$	$159^{a,AC}$	$218^{a,B}$	$153^{a,AD}$	$234^{b,BC}$	$202^{a,BCD}$	$176^{a,ACD}$	$208^{a,BCD}$	$46^{b,A}$	$115^{b,B}$	$170^{b,C}$	$37^{b,A}$	$37^{c,A}$	$163^{b,B}$
SD	58.7	60.1	65.0	62.9	50.3	47.1	96.0	56.4	52.0	51.8	33.0	73.8	33.9	29.6	7.9	43.3
								Daily transpiration rate (mm d^{-1})								
Tree mean	$1.5^{a,AC}$	$1.6^{a,AB}$	$1.7^{a,B}$	$1.3^{a,C}$	$2.4^{a,D}$	$1.6^{a,A}$	$2.4^{b,B}$	$1.6^{a,A}$	$1.4^{a,A}$	$2.3^{a,B}$	$0.5^{b,A}$	$0.9^{b,B}$	$1.9^{b,C}$	$0.4^{b,A}$	$0.3^{c,A}$	$1.9^{b,B}$
SD	0.6	0.6	0.5	0.5	0.6	0.5	0.9	0.4	0.4	0.6	0.3	0.6	0.4	0.3	0.1	0.5
Stand mean			$3.3^{a,A}$	$2.9^{a,B}$	$2.4^{a,C}$			$3.2^{a,A}$	$3.6^{b,B}$	$2.3^{ab,C}$		$1.4^{b,A}$	$1.9^{b,B}$		$0.7^{c,A}$	$1.9^{b,B}$
SD			0.6	0.9	0.6			0.8	1.2	0.6		0.8	0.4		0.3	0.5

Antiaris toxicaria reduced its transpiration rate significantly in the extremely dry period being significantly lower than that of cocoa plants under Cocoa-Antiaris and full sun. Observed variations in soil water content within the soil profile (down to 150cm) revealed reduction in soil water content for all the systems from the wet to dry periods (Fig. 6). Soil water was much more depleted in the dry and extremely dry periods in the top 60 cm of the soil profile, an indication of cocoa and shade tree roots concentration in that zone and hence competition for water resources. The soil texture was also different between the cocoa full sun and the tree systems (Table S4). As mentioned in the M&M section the soils in top 50cm for cocoa-Antiaris and full sun were sandy loam whiles that of the cocoa-Albizia were loam. There was no significant difference between the systems per season but the different texture meant different permanent wilting point. In the deeper depth (100-150cm) the texture for both shade systems were clay loam while that of full sun was sandy loam and sandy clay loam (Table 4 S4). Soil bulk density was higher in the full sun than in the shaded systems throughout the profiles. Comparing the shaded systems too, cocoa-Antiaris had the highest bulk density than the cocoa-Albizia system (Table S4). In the dry period, the soil water profile of Cocoa-Albizia was drier until 100 cm depth compared to Cocoa-Antiaris and full sun. The water content within the full sun system was hardly below $0.15m^3m^{-3}$ volumetric water content compared to the shaded systems which were usually below during the dry and extreme dry periods (Fig. 6).

4.5 Discussion

For the first time, this study showed that under field conditions in the case of extreme conditions (drought and heat) shade trees in cocoa agroforestry systems reduces rather than increases the resilience of cocoa plants. This finding rejects our basic initial hypothesis that the studied shade trees improve cocoa plant resilience to climate variability and change in drought-prone conditions.

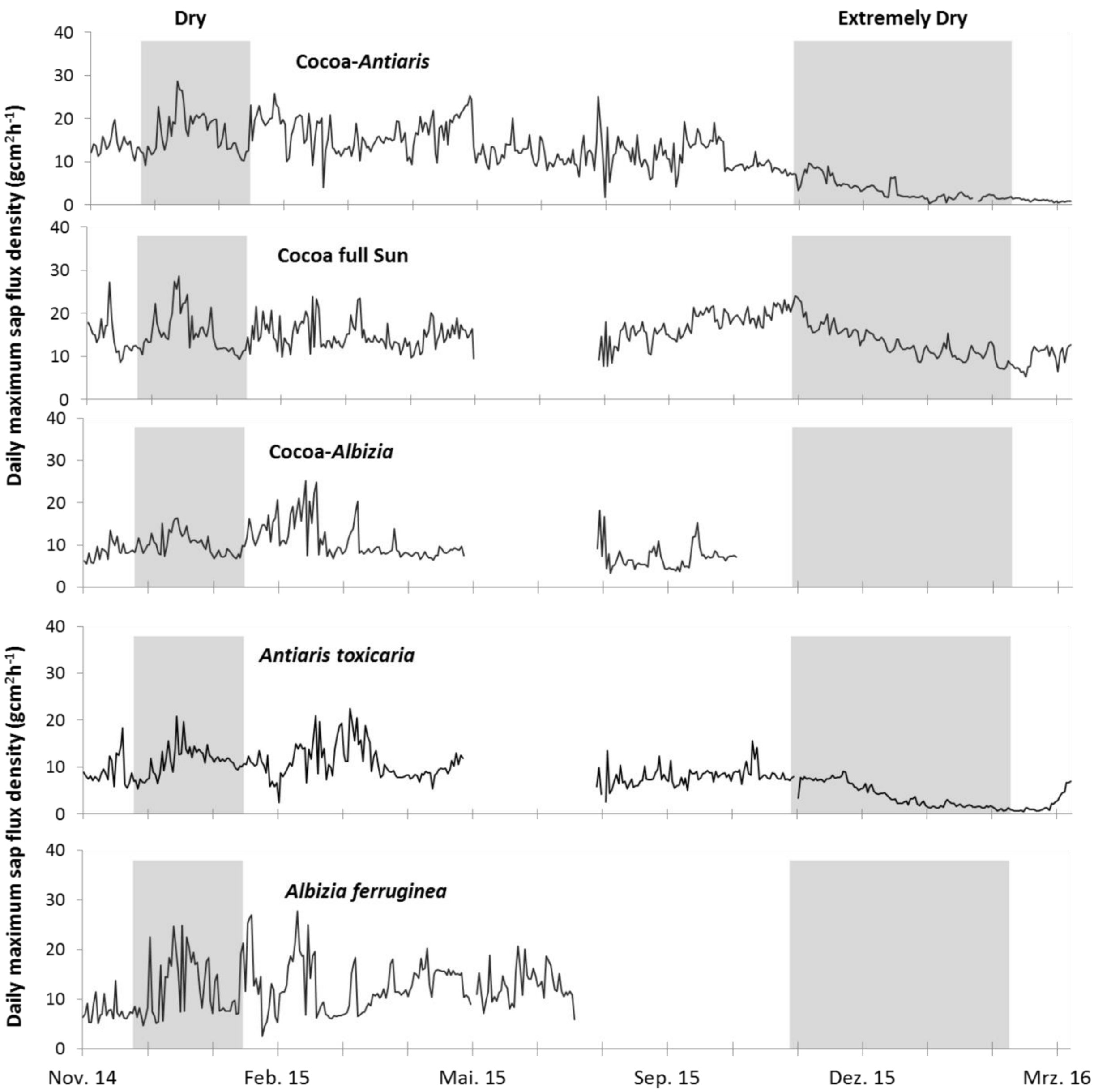

Fig.4 Mean hourly maximum sap flux density (g cm^{-2} h^{-1}) of cocoa and shade trees over the course of the study with the dry and extremely dry periods distinguished by grey. (n = 6 cocoa plants under *Antiaris* and *Albizia*, n = 4 cocoa plants under full sun cocoa system and n =4 *Antiaris* and *Albizia* trees each). The interruption in the monitoring period between May - August 2015 in cocoa-Albizia, cocoa-Antiaris, cocoa-full sun and *A. toxicaria* was caused by a sensor and recording breakdown. Cocoa-Albizia died in the extremely dry period.

The extremely dry period occurring during the experiment was caused by the exceptionally severe drought conditions triggered by the 2015/16 El Niño. Previous attempts to study impact of extreme drought on agroforestry systems such as cocoa and coffee were through either throughfall reduction or drought modelling which deviate from real drought conditions (Schwendenmann *et al.*, 2010; Cannavo *et al.*, 2011). While a recent study of Padovan *et al.* (2015) addressed such research gap in coffee, such results could not be found for cocoa in the existing literature. This is surprising given the global importance of cocoa, the widely accepted view that the region will experience more drought stress in the future due to climate change, and the relevance for the livelihood and economic contribution to its main producing countries in West Africa. The role of shade trees in micro climate moderation was confirmed especially during the dry and extremely dry periods of the study as significantly higher daily mean maximum air temperatures reaching up to 44 ˚C (Fig. 2), considered extreme for the cocoa plant (Asare, Asare, Asante, Markussen, & Ræbild, 2017), were reached in full sun while the two shaded systems recorded temperatures that were 6-7 ˚C lower.

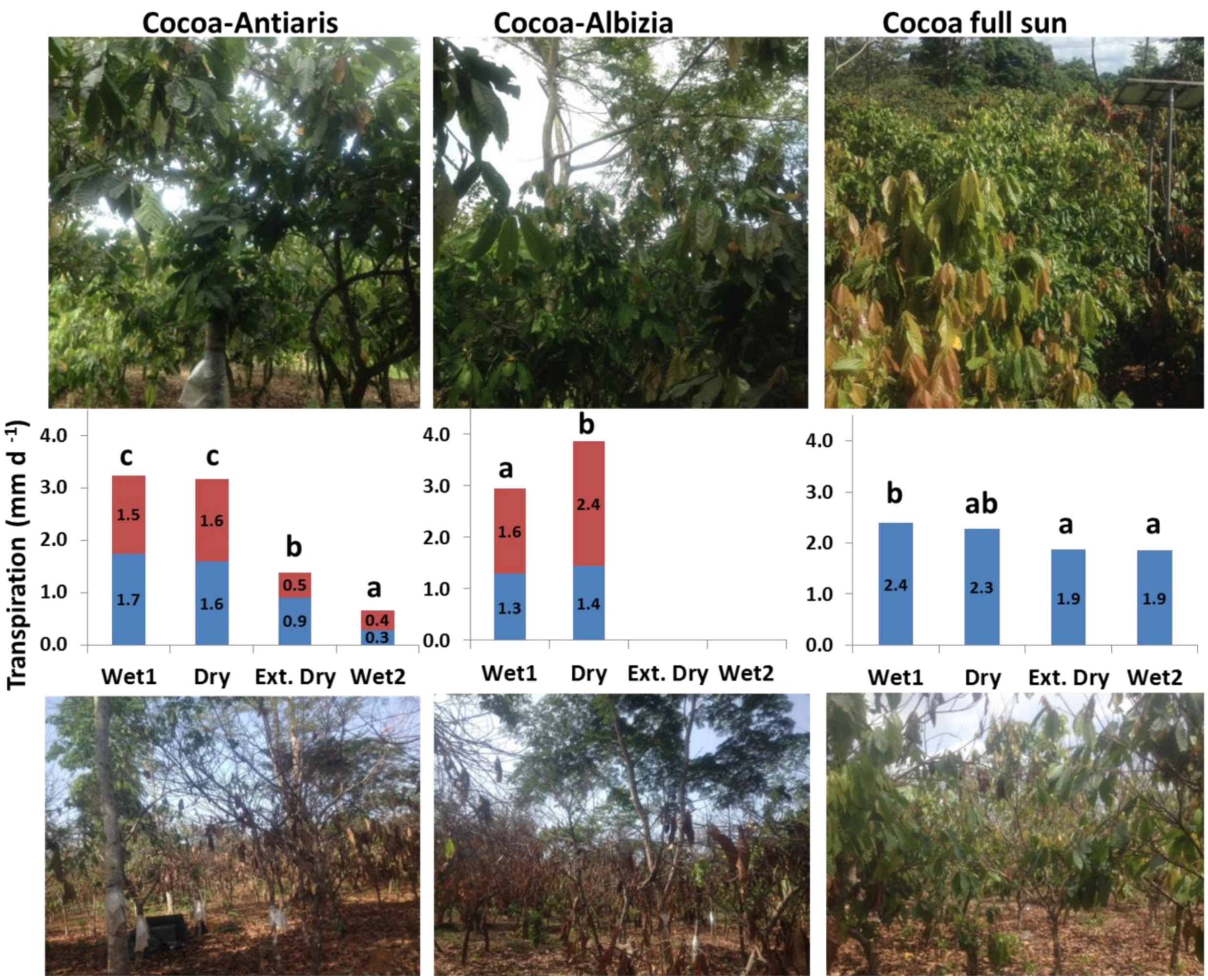

Fig. 5 Variations in mean daily stand transpiration of Cocoa-Antiaris, Cocoa-Albizia and full sun cocoa systems during the wet1, dry, extremely dry and wet2 periods (different letters indicate

significant differences between the periods within the systems at $p<0.05$). Upper red bars represent shade tree contribution to transpiration within the shaded systems and blue bars represent cocoa plant transpiration. Mean daily transpiration values in mm d^{-1} are indicated within boxes. Pictures in upper panel show the cocoa trees during the wet season and pictures in lower panel show cocoa after the extremely dry periods in the three studied systems, respectively. Note the dead cocoa trees in the Cocoa-Albizia system, while in full sun they have fresh leaves (see, lower panel).

