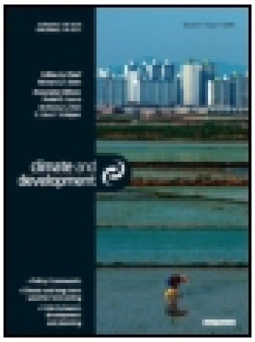

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RESEARCH ARTICLE

On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana

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Despite Ghana's large contribution to global cocoa production, average yields are low. Policymakers and practitioners are calling for implementation of a climate smart strategy by increasing yields and augmenting shade tree cover in cocoa systems. However, there have been few studies in West Africa on the relationship between shade and cocoa yield under field conditions. The objective of this study was to determine the effect of shade tree cover and other factors on on-farm cocoa yields over a four-year period. The study was conducted on 86 farm plots of 8–28 years' cocoa trees with varied canopy cover (CC) in Ashanti and Western regions of Ghana. A linear mixed model analysis showed that yields increased significantly with increased CC of shade trees, and indicated a doubling of yields when going from zero to approximately 30% crown cover. Fertilizer use gave a yield increase of 7%. Farms located in Western region had higher yields compared to Ashanti, and cocoa systems on short fallows had lower yields than farms cultivated on recent forest clearings and old fallows. Fungicide use, seed sources and land ownership had no significant effects on yield. We conclude that for a sustainable climate-smart cocoa agenda, promotion of shade trees is key.

Keywords: climate smart cocoa; canopy cover; yield; fertilizer; REDD+

1. Introduction

Ghana is one of the top global producers of cocoa (*Theobroma cacao* L.), but reported on-farm yields are among the lowest in the world at 400 kg/ha (Aneani & Ofori-Frimpong, 2013). Cocoa cultivation is a driver of deforestation and forest degradation across the high forest zone (GoG, 2010), due to expansive farming practices and encroachment into gazetted forests, illegal surface mining activities and human settlements. Expansive, migratory practices date back over 100 years (Berry, 1992), but the shift from high shade to low/no shade systems emerged with the introduction of chainsaws in the mid-eighties and the pervasive perception amongst farmers that shade trees have a negative impact on cocoa yields (Asare, 2010). Ghana's Forestry Commission and the Ghana Cocoa Board documented a ten-year historical deforestation rate (2000–2010) across the cocoa forest mosaic landscape of 1.4% per annum (GoG, 2014). Given that Ghana's Cocoa Board established a goal of producing 1 million tons of cocoa annually (Asare, Afari-Sefa, Gyamfi, Okafor, & Mva Mva, 2010), and that the country is pursuing a low emissions development strategy (GoG, 2011) and is committed to implementing reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+), it is imperative that the cocoa sector commits to a strategy that enables increases in on-farm yields while maintaining forests and trees in the landscape.

According to the FAO (2013), climate-smart agriculture (CSA) refers to agriculture that sustainably increases productivity, resilience (adaptation), reduces or removes GHG emissions (mitigation) and enhances the achievement of national food security and development goals. This concept gained prominence in 2010 during international climate change negotiations, as many countries and influential stakeholders felt that agriculture was not adequately captured in the evolving REDD+ space. Following international discussions, CSA also gained prominence in Ghana amongst government, private sector and civil society stakeholders (MLNR, 2012) engaged in the REDD+ space. Within the cocoa sector, the concept, which is referred to as climate-smart cocoa, was quickly seen as a strategy with the potential to sustainably increase

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yields and incomes while reducing rates of deforestation and forest degradation, as well as enhancing carbon stocks on farm (Asare, 2014; CSCWG, 2011). The synergies between CSA, cocoa and forestry sectors are many, including the focus on increasing productivity, the goal of resilience in the face of predicted changes in temperature and rainfall patterns (Läderach, Martinez-Valle, Schroth, & Castro, 2013), and the mitigation potential from increasing shade in the cocoa systems (Ruf & Zadi, 1998).