The mean daily minimum temperatures of 17 and 15 ˚C for the shaded and full sun systems, respectively, during the dry periods were within suitable range for cocoa as mean daily minimum temperature threshold is estimated at 15˚C (Daymond & Hadley, 2004). Even under the extremely dry period, minimum temperatures recorded for the full sun systems remained above this threshold. According to Baligar *et al.* (2008), cocoa plant transpiration rates increase with increasing VPD and as such positively relate to photosynthesis when there is sufficient soil water, but have negative effects under soil water limited conditions (Moser *et al.*, 2010). The significantly higher transpiration rate of cocoa plants under full sun than the shaded systems can be attributed to higher VPD during the wet and dry periods as cocoa transpiration is known to be responsive to high VPD values (Köhler *et al.*, 2010). The lower transpiration rate of cocoa plants under the shaded systems than in full sun conditions are partly attributed to the significant difference in VPD. Higher VPD in Cocoa-Antiaris than the Cocoa-Albizia system was mainly due to the *A. ferruginea* tree having dense and broad canopy that resulted in lower Tmax and higher relative humidity than *A. toxicaria* (Table 3). The significantly lower transpiration rate and sap flux density for cocoa under Cocoa-Albizia during the wet period might have also been due to reduced solar radiation as sap flux of cocoa plants under this system was much dependent on solar radiation (Table S4). There was lack of response in transpiration and sap flux of the cocoa under shade to the significant VPD reduction from extremely dry to wet2 period. This is mainly attributed to the fact that the cocoa plants could not recovered from the physiologically stress suffered during the extreme drought. In contrary, the cocoa plants in full sun showed much resilience by sustaining transpiration and sap flux over the entire periods.

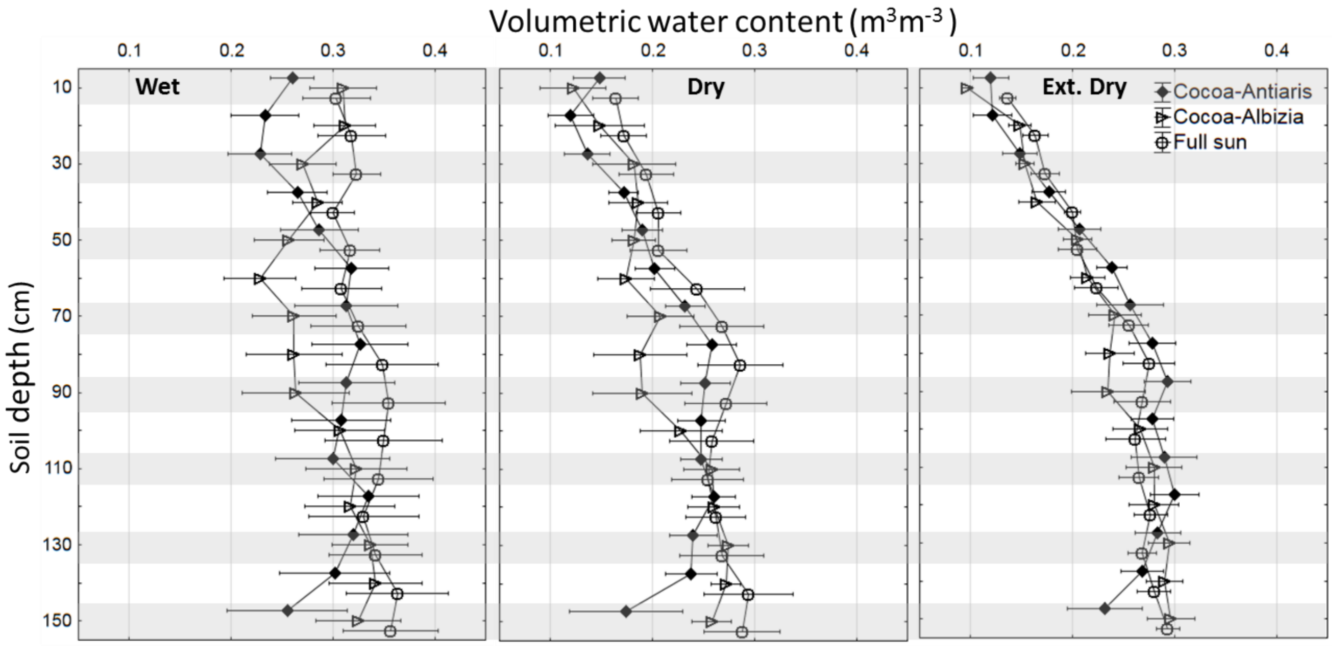

Fig. 6 Variation in mean volumetric soil water content within the soil profiles of the cocoa systems during (a) the wet month (October), (b) dry month (January 2015) and (c) extremely dry month (January - February 2016) respectively). Soil water measurements with Diviner 2000 probe was taken from six access tubes per system installed to a depth of 150cm. Bars representing standard errors.

The amount of rainfall during the dry season is crucial for cocoa plant production as shown by a simulation study by Zuidema *et al.* (2005). Since the dry season is characterized by limited and low intensity rainfall, amount of water reaching the soil by means of throughfall (percentage of total rainfall reaching the soil surface) is important to the soil water reservoir. Higher throughfall observed in the full sun than the shaded systems, especially for rainfall ≤10mm, could be attributed to absence of interception by shade trees as also observed in earlier studies on cocoa and coffee (Poppenborg & Hölscher, 2009; Siles *et al.*, 2010). Presence of evergreen and brevi-deciduos shade trees reduces the amount of water reaching the soil surface, particularly toward the end of the wet season and at the onset of the wet season when rainfall events are not intense but critically needed. Under the extremely dry period, the long-term soil water availability under the shaded system was therefore much affected by the combined effect of higher rainfall interception and higher evaporation of the shaded systems compared to full sun.

Low water uptake of cocoa plants under *Albizia* during the wet period could be attributed to limited solar radiation and low VPD conditions as similar shade effect on cocoa plant photosynthesis and stomatal conductance rates were observed by Acheampong *et al.* (2013). The increase in mean hourly sap flux density of all cocoa and shade trees from the wet to the dry periods could be attributed to the moderate VPD increase resulting in high evaporative demand during the relatively less severe and short dry periods typical of the current climatically suitable cocoa growing regions across West Africa. Reduction in daily maximum sap flux density for all trees (Fig. 4) at the latter stages of the dry periods has also been reported in other studies (Köhler *et al.*, 2010). This is mainly due to increasing plant soil water demand at higher VPD (Lobell *et al.*, 2013). Increase in the drought duration and severity resulted in soil water in the top layers reaching critical limits with the shade systems experiencing the highest reduction (Fig. 6). The soil water limitation was offset by the early return of the rainfall restoring both the soil water and recovering transpiration. During the extreme drought from December 2015 to February 2016, it was expected that sap flux density of cocoa trees under the shaded system would be increased or maintained in response to the increased VPD assuming that soil water was better conserved and complementary soil water use took place between cocoa and shade trees as demonstrated by Schwendenmann et al. (2010). However, significant reduction was observed due to water limitation in the soil, similar to the findings of Padovan *et al.* (2015) for coffee. Based on the work of Isaac et al. (2014) in Ghana, cocoa and shade trees might share similar rooting zones depending on the shade tree species, age and soil characteristics. From the soil water content (Fig. 6), it was established that soil water was much depleted within the top 60 cm, and hence indicating that both cocoa and shade tree roots occupied this zone as shown by Moser *et al.* (2010), resulting in a strong competition for the limited soil water between cocoa and shade trees. Wu *et al.*, (2016a) stated that competition rather than complementarity likely occurred under cocoa shaded by rubber trees due to the similar root distributions. This implied cocoa plants that have similar rooting system as high canopy shade trees are faced with water competition. Although Schwendenmann et al. (2010) noted that cocoa plants could withstand soil water levels lower than 0.2 m^3 m^{-3} in the top 75cm, this was still far higher than the 0.08 m^3m^{-3} permanent wilting point for sandy loam. Therefore, the water limited conditions established by Schwendenmann *et al* (2010) were not really extreme. According to Saxton & Rawls (2006), permanent wilting point of loam and sandy loam soils are reached at approximately 0.14 and 0.08m^3m^{-3} volumetric soil water content, respectively. Since the soils in cocoa-Antiaris and full sun was sandy loam, permanent wilting point might not have been reached earlier than in the Cocoa-Albizia system which was loamy soil. Bulk density under the full sun was higher than under the two shaded systems and might have contributed to higher available soil water. Higher relative humidity and lower VPD during the study of Schwendenmann *et al* (2010) also implied lower evaporative demand and hence less water requirement by the cocoa tree under shade than would have been expected for full sun cocoa. The leguminous *A. ferruginea* trees during dry conditions increased their water use significantly and resulted in direct reduction of soil water under the cocoa-Albizia system. Leguminous trees, having access to additional nitrogen, have a higher water demand even under water limited environments (Adams *et al.*, 2016), and hence competitive advantage over cocoa plants under *A. ferruginea*. The combined transpiration rate of the shade trees and cocoa plants under shaded system resulted in higher water uptake with consequent reduction in soil water than under the full sun system. Similar observations were also made in coffee systems where full sun system always had higher soil water content during dry and extremely dry periods (Padovan *et al.*, 2015).

Cocoa plants under shade trees suffered severe water stress resulting in complete plant death under *A. ferruginea* and 33% survival rate under *A. toxicaria*. When soil water content was reaching critical limits, cocoa under full sun showed the highest drought resistance. Due to the severity and duration of the drought in 2015/16, cocoa plant recovery was not possible under the shaded systems as transpiration and sap flux decreased significantly further while the cocoa plants under the full sun recovered. Our findings provide completely new insights regarding the resilience of cocoa systems under marginal climatic conditions and under severe climatic events that are projected to increase in future for half of the cocoa cultivation areas of West Africa due to expected climate change. Summarizing, we found that:

1. During wet periods when soil water is not limiting, high shade as in *A. ferruginea* reduces transpiration rate of cocoa plants as a result of reduced VPD and incident solar radiation
2. When dry periods are normal as in the dry period of this study (moderately severe and short duration), cocoa under shade increases its transpiration rate in response to moderate rise in temperature, VPD and improved soil nutrient availability, especially under the leguminous, nitrogen-fixing *Albizia ferruginea* (Table 2a).

3. Under extreme climate with severe drought conditions, the role of these popular shade trees on cocoa plants becomes critical as competition for soil water is intensified with cocoa plants. In such situation, water limitation overrides the seemingly favourable microclimatic moderations brought about by the association of cocoa with shade trees. Cocoa plants under full sun have higher resilience and acclimatization capacity to increasing drought events than shaded cocoa as revealed by this study.

Based on our findings, the promotion of cocoa agroforestry systems, i.e. shade trees for cocoa in West Africa and other regions of the world has to be reconsidered in regions where extended droughts already occur or will likely occur under future climatic conditions. Farmers might need to be advised to shift from cocoa cultivation to other crops and income sources to improve their livelihood or may require access to affordable and profitable irrigation technologies. This applies at least to conditions where climate change will be characterized by extreme drought and heat events. Actually, our study demonstrated that in such situations the opposite strategy, cocoa under full sun, appears to be more climate-resilient than systems with shade trees. We recommend conducting similar studies on shade tree and cocoa plants intercropping especially in West Africa where such studies are completely lacking.

4.7 Acknowledgements

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Supporting Information

Table S2a – S2c are presented as Table 1,2 and 3 in Chapter 1 of this thesis.

Table S3. Seasonal variations of microclimatic parameters: vapour pressure deficit (VPD), maximum and minimum temperature (°C), and solar radiation (kW m^{-2}). Lower case letters indicate significant difference between seasons for each system; upper case letters indicate differences between systems within a season (Anova at $p<0.05$)

Season	Wet1			Dry			Extremely Dry			Wet2		
System	Cocoa Antiaris	Cocoa Albizia	Cocoa Full sun	Cocoa Antiaris	Cocoa Albizia	Cocoa Full sun	Cocoa Antiaris	Cocoa Albizia	Cocoa Full sun	Cocoa Antiaris	Cocoa Albizia	Cocoa Full sun
Mean VPD (kPa)	0.86^{a,A}	0.84^{a,A}	1.04^{a,B}	1.18^{b,A}	1.04^{a,AB}	1.25^{a,AC}	1.94^{c,A}	1.87^{b,A}	2.35^{b,B}	1.72^{d,A}	1.50^{c,A}	1.72^{c,B}
SD	0.25	0.27	0.32	0.29	0.25	0.35	0.37	0.36	0.40	0.53	0.45	0.53
Max temp. (˚C)	32.0^{a,A}	31.6^{a,A}	37.0^{a,B}	32.7^{a,A}	31.9^{a,A}	36.4^{a,B}	36.8^{b,A}	38.1^{b,A}	44.1^{b,B}	40.7^{c,A}	38.1^{b,A}	40.7^{c,B}
SD	3.2	3.1	4.8	2.1	2.5	3.7	2.7	2.3	2.5	4.7	3.9	4.7
Mean temp. (˚C)	25.5^{a,A}	25.5^{a,A}	26.1$^{a, A}$	23.5^{b,A}	23.2^{b,A}	23.2^{b,A}	24.6^{c,A}	24.3^{c,A}	25.5^{a},^{AB}	28.9^{d,A}	28.4^{d,A}	28.9^{a},^{AB}
SD	1.4	1.4	1.7	2.1	2.1	2.6	2.6	2.6	2.5	2.0	1.8	2.0
Min temp. (˚C)	21.2^{a,A}	21.4^{a,A}	20.4^{a,B}	16.5^{b,A}	16.7^{b,A}	14.9^{b,B}	14.9^{c,A}	14.8^{c,A}	13.7^{c,A}	22.7^{a,A}	23.6^{d,A}	22.7^{d,A}
SD	1.3	1.3	1.4	3.5	3.3	3.7	3.6	3.9	4.0	1.4	1.3	1.4
Solar radiation (kW m^{-2})	17.6^{a,A}	12.2^{a,B}	35.0^{a,C}	19.0^{a,A}	13.6^{a,B}	33.9^{a,C}	23.7^{b,A}	15.6^{b,B}		35.6^{c,A}	10.6^{a,B}	
SD	5.9	4.1	11.8	4.0	3.7	9.6	3.0	6.6		8.2	2.1	

Table S4. Correlations between hourly sap flux density and micro-climatic variables. Sap flux was significantly correlated with all variables at $p<0.01$

		VPD	PAR	Temp
Species	Season	R^2adj		
Antiaris toxicaria	Wet	0.79	0.19	0.80
	Dry	0.85	0.66	0.70
Albizia ferruginea	Wet	0.78	0.27	0.82
	Dry	0.58	0.54	0.45
Cocoa -Antiaris	Wet	0.56	0.31	0.63
	Dry	0.40	0.32	0.32
	Wet	0.48	0.54	0.51
Cocoa-Albizia	Dry	0.47	0.21	0.40
	Wet	0.62	0.31	0.67
Cocoa Full Sun	Dry	0.65	0.49	0.56

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4.8 Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun: Reply to Norgrove (2017)

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The critique of Norgrove, (2017) addresses two main points, which are discussed below:

(i) Resilience of cocoa agroforestry versus full sun under extreme climatic conditions

In our study we covered extreme climatic events, a heat-wave combined with a severe dry season lasting longer than usual and killing cocoa trees under shade. These climatic conditions were not only observed at our study plots, but also in the larger cocoa cultivation region (Fig 1). In line with our observations, "certain cocoa cooperatives in Ivory Coast reported that shade trees in their cocoa fields accentuated the drought stress during the 2015 drought event" ([1]Andrew Broosk, pers comm).

In the specific case of our study the two shade tree species associated to cocoa resulted in strong competition for water and became a disadvantage to the cocoa plants contrary to expected positive effects. So far, the general discourse in the cocoa sector has been that shade trees are needed for climate change/drought adaptation. However, we show it is rather a function of location, severity of the drought event, shade tree species type and root characteristics as concluded by Norgrove. There are clearly different shades of grey that need to be considered.

We do not advocate promotion of full sun or shade tree cocoa agroforestry as the best adaptation strategy, but rather encourage conducting further studies in this respect, in line with what Norgrove suggests as “cocoa merits a fine sampling”. We also acknowledge the further challenge in planning such studies due to unpredictable occurrence of such extreme drought events and the limitations of using experimental droughts. In experimental drought studies in field conditions, important factors such temperature, radiation and vapour pressure deficit increases associated with extreme droughts do not occur (Schwendenmann et al., 2010).

Fig. 1 a) Map of Ghana with cocoa climatic transect, b) in additional monitored plots along shade gradient in the region (Abdulai et al, in prep.), plots with high shade cover suffered much drought stress and mortality in the studied region c) cocoa plot during the drought shaded and e) unshaded plots

ii) Sampling design

Graefe et al. (2017) reported 1576 cocoa trees ha^{-1} and 49 shade trees ha^{-1} for the study region. Therefore, the cocoa tree density at the sap flux site can be considered representative. One main constraint of our experimental set-up was certainly technical requirements for conducting sap flux studies, which limited the selection of shade tree species for the study. However, *A. toxicaria* is one of the most common shade tree species in the region, which can be found in nearly all farmers' cocoa plots (Graefe *et al.*, 2017). A similar approach of studying individual shade tree effect on cocoa has been applied for soil fertility evaluation under shade tree cocoa agroforestry in Ghana (Blaser *et al.*, 2017). On justification of plot size for the full sun plot, we did not restrict the size and, therefore, selected available area under no shade tree influence.

We do acknowledge that there are less cocoa trees under direct shade tree influence considering the shade and cocoa tree density. Recommending planting of cocoa away from shade tree canopy as suggested by Norgrove, however, would defy the benefit of microclimate buffering, observed in our study when drought was not extreme, and reduced cocoa plant density. Actually, it would move the system closer to a full sun cocoa system.

Finally, the conclusions from our paper were put rather cautiously and restricted to the specified situations where extended droughts already occur presently or then are likely to occur more frequently in the future. Only for such situations, we recommended a shift away from cocoa to other crops and income sources for improving farmers' livelihoods. This is of paramount importance for adaptation planning since climate change scenarios predict drier climate for the northern cocoa belt of West Africa (Schroth *et al.*, 2016a).

[1]Note: Andrew Brooks is Olam's Head of Cocoa Sustainability and in that position has been advocating for the use of shade trees in Ivory Coast.

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Chapter Five

Cocoa plant productivity under shade tree agroforestry along a climatic gradient in Ghana

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5.1 Abstract

Climate suitability studies within the cocoa belt of West Africa show projected reductions in cocoa production area. On top of the negative impact on the global supply of cocoa, the livelihoods of over 2 million smallholder households are threatened. Region specific adaptation is required to sustain cocoa production. Such adaptation would be facilitated by a better understanding of current productivity as affected by different climatic conditions. We studied cocoa tree productivity through monthly recordings of flowering intensity, fruiting (Cherrels count), harvested pods, and cherrels and pods damaged by pests and diseases on 20 trees per plot. Whole plot fertilizer (PK 0-22-18 +9 CaO, +7 S, +6 MgO) applications, weeding, pesticide and fungicide application frequency were also recorded. Three cocoa plots were sampled for each of the three agroforestry systems studied, i.e. high shade, medium shade and open sun. These were investigated along a climatic gradient comprising three regions denoted as dry, mid and wet from the north to the southern regions of the cocoa belt in Ghana. Data were collected from July 2015 to July 2016. Cocoa tree productivity, especially harvested pods, was highly influenced by climatic region difference that is mainly in precipitation. The system effect on cocoa plant productivity was only observed at the dry region with the open sun producing the highest yield of 10 harvested pods per tree per year. The high and medium shade cocoa plants produced only 4 and 5 pods, respectively and were significantly lower than the open sun system. The reasons for such difference have been attributed to water limitation resulting in potential competition between shade and cocoa trees. No significant yield difference was observed between the systems in the mid and wet regions. In the mid region, harvested pods for high shade, medium shade and open sun plots were 14, 15 and 13 respectively. The cocoa plants in the wet region produced the highest yield of 22, 18 and 23 for high shade, medium shade and open sun, respectively. Cherrels production and harvested pods in the open sun system in the dry region was comparable to the mid region. Open sun system might therefore be a more adaptable system to this location. Future cocoa production in the dry region is risky considering projected decrease in climate suitability due to increase in intensity and frequency of drought events. An obvious solution would be switching to more drought tolerant crops. Since the mid region is projected to experience climatic conditions similar to presently in the dry region, either open sun

system, or an agroforestry system with trees that have complementary soil water use with cocoa plants could be adapted to ensure high cocoa plant productivity in the future.

5.2 Introduction

Cocoa plant productivity like many other crops is highly influenced by agro-ecological conditions under which it is grown (Tittonell & Giller, 2013). Cocoa production within West Africa has been shown to be vulnerable to changing climatic conditions (Schroth *et al.*, 2016a). The agro-ecological conditions in which cocoa cultivation takes place covers a wide range forest Savanah transition to high rainfall moist evergreen forest regions (Schroth *et al.*, 2016a). In the world's leading cocoa producing countries of Ivory Coast and Ghana, rainfall and temperature levels characterize different climatic suitability zones (Läderach *et al.*, 2013). In these countries, much productive and relatively drier cocoa growing areas has experienced increased temperatures, drought severity and duration and has triggered a shift in production towards wetter forest locations (Asante et al., 2016; Ruf et al., 2015). Existing cocoa cultivation systems vary from full sun to agroforestry where diverse shade tree species and cocoa are intercropped (Vaast & Somarriba, 2014). Cocoa agroforestry systems have been identified as sustainable practice with multiple benefit of maintaining soil fertility and providing ecosystem benefits (Schroth et al., 2016a; Tscharntke et al., 2011). Soil nutrient levels in cocoa agroforestry systems have been found to be lower than under natural forest (Blaser et al., 2017; van Vliet and Giller, 2017). Recent studies have found limitations in the ability of shade trees in cocoa agroforestry systems to increase soil fertility to sustain cocoa yields (Blaser *et al.*, 2017; Wartenberg *et al.*, 2017) . On the other hand, soil properties such organic carbon, for instance, have been found to be higher in cocoa agroforestry system than full sun (Bai *et al.*, 2017). Cocoa agroforestry has been described as climate friendly and a good climate change adaptation option for cocoa production due to microclimate moderation and complementary soil water between cocoa and shade trees (Schroth et al., 2016a; Vaast and Somarriba, 2014; Schwendenmann et al., 2010). Shade trees on cocoa farmers field are mainly naturally regenerated with lack of spatial arrangement (Asare & Ræbild, 2015). Farmers are still far from establishing ideal cocoa agroforestry system as described by Tscharntke et al. (2011). Cocoa agroforestry evaluated under extreme drought conditions was found to be rather less drought resilient than cocoa in full sun (Abdulai *et al.*, 2017). Alternative to cocoa agroforestry is monoculture usually referred to as full sun system. Full sun systems are known to be high yielding with positive economic returns and it's the most commonly practised system by farmers in West Africa (Tondoh et al., 2015; Ruf, 2011). High productivity from less area under full sun system could actually better ensure forest and biodiversity conservation through land sparing (Wade *et al.*, 2010). Adoption of full sun cocoa cultivation systems has been facilitated by the introduction of high yielding cocoa varieties that require no shade (Ruf, 2011). Farmers preference for full sun over shade cocoa agroforestry system has also been attributed to high incidence of black pod disease, nutrients and soil water competition between cocoa and shade trees (Smith Dumont *et al.*, 2014). Farmers' choice of cultivation systems have been found to be influenced by climatic region in Ghana (Abdulai et al, 2017). Farmers in different climatic regions within the cocoa belt of Ghana showed different preference and knowledge of cocoa cultivation systems, especially regarding the use of shade trees in cocoa agroforestry system (Graefe *et al.*, 2017). There are currently limited studies on cocoa plant productivity between full sun and shade cocoa agroforestry (Isaac *et al.*, 2014) under varying climatic conditions. The basic understanding of how these systems affect cocoa plant yield could serve as guide in designing climatic condition specific cocoa productions systems. Such systems could enhance the adoption of highly productive and climate change resilient cocoa cultivation systems. This study aimed at a detailed assessment of the effect of both climatic conditions and cultivation system on cocoa plant productivity along a climatic gradient in Ghana. The objectives were to assess (i) the existing variations in above cocoa canopy microclimate between full sun and two shade level cocoa agroforestry systems, and (ii) climatic region and system effects on cocoa tree productivity (flowering, fruiting, wilting, pest and disease, pod harvest/yield).

5.3 Materials and methods

Study sites

Three regions within the cocoa belt in Ghana along a climatic gradient were selected (Fig.1). The sites were Asankragua, Goaso and Akumadan in the Western, Brong Ahafo and Ashanti locations respectively. These sites are classified as dry, mid and wet regions based on rainfall and microclimatic variability (Fig. 1).

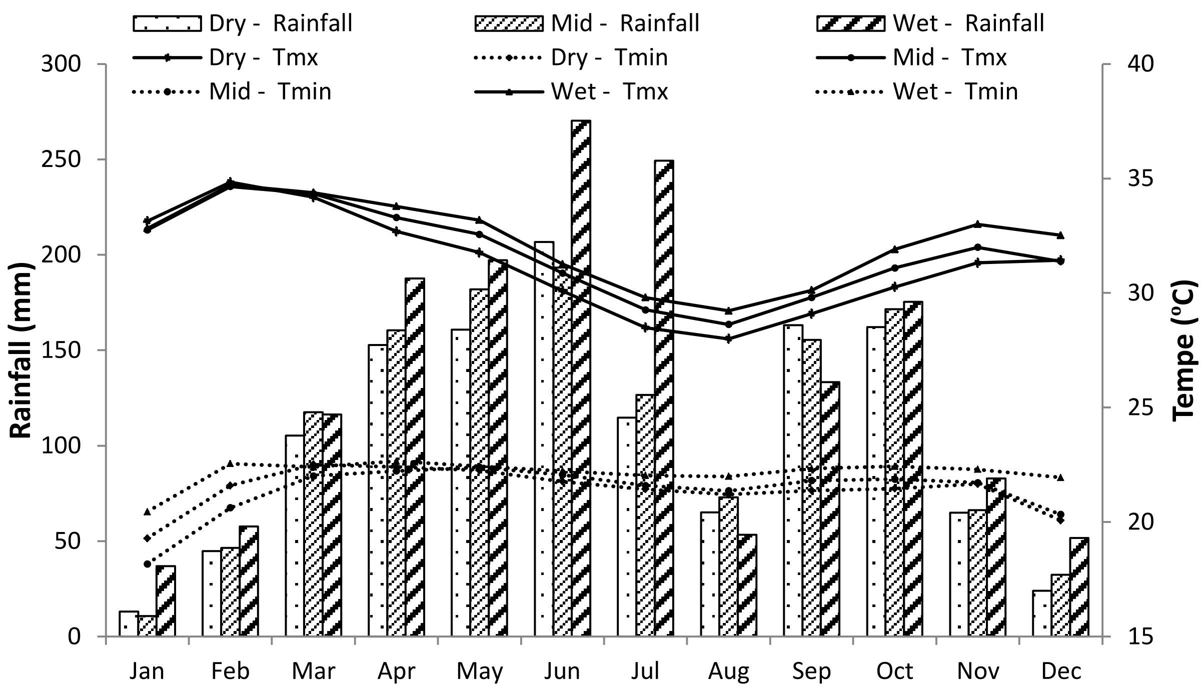

Fig. 1 Climate diagram of the studied sites. Monthly rainfall and min-max temperature from 1986 - 2016 (Source: Ghana Meteorological Service 2016)

Studied systems, plot selection and cocoa tree sampling

The studied systems were open sun, medium and high shade systems with mean plot shade tree canopy cover percentage of 34, 19 and 9% for the dry, 34, 13 and 9% for the mid and 32, 12 and 8% for the wet region, respectively (Fig.2). Three plots of each agroforestry system were monitored per region.

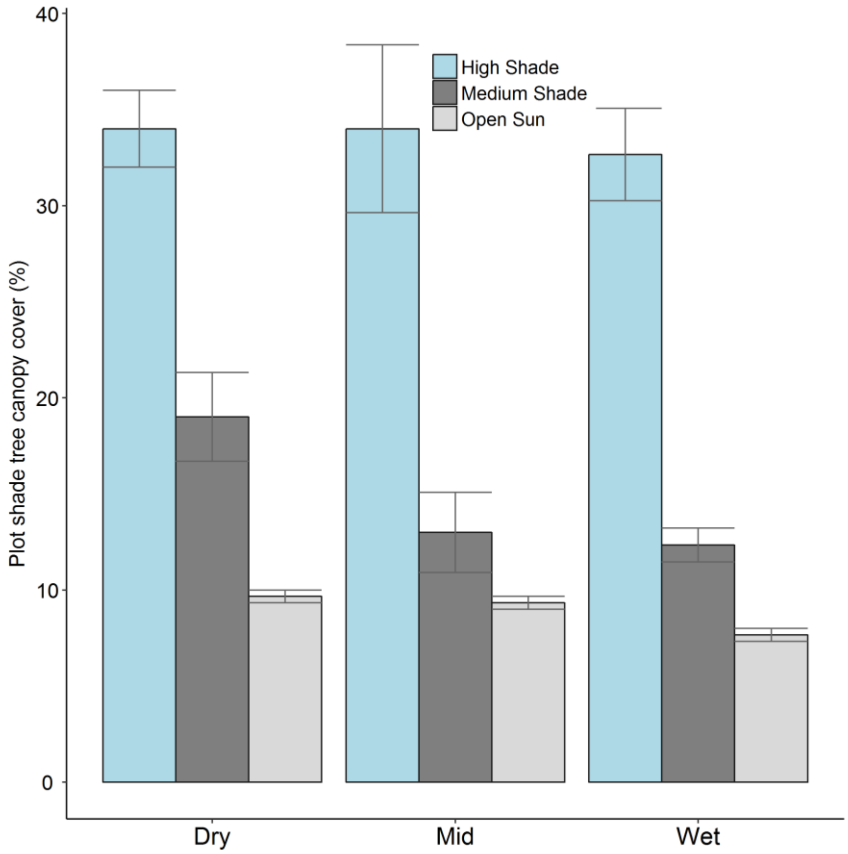

Fig. 2 Shade tree canopy cover percentage between the studied systems along the dry, mid and wet locations

Twenty (20) cocoa trees/plot were selected and tagged for three plots per system per location (total of 540 cocoa trees). Temperature and relative humidity were recorded with two iButton® (DS1923—Hygrochron Temperature and Humidity Data Logger) per high and open sun cocoa system. A total of 12 iButtons, six per region were installed above the cocoa trees to monitor temperature and relative humidity over the studied periods. The i-Buttons were set to record temperature and relative humidity every hour. Calibration error resulted in lacking valid temperature and relative humidity recordings for the period of January to March for the wet location. To ensure cocoa tree selection was representative of the cocoa plot, diagonal lines in an imaginary rectangle were established to divide the plot into 4 quadrants. Five cocoa trees were then sampled within each of the four sections ensuring even distribution.

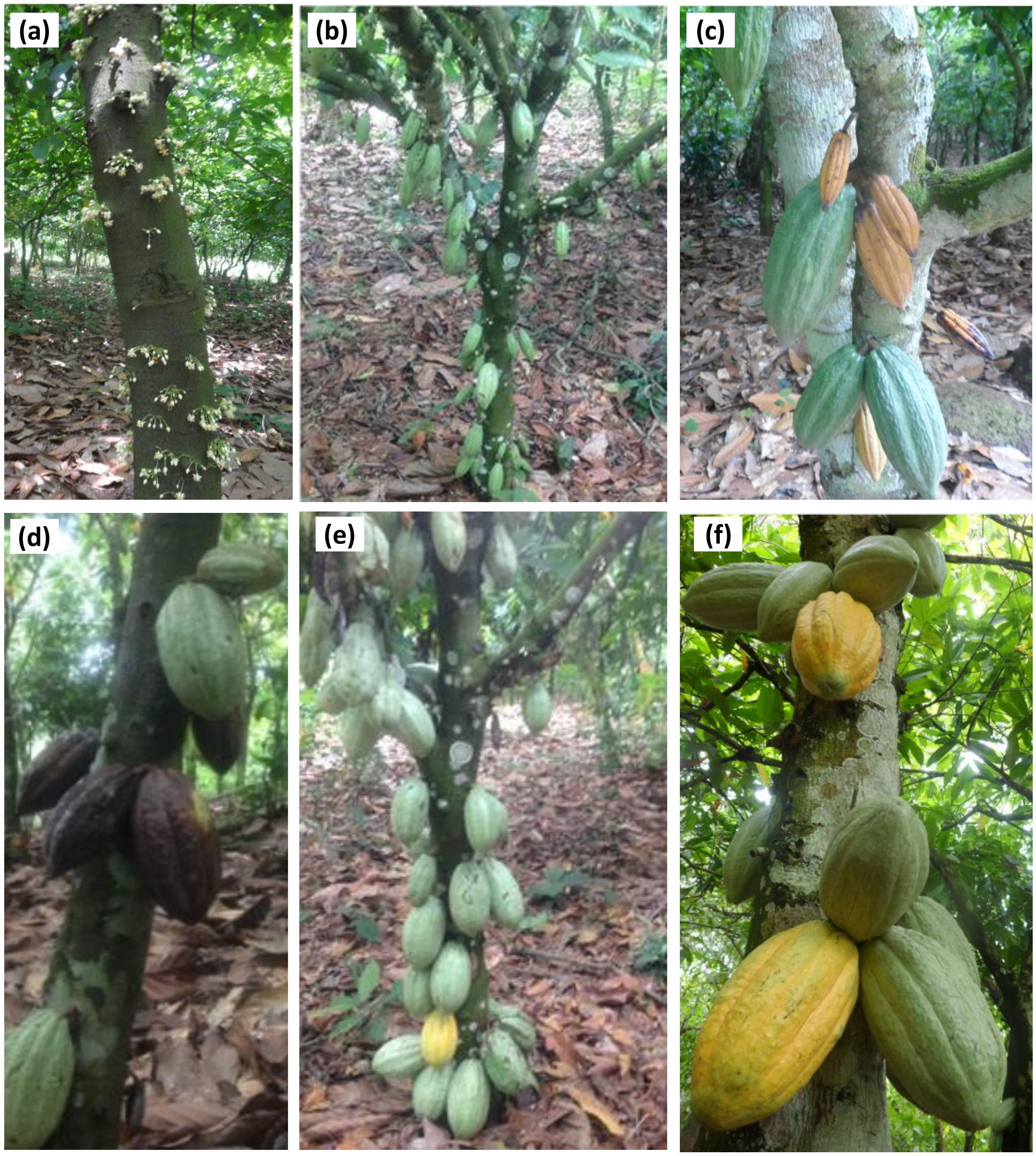

Fig. 3 Studied cocoa plant productivity indicators, (a) flowering, (b) fruiting (Cherrels), (c) Cherrels wilt, (d) black pod infested pods, (e)&(f) matured and ripped pods

Cocoa plot and management characteristics between the locations

Management activities varied between the different locations. Weeding frequency was higher at the mid and wet regions than at the dry. Pesticide application frequency was similar at the dry and mid regions but higher at the wet location. The open sun system had the highest pesticide application frequency of eight times per year. Fungicide application frequency of 3 times per year in the high shade systems was the highest in the dry region. No fertilizer application was recorded for the mid location and the high shade system in the dry region. Quantity of fertilizer applied was higher in the wet than the dry region. Interestingly, fertilizer use increased with increasing shade in the wet region (Table 1)

Table 1 Mean (SD) plot size, fertilizer quantity and recorded farmer weeding, pesticide and fungicide application frequencies over the studied period between high shade (HS), medium shade (MS) and open sun (OS) systems across the locations

Location	System	Plot size ha	Weeding frequency	Pesticide frequency	Fungicide frequency	Mineral Fertilizer* (kg/ha)
Dry	HS	1.5(0.2)	2(0.6)	2.0(2.0)	3(0.6)	0(0)
Dry	MS	0.7(0.3)	1(0.6)	2.7(2.3)	2(0.6)	141(130)
Dry	OS	0.6(0.2)	2(1.5)	1.3(1.5)	0(0.6)	142(193)
Mid	HS	1.4(0.6)	7(2.6)	2.0(1.0)	1(0.6)	0(0)
Mid	MS	2.5(1.2)	6(1.2)	2.3(2.5)	1(0.6)	0(0)
Mid	OS	1.6(0.7)	6(3.2)	3.3(2.1)	1(1.0)	0(0)
Wet	HS	0.6(0.2)	4(1.5)	4.0(1.0)	1(0.6)	440(191)
Wet	MS	0.7(0.1)	7(1.2)	6.7(2.3)	1(1.2)	379(123)
Wet	OS	0.9(0.1)	7(2.1)	8.0(1.0)	0(0.6)	193(180)

*Fertilizer commonly applied contains PK 0-22-18, magnesium and sulphur (PK 0-22-18 +9 CaO, +7 S, +6 MgO)

Data collection and analysis

Cocoa tree performance indicators were recorded by both quantitative and qualitative measurements (Fig. 2). Monthly flowering was assessed by a ranking scale, ranging from 0 to 4, whereby 0 meant no flowering to 4 meaning highest possible flowering intensity. Count of immature fruits (Cherrels), ripped, pest and diseases (black pod, capsids and bugs) infested pods were also recorded every month. Whole plot level fertilizer input as well as weeding, pesticide and fungicide application frequencies by the farmers were also recorded during each monthly visit. The results from these whole plot management activities are described in the method section. Daily minimum and maximum temperature (Tmin and Tmax) and relative humidity above cocoa plant canopy, monthly cocoa plant flowering intensity and cherrels counts are presented in Figures 4 to 7, respectively. Cocoa plant yield (total number of harvested pods), number of pest and disease damaged pods and cherrels between the systems were analysed and compared across the climatic regions through Anova at 0.05 significance level using R software (R core team, 2017). Individual cocoa trees were considered as a random factor in order to account for the high tree yield variability associated with cocoa trees (Wibaux et al., 2017).

5.4 Results

Below-canopy microclimatic variations of cocoa along the climatic gradient

The dry and mid regions showed similar patterns of much divergence during the dry months. The dry months (with high Tmin and Tmax divergence) lasted from December to mid and late February in the dry and mid regions, respectively (Fig. 4). The high shade did not show distinct variations from the open sun as the shade trees were mostly and had lost their leaves. In the wet region, no high Tmin and Tmax divergence could be observed in the study period. The drought effect was mainly seen at the dry and mid regions. The change in Tmin from the wet to dry season was 16.8 to 8.9 and 20.6 to 14.3 $^{\circ}$C for the dry and mid region, respectively. The regions showed different levels of relative humidity during the dry season. Relative humidity in the dry region dropped below 40% in both high shade and open sun system. In the mid region, relative humidity was hardly below 50% throughout the dry season irrespective of the system. High relative humidity was maintained throughout the dry month of December in the wet region (Fig. 4). In the wet season (July – November 2015 and March to August 2016), relative humidity still followed the climatic gradient with the highest relative humidity at the wet region but without pronounced differences among study regions.

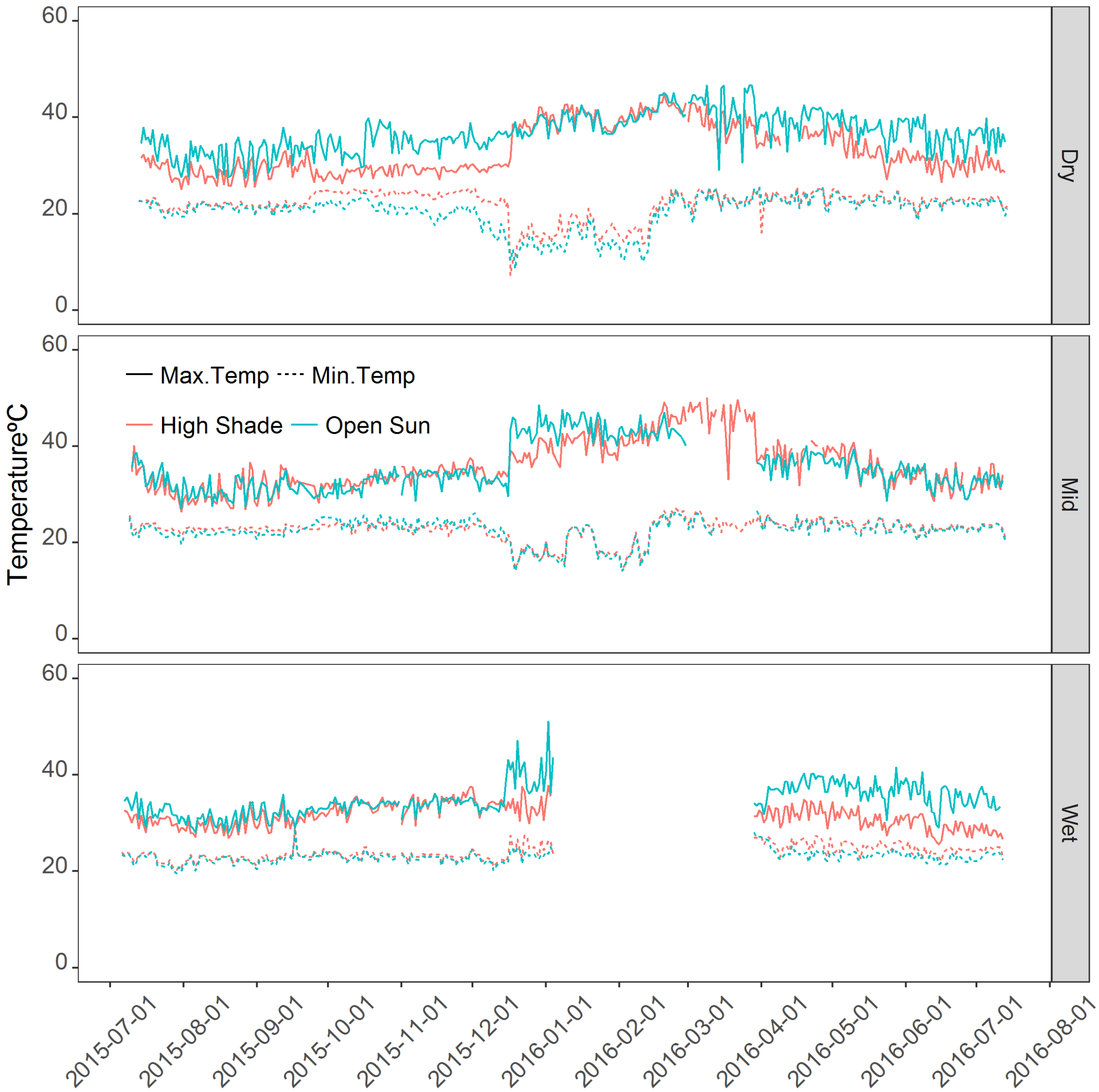

Fig. 4 Difference in above cocoa canopy temperature between high shade (red line) and open sun (blue line) systems along climatic regions in Ghana (July 2015 to August 2016)

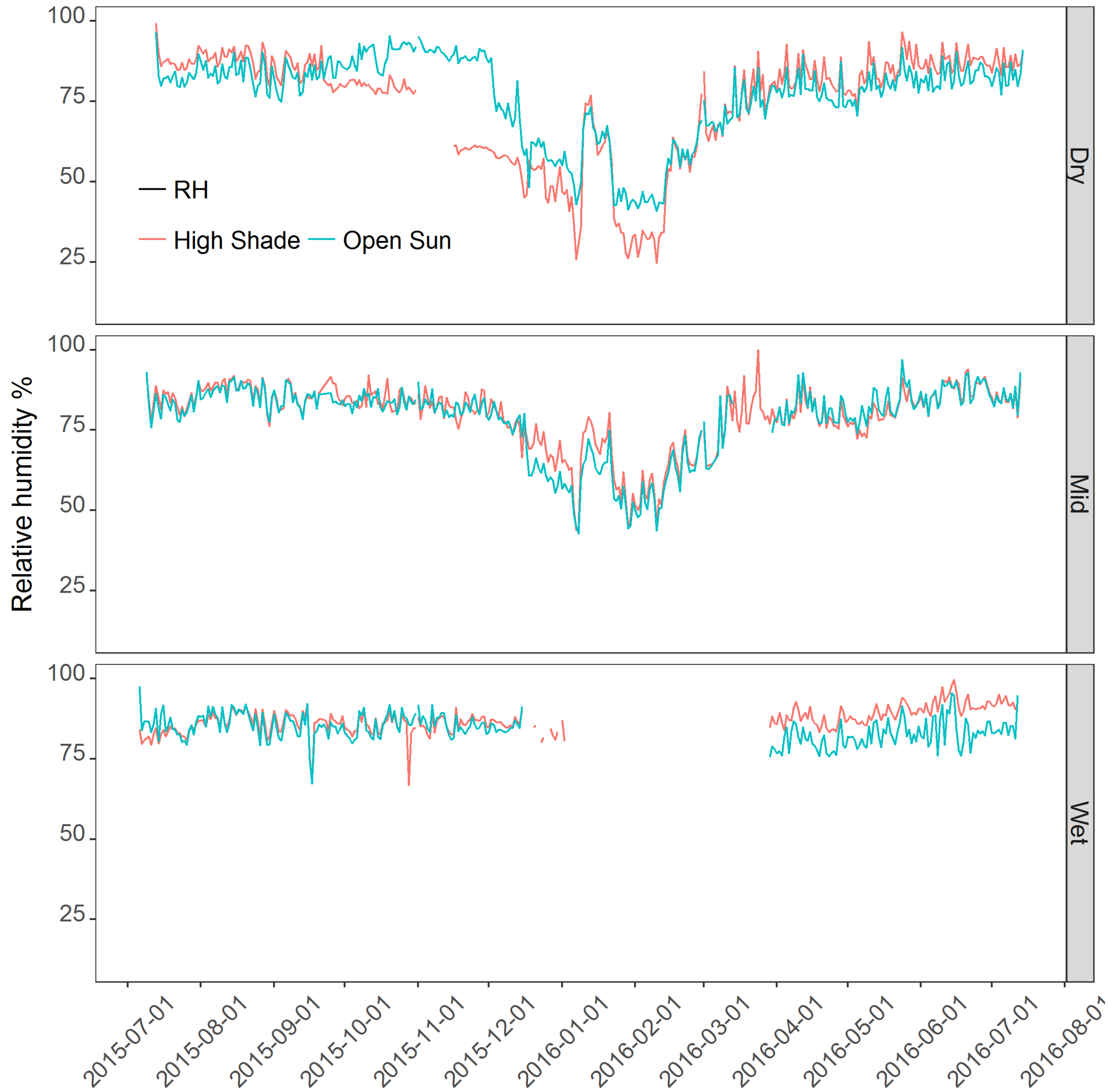

Fig. 5 Difference in above cocoa canopy relative humidity (%) between the shaded (red line) and open sun (blue line) systems in the dry, mid and wet climatic regions in Ghana

Cocoa tree flowering, fruiting, pest and diseases damage between the systems along the gradient

Flowering intensity was highest at the wet region during the entire monitoring period. The dry and mid regions had similar flowering intensity in August and October but the dry region became lower in the subsequent months of December to June the following year. Between the systems, all were similar from August to October (Fig. 5). For most part of the remaining period, no clear trends could be observed between the systems.

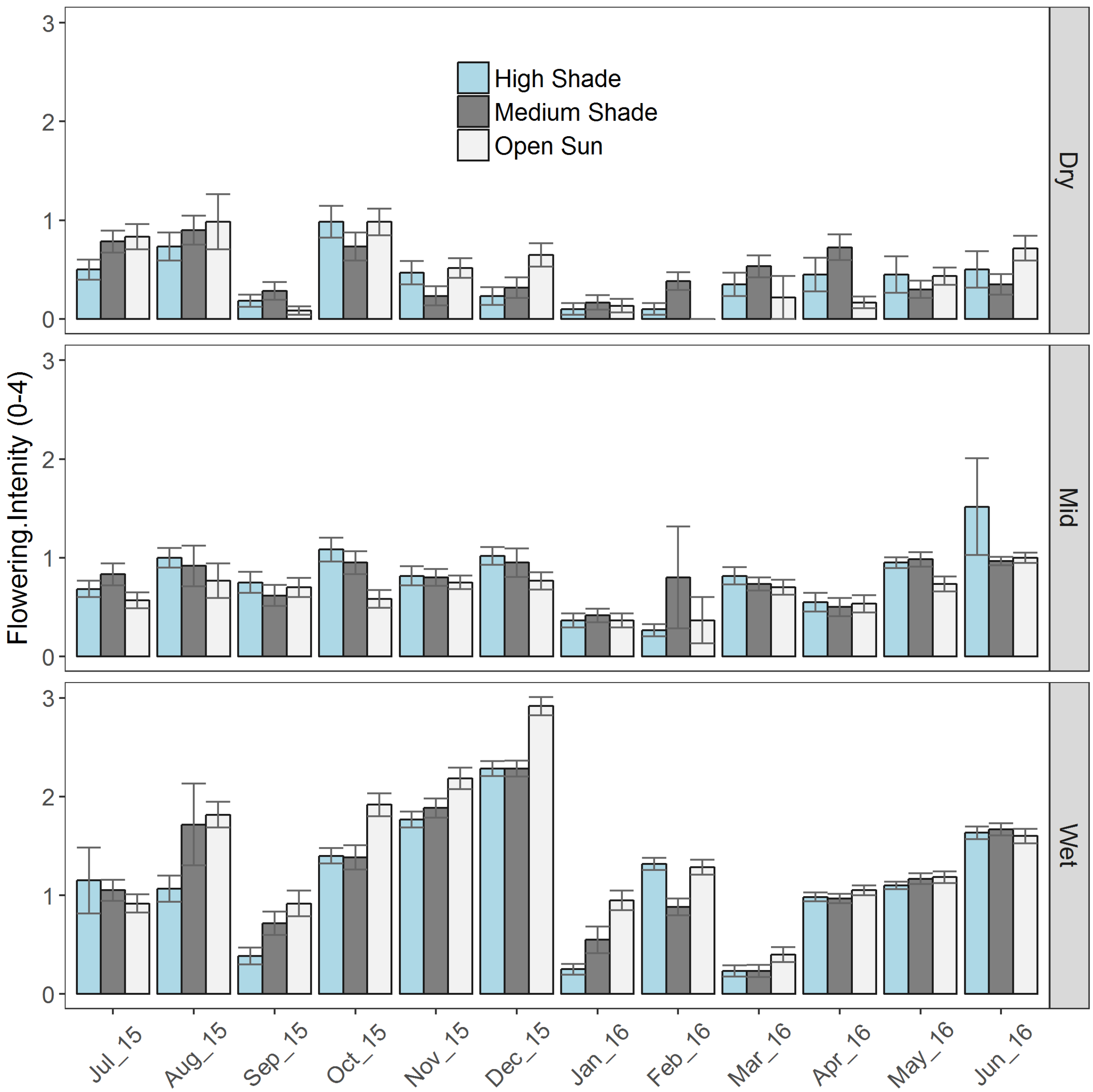

Fig. 6 Flowering intensity between high shade, medium shade and open sun cocoa systems along dry, mid and wet regions

For the immature fruits (Cherrels) production, the cocoa plants under the different systems produced similar numbers in the mid and wet regions. At the dry region, clear difference could be observed between the open sun and the two shaded systems. The open sun cocoa plants consistently produced higher number of cherrels over most of the period. The cherrels count was much lower after January due to effect of drought event. General decline in cherrels production was observed in the mid region from January to June. The wet region showed consistent cherrels production and recovery from slight dip in the dry months of January and February 2016. The peak cherrels production was observed to be mainly between Jun to September. These cherrels are therefore the resultant pods for the main crop season which span from September to January (Asare et al., 2017). In the mid and wet region, relatively high cherrels production was maintained from October to February. High cherrels production during this period resulted in high harvested pods for the mid and wet regions.

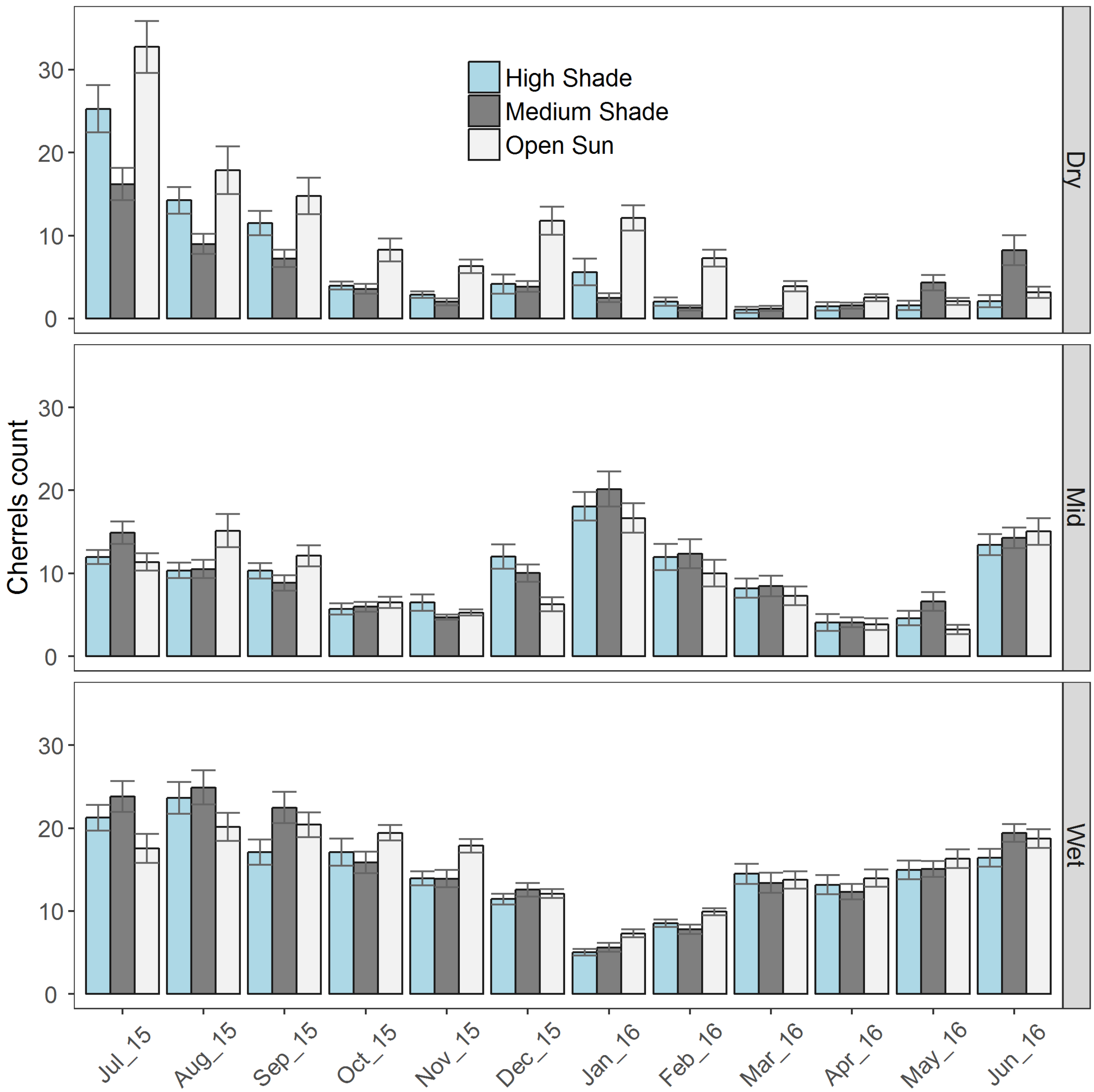

Fig.7 Cocoa tree fruiting (Monthly cherrels count) between high, medium shade and open sun cocoa systems along the gradient from dry via mid to wet regions over the monitoring period July 2015 to June 2016.

Table 2 Mean (SD) of wilted cherrels, pest and diseased cherrels and pods between the high shade (HS), medium shade (MS) and open sun (OS) systems across the regions . BP=black pod disease, P&D= Pest and disease. N= 60 trees.

Location	System	Cherrels wilt	Cherrel P&D	Pods/ BP	Pods/ pest
Dry	HS	4.3(4.7)	18.7(18.3)	0.1(0.7)	0.0(0.3)
Dry	MS	4.4(10.9)	12.9(12.1)	0.1(0.5)	0.0(0.1)
Dry	OS	9.6(8.8)	33.3(24.2)	0.2(0.9)	0.0(0.0)
Mid	HS	14.6(9.2)	28.6(14.7)	2.6(2.5)	1.4(1.8)
Mid	MS	17.5(9.9)	30.2(13.8)	2.6(2.6)	1.8(2.1)
Mid	OS	13.9(7.8)	25.5(14.1)	1.9(3.1)	1.7(3.2)
Wet	HS	29.5(14.5)	28.3(9.6)	1.7(2.7)	1.8(1.9)
Wet	MS	28.8(15.3)	26.0(10.5)	1.5(2.3)	1.9(2.3)
Wet	OS	32.7(18.5)	18.9(11.6)	0.5(1.4)	1.0(2.5)

No significant difference could be observed between the systems per region for cherrels wilt, pest and disease damaged cherrels, black pod and pest damaged matured pods. The number of infections at the dry region was proportional to the number of cherrels produced by the trees. More cherrels damage were observed in the open sun plants which produced the highest number of cherrels. For pest and disease damaged cherrels, the open sun had the lowest numbers at the mid and wet regions. The number of infections for matured pods were quite low across the regions (Table 2)

Differences in cocoa tree yield among the systems and along the climatic gradient

The yield which is defined as the total number harvested pods from a cocoa tree within a year showed significant differences among the systems only at the dry region (Fig. 8). The mean yield of 10.03 pods /tree/year for the open sun system was significantly higher than the 4.6 and 5.0 recorded for high and medium shade systems, respectively (Fig. 8). At the mid and wet regions, no significant cocoa tree yield difference could be observed between the open sun and shaded systems.

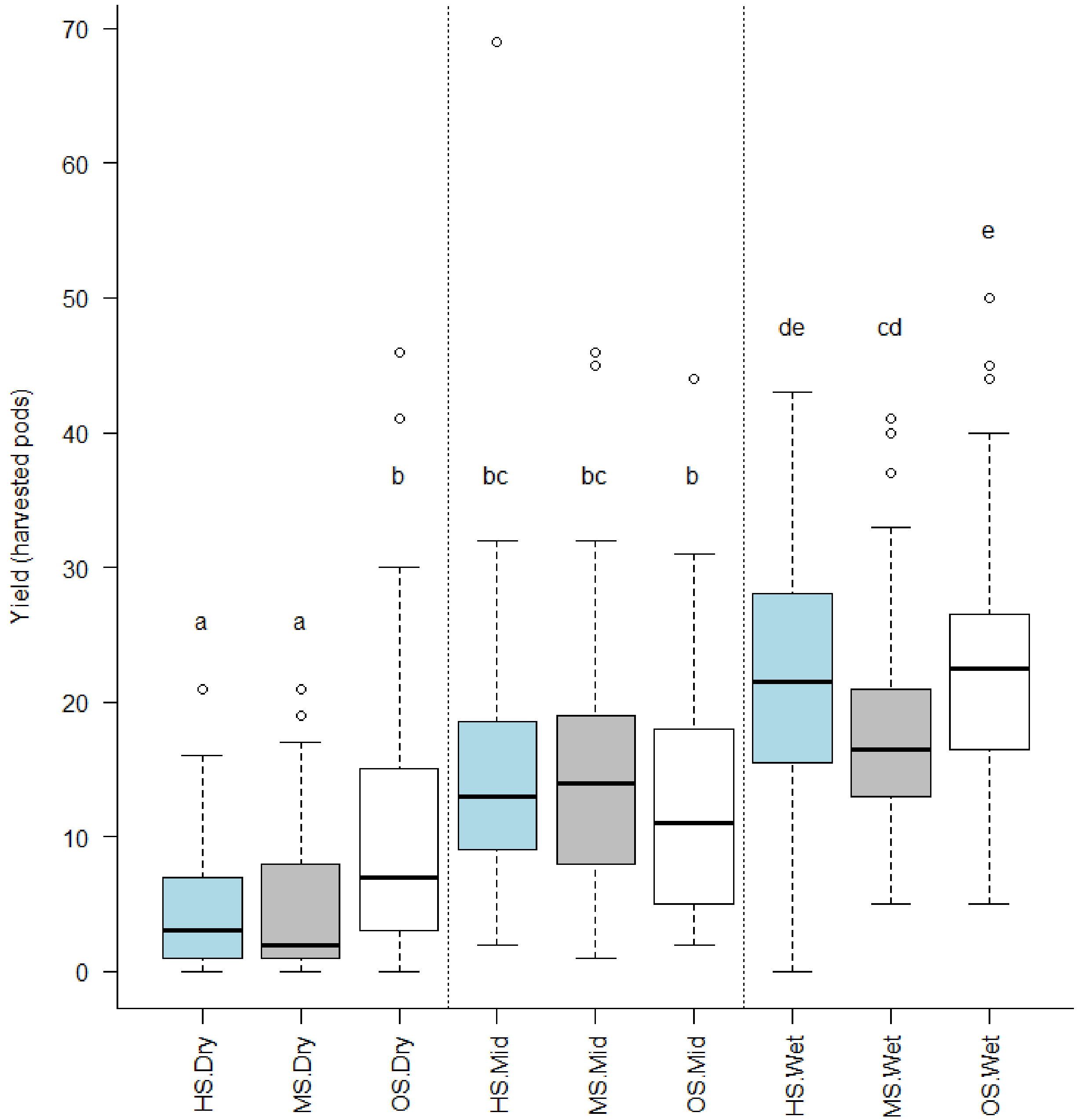

Fig. 8 Individual cocoa tree yield (harvested pod count) between high shade (HS), Medium shade (MS) and open sun (OS) systems across dry, mid and wet regions. Different letters indicate significant differences at 0.05. Black horizontal lines indicate the median and open circles indicate the outliers.

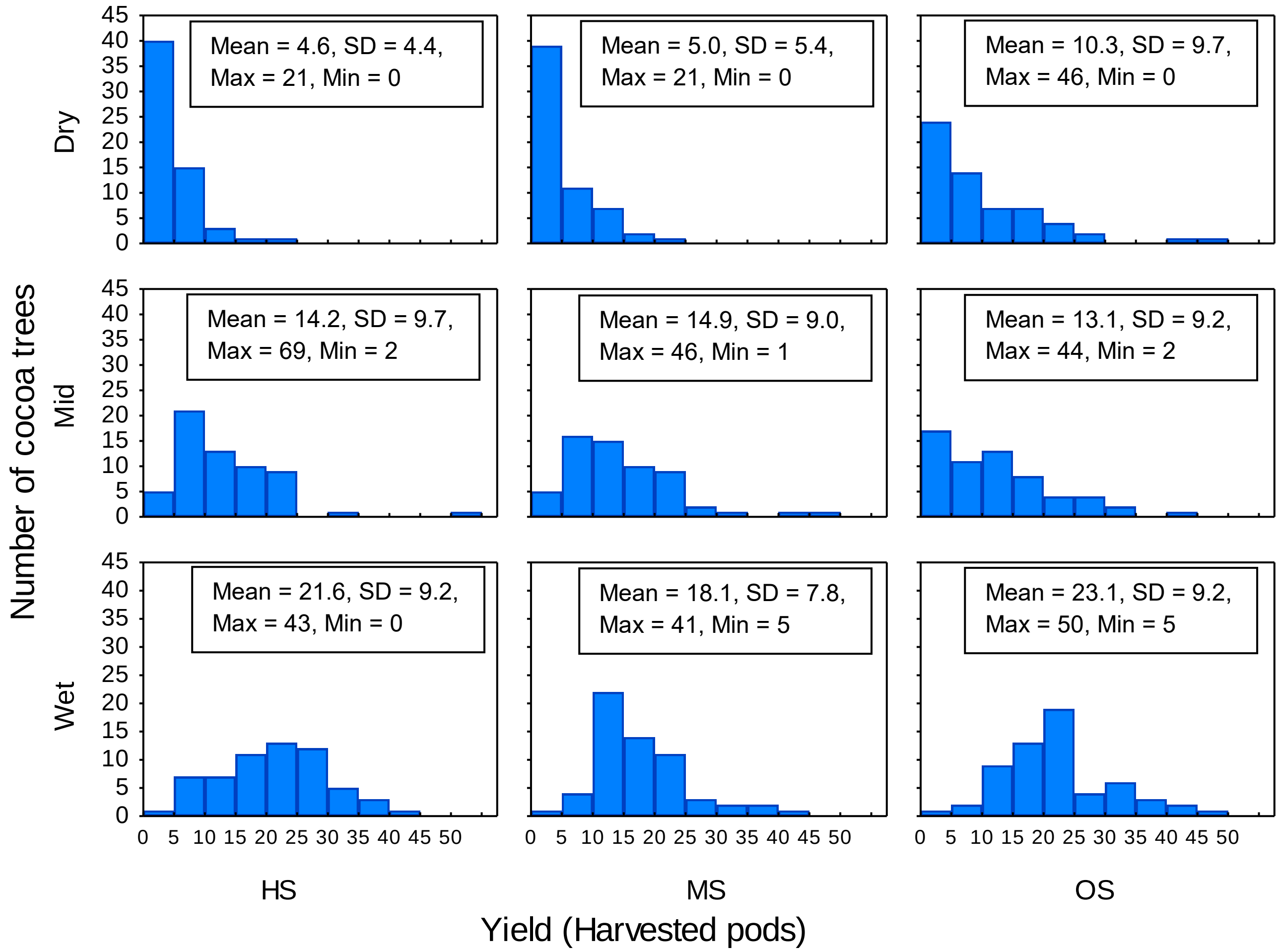

Fig.9 Distribution of average cocoa tree yield (harvested pod count) between the systems along the dry, mid and wet regions, N=60 trees per system

The systems showed variations in cocoa tree yield levels distributions across the regions. High numbers of unproductive cocoa tress (< 5 harvested pods) were higher in the high and medium shade systems than in the open sun at the dry region (Fig. 8). The number of unproductive trees decreases from the dry to the wet regions for all the systems. The open sun system at the dry region had similar distribution pattern to the mid region with maximum pods harvest of 46 and 44, respectively. At the dry and wet locations, the highest pod producing trees were in the open sun system with 46 and 50 respectively.

5.5 Discussion

In addition to rainfall variations, dry season relative humidity and minimum temperatures were observed to be much influenced by the regions selected along the climatic gradient from the north to the southern zones of the cocoa belt in Ghana. The study revealed strong influence of existing climatic variation within the cocoa belt on cocoa tree productivity. Differences in cocoa plant productivity between shade and open sun systems are most evident in the dry region. We found low cocoa plant productivity under shaded system in the low rainfall regions, an indication of water limitation and competition effects of shade trees on cocoa plants. At the mid and wet regions, higher cocoa plant productivity was observed for both shaded and open sun systems.

Micro-climates along the climate gradient

Temperature and relative humidity among the locations showed different seasonal dynamics with highest fluctuation at the dry and mid regions. Low rainfall and the observed high microclimatic fluctuations at the dry location are the main factors associated with the characterization by Läderach et al. (2013) of the dry region as being of marginal suitability. In practice, these and associated limitations such as wildfires have been identified as the underlying reasons of observed shifts from cocoa to short rotation annual crops at the dry region (Asante et al., 2016: Adjei-Nsiah and Kermah, 2012). Cocoa production in the dry region becomes even much more challenging under conditions of extreme drought when soil water reduce to critical limits and temperature reached >44ºC (Abdulai *et al.*, 2017). Relative humidity showed variation between the regions and might be much more limiting than temperature. This is because the difference especially in Tmax was not pronounced between the regions. Effect of high temperature on cocoa plants in the mid and wet regions might have been offset by the high himidity which lowers the vapor pressure deficit (VPD) to help maintain photosytetic rate (Baligar *et al.*, 2008). Difference in above cocoa canopy temperature and relative humidity between the shaded and open sun systems over the entire period was small. Considering that cocoa plants could withstand temperatures even above those recorded for open sun (Abdulai *et al.*, 2017), the role of shade trees on microclimate moderation can be considered as minor (Asare et al., 2017).

Cocoa plant productivity along a climatic gradient

Cocoa tree productivity as expressed by periodic flowering, cherrels production and subsequent pods harvest showed distinct variations between the studied regions representing different climatic conditions. Productivity difference between shaded and open sun system was only observed in the dry region. Previous studies have attributed high variability in cocoa tree yield to genetic and management effects (Wibaux et al., 2017; Adomako and Adu-Ampomah, 2003). The potential effect of climatic, mainly inter- and intra-annual rainfall variability on cocoa yield has been emphasized by Asare et al. (2017). Differences in climatic conditions between the studied regions might have an overriding effect on cocoa tree productivity considering the observed increments in flowering intensity, cherrels count and harvested pods from dry to the wet regions. The drought period had higher effect on cocoa productivity in the dry egion where cherrels production could not be recovered.

The open sun system had significant productive cocoa trees with mean pod production of 10 harvested pods per year. The medium shade and high shade system trees were less productive than the open sun system as the respective mean pod yield of 4.6 and 5.0 with majority of the cocoa trees producing only 0-5 pods (Wibaux et al., 2017). Although the medium shade and open sun plots in the dry region had similar quantities of fertilizer applied the yield difference was still high in the open sun system. In addition to the shade tree effect, the timing of the fertilizer applications might also have affected the observed difference (Asare et al., 2017). One of the driving factors for such yield difference between open sun and the shaded systems might be water limitation resulting from competition between cocoa and shade trees as such effect was not observed in the wet region (Abdulai et al., 2017; Asare et al., 2017). Soil nutrient improvement by shade trees has been found to be limited with even a negative effect of shade on both cocoa tree and plot level yield at the southern part of the dry region (Blaser *et al.*, 2017). The lack of difference between the shade and open sun system in the mid and wet region might therefore be partly attributed to lack of water limitation. Shade systems with fertilizer applied have been actually found to produce comparable yield with the open sun during certain periods of the cocoa growing season in the wet region (Asare et al., 2017). Breeding for high yielding cocoa planting materials and effort to eliminate low productive materials have been requested to address tree level yield variability to increase plot yield and to also ensure agronomic efficiency (Wibaux et al., 2017). It is therefore also important that breeding programs consider climatic effect on cocoa plant yield considering the projected changes in climate suitability (Anim-Kwapong & Frimpong, 2004; Schroth *et al.*, 2016a). Planting materials that are more adaptable to water limitation have been recommended to enhance farmers adaptation to projected climate change in the cocoa belt of Ghana (Anim-Kwapong & Frimpong, 2004). Low cocoa plant productivity in the dry region is therefore a confirmation the regions characterized by marginal cocoa climate (Adjei-Nsiah & Kermah, 2012; Läderach *et al.*, 2013). Cocoa plants in the dry region are less productive, hence changing to other productive short rotation or drought tolerance crops such as cassava, maize and cashew might occur (Adjei-Nsiah & Kermah, 2012).

5.6 Conclusions

The study revealed effect of climatic region on cocoa tree productivity especially between the dry and wet regions. Higher cocoa plant productivity was observed for the mid and the wet regions than in the dry region. Shade tree canopy cover did not influence cocoa plant productivity at mid and wet regions. There was higher cocoa plant productivity under open sun system than the shaded systems at the dry region. The results are consistent with other studies that compared productivity of shaded and full sun cocoa systems in Ghana (Bisseleua Daghela *et al.*, 2013; Asare *et al.*, 2017). The reason for low productivity in shaded system in the dry region is partly attributed to potential competition for water between cocoa and shade trees. Since this and other similar studies are limited in the number of plots monitored, we recommend future studies to expand the plot number with productivity monitored over multiple years to account for temporal variations associated with perennial crops. Detail meteorological, soil nutrient and water data will also be required to help establish the direct effect of climatic condition on productivity.

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Chapter Six

General discussion and conclusions

A significant part of the current cocoa growing area in West Africa is projected to become climatically less suitable for current cultivation practices (Schroth et al., 2016). In addition, cocoa producing countries are under pressure to protect the remaining natural forests as both buyers and consumers demand cocoa beans and products that are sustainably cultivated (Fountain and Hütz-Adams, 2018; Kroeger et al., 2017). Farmers facing marginal climatic conditions will need to adapt their production systems as land at more suitable regions is limited (Ruf *et al.*, 2015; Noponen *et al.*, 2014). Climatic region-specific cocoa production systems are required to adapt production to different climate suitability levels that exist among the various regions (Schroth et al., 2017; Abdulai et al., 2018, this thesis). More comprehensive studies on the effect of climatic regions on cocoa productivity and the farmer choices regarding the particular production system are needed. Knowledge on productivity, production systems and climate resilience could guide the design of future adaptation strategies.

In line with this rationale, the first part of the thesis focused on cocoa production, income diversification and shade tree management (Chapter 2), as well as on variations in yield gaps and soil fertility in smallholder cocoa systems along a climatic gradient in Ghana (Chapter 3). Empirical evidence of the effect of "climatic region" on cocoa production and farmer response are discussed and aligned with projected changes along the gradient to help propose climate change adaptation options. Although agroforestry is promoted to enhance climate resilience and represent a more sustainable cocoa production system than cocoa in mono-culture, there are limited studies that evaluate the performance of such agroforestry systems.

The second part of the study contributed towards closing this knowledge gap, by studying the resilience of cocoa under agroforestry and full sun under farmer field conditions in a marginal cocoa region. A sophisticated sap flow experiment was conducted to measure water uptake, microclimate and soil water over wet, dry and extremely dry periods (Chapter 4). This part is discussed to highlight the potential limitation of agroforestry as a climate change adaptation strategy under projected extreme drought conditions of marginal cocoa regions. To further understand the effect of climatic regions and agroforestry on cocoa plant productivity, cocoa plant productivity under an agroforestry system along a climatic gradient in Ghana was studied over an entire year with monthly data collection (Chapter 5). The results from this research underlined the need for further studies on climate resilience and the productivity of cocoa agroforestry systems.

The approach of studying characteristics of cocoa production systems and yield dynamics across a climatic gradient makes this study unique by providing substantial information relevant for discussions on potential future climate change impacts. The occurrence of the extreme drought during the study (triggered by the strong El Nino event of 2015/16) allowed for an evaluation of extreme drought impacts on cocoa plants under shade trees and full sun system. This was the first study of its kind. Since the projected suitability changes will be characterized by similar climatic conditions as faced in this study more frequently, the results have also increased the awareness of the need for effective adaptation options.

In the following section, this thesis is discussed with respect to the climatic region effect on cocoa production and climate resilience of cocoa plants under shade tree agroforestry versus full sun systems.

6.1 Cocoa yield and farmers choice of intensification and production system is influenced by climatic regions

The annual rainfall limits for cocoa cultivation are around 1250mm minimum and 2800mm maximum, which must be evenly distributed to avoid water deficits, excess and disease pressure, respectively (Wood and Lass, 1985). Rainfall is the most critical factor in this study as temperatures are within the maximum and minimum range of 30 – 32 and 18 – 21°C suitable for cocoa cultivation (Wood and Lass, 1985). The regions studied were identified as dry, mid and wet, with an estimated annual rainfall of 1200, 1400 and 1800mm respectively; a gradient of marginal to optimum climatic cocoa growing areas in Ghana. The different climatic regions proved to be crucial for cocoa production and farm management approaches. The effect of climatic region, especially rainfall, restricted the effect of management intensity on yield as shown for example by the fact that lower cocoa yields were recorded in the marginal dry region compared to the mid and wet regions.

In the dry region, both average farmer yield and attainable yield only reached 211 and 645 kg ha^{-1} $year^{-1}$ respectively, and showed the highest yield gap (67%) expressed as the percentage of farmer yield to attainable yield under rainfed conditions. Both, average farmer yield and attainable yield levels are very low and underline the marginal climatic suitability of the region for cocoa production. The high climatic suitability of the high rainfall wet region was demonstrated by the high average farm yield of 999 kg $ha^{-1}year^{-1}$ and attainable yield of 2125 $kgha^{-1}year^{-1}$for the three year period of 2013 to 2015. A lower yield gap of 53% and 59% for the mid and wet region respectively suggest the higher intensification level has likely been facilitated by the more favourable climatic suitability. The yield trends along the gradient follow the climate suitability levels presented by Läderach et al. (2013) and, therefore, highlight potential yield changes that could be expected with climate change. Farmers are regarded to be risk averse under marginal climatic conditions regarding crop cultivation practices and they will usually opt for low input but diversified farming systems to reduce the risk of low gross margins, financial loss and crop failure (Waha et al., 2018- in press; Menapace et al., 2013; Rötter et al., 1997; Rötter and van Keulen, 1997). This could be attributed to the farmer characteristics in the marginal dry region. Farmers in the dry region diversified their income sources with non-cocoa crops and off-farm activities as adaptation strategies. The high yields and farmer dependence on cocoa for over 80% of their annual income in the mid and wet regions further confirm the "climatic region effect" on the decision on whether to specialise and/or intensify management activities. The difference in intensification along the climatic gradient could also be inferred from yield gap determining factors. For example, fungicide and pesticide quantity and application frequency were lower in the dry region and were the most significant determining yields gap factors. In the mid and wet region, the negative yield determining factors were not directly dependent on management practices but rather on farm size, parasitic mistletoe, and type of planting material. Although soil fertility, namely soil organic carbon (SOC)(1.32 – 1.71%), Total N (0.12 – 0.15%), P (9.22 – 13.85cmol/kg) and K (0.18 – 0.23cmol/kg) was low across all regions, a study by Ruf (2007) found that farmers in the wet region have been intensively using pesticides and fertilisers. Even with different levels of intensification between the regions, factors such as cocoa farm age, planting density, shade cover and shade tree basal area did not significantly influence soil fertility. Another important factor influenced by the climatic region is the farmers' choice of shade tree maintenance throughout their cocoa farms. Two shade systems were identified across all regions and classified as medium and low shade cocoa agroforestry systems. Interestingly, shade tree use was higher in the dry region, perceived as an adaptation strategy by farmers to diversify cocoa farm income to compensate for lower cocoa yield under the marginal climatic conditions (Graefe et al., 2017). The low shade system showed significantly higher yield than the high shade system in the wet region but there was no difference between the systems in the mid and dry regions. The shade tree species in the dry region were dominated by fruit trees, while the wet region was dominated by timber trees. In the dry region, farmers used the shade trees to diversify agricultural production and increase the economic output from the cocoa farm rather than for micro climate moderation under marginal conditions. Climatic characteristics therefore highly influence cocoa productivity and farmer choice - in particular in terms of the production system.

6.2 Climate resilience of cocoa cultivation systems: shaded versus full sun, effect on water use under drought

The association of cocoa plants with shade trees has been traced to its origin in the Amazon region where it is noted to grow as an understory plant (De Almeida and Valle, 2007; Wood and Lass, 1985). This has led to the believe that the cocoa plant thrives best under shade trees and as such the shade trees could play crucial role of improving soil fertility, reducing extreme climatic effect of heat stress on the cocoa plants (Vaast et al., 2016; Tscharntke et al., 2011). In terms of soil fertility improvement by shade trees in agroforestry systems, Blaser et al. (2017) argued that the effect is dependent on the cropping system. For cocoa agroforestry systems, so far no scientific evidence of the positive effect of shade trees on soil fertility has been established (Blaser et al., 2017; Wartenberg et al., 2017). Even in annual cereal cropping systems where shade trees are perceived to be more compatible than perennial tree crop systems, huge trade-offs still exist (Sida et al., 2018; Ndoli, 2018). In these systems, there are indeed positive effects of shade trees at both household and farm level. The effect is limited to the species type of which compatible tree species such as the unique *Faidherbia albida* (Sida, 2018), are quite rare. A critical factor for successful agroforestry systems is the required knowledge and cost of management measures (e.g. material input such as mineral fertilizers and biocides) which might be the reason for limited practice by smallholder farmers despite the perceived benefits. Payment of ecosystem services to compensate for low yield in cocoa agroforestry could incentivise farmers to adopt such environmentally friendly systems.

An obvious effect of shade trees on cocoa is the influence on pest and diseases dynamics, which have been noted to influence farmers' decisions to reduce or totally eliminate shade trees from their farms (Ruf and Varlet, 2017; Ruf, 2011). The major disease is the fungal black pod disease (*Phythphora megackarya and palmivora*), which is noted to increase in severity and could lead to total crop loss under high shaded cocoa systems due to higher air humidity (Beer et al., 1998). Although the prevalence of the disease might be higher in the wet regions (Ruf, 2011), it is still a huge problem across all cocoa regions as it occurs during the rainy season when humidity is high even in the dry regions (Aneani and Ofori-Frimpong, 2013). Climate change now comes as an additional constraint to the already existing low soil fertility and pest and disease pressure faced by cocoa farmers. Nonetheless, cocoa agroforestry is perceived as a good strategy to ensure climate change adaptation and further mitigation (Tscharntke et al., 2011). In their review about the functions of shade trees in agroforestry systems, Tscharntke et al. (2011) stated that shade trees reduce drought stress on cocoa plants by reducing air and soil temperature, while at the same time keeping air humidity high to reduce evaporative demand but there are no evidence of field measurements and hence remain speculative. However, they also acknowledged the possibility that, depending on the severity of the drought, the combined water use of shade trees and cocoa plants could result in higher water demand and hence make agroforestry susceptible to drought rather than resilient. The most significant climate change effect on cocoa production is drought, which is projected to increase in frequency and severity, especially in the West African cocoa belt (Schroth et al., 2016). For cocoa agroforestry systems to be climate resilient there should be enough soil water to sustain the cocoa plants as they are sensitive to soil water limitations (Carr and Lockwood, 2011), while the shade trees could provide favourable microclimatic conditions during drought periods. Water use is very critical for the success of cocoa agroforestry systems, as many shade trees have competitive water uptake advantage over cocoa plants. This could lead to the mortality of cocoa trees during extreme drought. Competition for soil water could possibly be avoided through the use of shade tree species that exhibit complementary soil water use with cocoa plants by sourcing water from different depths within the soil profile, especially during critical periods of water limitation (Schwendenmann et al., 2010). Such complementary behaviour has been shown by *Gliricidia sepium* under drought simulation experiments by Schwendenmann et al.,(2010), and it seems this might be a similar case of a rare species according to the recent work by Rajab et al. (2018), who found no complementarity in root partitioning of cocoa and multiple indigenous shade tree species for complementary soil water use. Another study by Isaac et al. (2014) also found that cocoa plants in monocultures had lower rooting depths than in agroforestry systems, an indication of potential competition for root space. This shows the difficulty in ensuring complementary soil water use since the cocoa plant rooting depth is dynamic depending on water availability and competition for root space. To further examine whether the concept of agroforestry fulfils the promise of representing climate resilient cocoa systems, water use and microclimatic conditions were monitored during wet, dry and extremely dry periods comparing cocoa in full sun and agroforestry systems (Chapter 4). The Cocoa Research Institute of Ghana (CRIG) recommended leguminous shade tree species for soil nutrient and microclimatic condition improvements, *Albizia ferruginea* (Asare, 2005) and the most popular species in the in the studied region *Antiaris toxicaria,* were used in the study. The water demand of the agroforestry system was high and even increased with increasing drought condition. Combined transpiration of cocoa plants and shade trees was significantly higher resulting in high water demand for the agroforestry system compared to full sun. The transpiration rate of cocoa plants under the high shade of *A. ferruginea* was significantly lower than cocoa under less shade *A. toxicaria* and full sun systems during the non-water limited wet periods. The reduced transpiration under the high shade tree species of *A. ferruginea* is attributed to a reduction in solar radiation reaching the cocoa plant. This has been noted to significantly affect the net primary production of the cocoa plant, which subsequently results in lower cocoa yield (Acheampong et al., 2013). In addition to the lower pod production, the probability of the pods to be affected by the black pod disease is also high. Cocoa plant mortality was severe under the agroforestry system compared to full sun during the extreme drought of 2015/16. During this period, all cocoa plants under *A. ferruginea* died. Higher cocoa plants mortality of 77% with massive stress under *A. toxicaria* and only 12% mortality under full sun system. Water uptake, recorded as sap flux density, was significantly lower for the cocoa plants under *A. toxicaria* that survived compared to those under full sun, an indication of water limitation in the agroforestry system. The resilience of systems was then evaluated, which was defined as the return of the cocoa plants to healthy conditions after the extreme drought (Folke et al., 2002). The cocoa plants in full sun recovered their water uptake sap flux rate and healthy vegetation, which was not the case for those under *A. toxicaria*. The agroforestry system's lack of resilience is attributed to water competition as the soil water content in full sun was higher than in the agroforestry system. So far, the general discourse in the cocoa sector has been that shade trees are needed for climate change/drought adaptation (Vaast et al., 2016). However, recent results (including those presented in this thesis) show that adaptation should is rather be a function of /or in line with location, severity of the drought event, shade tree species type and root characteristics. It is important to highlight these drawbacks of agroforestry systems to avoid the general perception of agroforestry as the silver bullet for climate change adaptation. Promoting shade cocoa agroforestry as drought resilient systems, especially under varying climate conditions, needs to be further studied. Shade tree species may constitute a major risk to cocoa functioning under extended severe drought but their role in ensuring sustainable and environmentally friendly cocoa production in suitable climatic conditions also should be acknowledged.

6.3 Effect of shade level on cocoa plant productivity under different climatic conditions

In the final chapter (Chapter 5), cocoa plant productivity between different shade levels along a climatic gradient was assessed to show that climatic region matters for cocoa plant production in agroforestry systems. From the previous chapter, it is evident that the concept of complementary water use could not be confirmed. Agroforestry system practice might need to be concentrated in areas where drought conditions would not reach such extreme levels, even with extreme climatic events. It was observed that during the extreme drought along the studied gradient, from dry via mid to wet regions in Chapter 2 and 3, the climatic conditions in the mid and wet regions did not reach such critical limits as observed in the dry region. Although temperature has been noted as the critical factor to affect cocoa plants along the climatic gradient in cocoa regions (Schroth et al., 2016), no obvious difference was observed. However, relative humidity was drastically reduced in the dry region when compared to the mid and wet regions during the extreme drought of 2015/16. This undoubtedly played a significant role on the water demand of both the cocoa and shade trees and hence the productivity of the cocoa. Cocoa plant productivity, especially harvested pods, was highly influenced by climatic regions with lower yield in the dry region. The effect of the agroforestry system on cocoa plant productivity was only observed in the dry region where the full sun system produced significantly higher yield than the agroforestry system. Linking this finding to the previous chapter (Chapter 4), the reason for the lower yield in the agroforestry system is attributed to water limitations resulting from the soil water competition. However, in the mid and wet region there was no yield difference between the full sun and the agroforestry systems in terms of the cocoa plant yield. Overall, the cocoa plants in the wet region produced the highest yield and were least affected by the extreme drought in terms of cocoa plant performance. This further confirms the high climate suitability of the regions for cocoa production. Cherrel production and harvested pods in the full sun system in the dry region was comparable to the mid region, pointing to the fact that full sun might rather be the best adaptation option in such marginal climate regions.

6.4 Conclusions

Overall, the detailed studies have found that monoculture cocoa production systems might be a more adaptable production strategy in dry cocoa growing regions that occasionally experience extreme drought events. Future cocoa production in dry regions is risky considering the projected decrease in climate suitability, due to an increase in the intensity and frequency of drought events. An obvious solution might be to switch to more drought tolerant crops such as cashew (Fig 6.1).

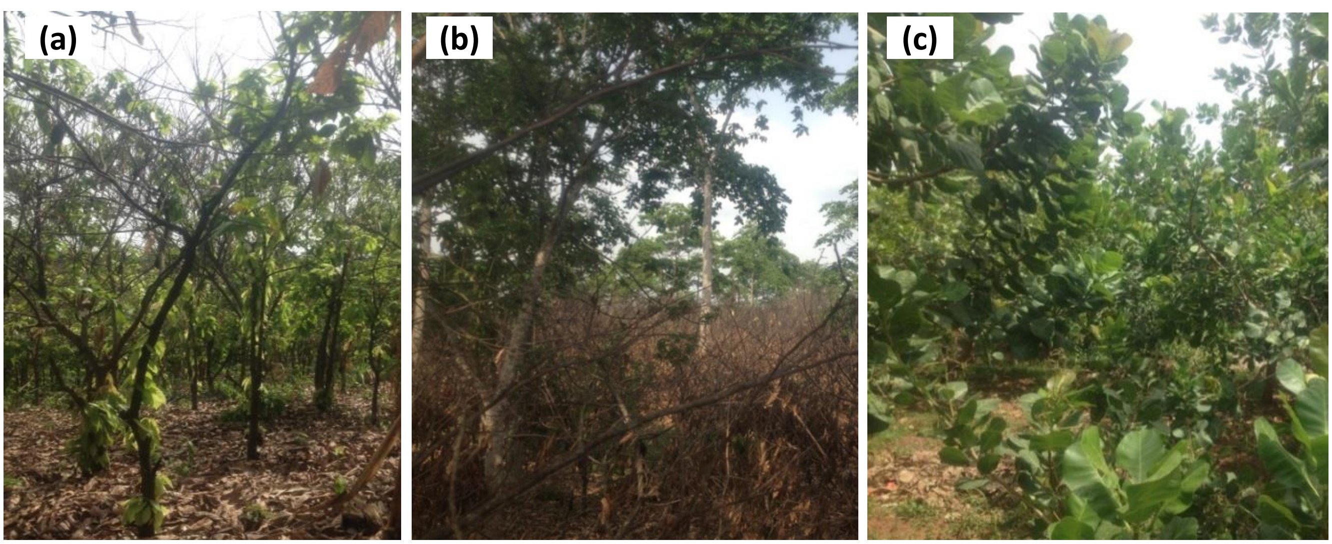

Figure 6.1 Cocoa plants under a) full sun b) agroforestry and c) cashew plants after extreme drought of 2015/16 in the dry region. Cashew is an important cash crop and could serve as alternative to cocoa due to its drought resilience.

In the mid region where climatic conditions are projected to become similar to those currently experienced in the dry region, the full sun system might be a potential adaptation option. However, there could be alternatives. For instance, research efforts should further focus on identifying shade tree species with complementary soil water use when combined with cocoa plants, to facilitate agroforestry recommendations for climate change adaptation. In the wet region, cocoa agroforestry recommendations should further address their management requirements, especially in terms of soil fertility management and plant protection, to ensure high cocoa plant productivity in the future. Targeted research for different climatic regions is required to better identify appropriate species and management systems for effective implementation of agroforestry systems. This could help work towards the sustainable intensification of cocoa production in Ghana and beyond.

6.5 Outlook

For the future, in-depth studies on water use dynamics and root characteristics of different shade trees species under marginal climatic conditions in all major cocoa cultivation regions around the globe are required to fully evaluate the potential of agroforestry as a climate resilient system. Evaluations should look at the effect of different shade tree species and traits (such as tree size, height, canopy density, nitrogen fixation and phenology) on the availability of nutrients, light and water and their use efficiencies. The effect of climatic regions on cocoa and shade tree rooting depth and water uptake characteristics will help to understand the (hidden) complexities in cocoa agroforestry systems. Identifying shade trees with complementary soil water and nutrient use with cocoa will help guide species selection for productive cocoa agroforestry systems even under increased climatic variability. As a follow-up, jointly with strong research groups, I plan to perform a comprehensive study, including root characterization, water use and productivity using controlled experiments and field studies over different climatic gradients. A basic knowledge gap is the lack of established thresholds for different cocoa varieties (Wood and Lass, 1985) to help identify the cultivation range to avoid serious climatic effects. This knowledge gap will be addressed through greenhouse and climate chamber experiments for different cocoa genotypes and different climatic conditions using soils from West Africa. The evaluation of potential alternative crops to cocoa in the marginal regions will also be studied to guide transformational adaptation in line with projected climate change.

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D E C L A R A T I O N S

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

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