Engaging in "reforestation" through the introduction of diversified shade systems on degraded lands or low/no shade farms would also produce valuable co-benefits. Diversified shade cocoa farms and multi-strata cocoa farms that contain crops, native forest trees, and fruit trees are valuable, because they offer farmers a range of agronomic, economic, cultural, and ecological benefits (Gockowski, Tchata, Hietet, Fouda, & Moneye, 2006; Sonwa et al., 2001), in addition to maintaining biodiversity in the landscape (Griffith, 2000; Schroth & Harvey, 2007). Besides, shade trees increase the economic rotation age of hybrid cocoa trees (Obiri, Bright, McDonald, Anglaaere, & Cobbina, 2007). Diversified farms enable farmers to exploit the different components in the system to meet subsistence needs, maximize incomes, and reduce risks against fluctuations in world market prices of cocoa beans (DiFalco & Perrings, 2003; Duguma, Gockowski, & Bakala, 2001; Rice & Greenberg, 2000). This is more evident in low input agriculture, where sustainability rather than maximization of productivity tends to be the major concern (Beer, 1987). Finally, in terms of biodiversity conservation, multi-strata cocoa forests can help to connect forest patches (Asare, Afari-Sefa, Osei-Owusu, & Pabi, 2014), to regenerate and conserve forest tree species, and to provide habitat for key animal species (Greenberg, Bichier, & Angon, 2000; Schroth et al., 2004; Siebert, 2002) that play vital roles in maintaining and conserving forests.

Even though cocoa can grow in a low light environment (Hutcheon, 1981), the shade requirement of cocoa has been questioned as many farmers perceive a negative relationship between shade cover and yields (Asare, 2010). This perception is founded on the first shade and fertilizer trials conducted on a research station in a forest environment in Ghana in the 1950, 1960s and 1970s (Ahenkorah, Akrofi, & Adri, 1974; Ahenkorah, Halm, Appiah, Akrofi, & Yirenkyi, 1987; Cunningham & Arnold, 1962). Results showed very high yields of well-established cocoa plantations on fertilized soils after complete shade removal. These trials have shaped the current perceptions about shade and cocoa yields, as findings recommended removal of shade cover for improved productivity of the cocoa trees, even though the same research found dire consequences of unshaded cocoa without the requisite compensatory agro-chemical application (Ahenkorah et al., 1987). Subsequent research on shade reduction in cocoa systems have recorded increased damages due to pests and diseases (Campbell, 1984), faster weed growth and greater nutrient demands from the cocoa trees (Ahenkorah et al., 1974). For example, severe dieback diseases and excessive vegetative growth at the expense of pod production was recorded under no-shade conditions (Gerritsma & Wessel, 1994). There may also be quality issues as it was reported that young and unshaded cocoa produced a high percentage of small category G beans (Adu-Ampomah et al., 1998). In effect the literature seems to argue that while eliminating shade has a productive advantage that boosts yield, these systems may not be economically justified considering the negative effects that come from a lack of shade and the increased demand for agrochemical inputs to maintain productivity (Alvim, 1977), since in its natural environment, the cocoa tree is an understory species (Purseglove, 1968).

Two recent studies of on-farm yields show somewhat contradicting results. Wade et al. (2010) in a cocoa farming community in the Eastern region of Ghana found that cocoa yields decreased with an increase in shade levels. In a different study on on-farm plots in the Ashanti and Western Regions, results showed that non-shaded plots tended to have higher yields than plots with shade trees. However, increasing shade within the shaded plots resulted in higher yields, often above that of non-shaded plots (Asare, Asare, Asante, Markussen, & Ræbild, 2017). The complex differences between open and shaded plots made the authors to suggest that studies should be extrapolated to a whole-farm scale level to understand the full effect of canopy cover (CC) on cocoa yields. The main objective of this study was therefore to examine the effect of shade on cocoa yields applying a whole-farm perspective, taking into consideration other variables such as management and social factors. The focus on the relationship between CC (shade) and cocoa yield under low-input field conditions is critical to fully understanding the use of shade trees as an adaptation strategy for the implementation of climate-smart cocoa.

2. Materials and methods

2.1. *Study area*

The study was conducted in the Ashanti and Western regions of Ghana, targeting four communities located in four different administrative districts: Amansie West (Jeninso: $N = 20$), Atwima Nwabiagya (Nerebehi: $N = 21$), Wassa Amanfi West (Nkrankrom: $N = 22$) and Sefwi Wiawso (Nsuosua: $N = 23$) (Figure 1). The study sites in the Ashanti region fall under the Moist Semi-Deciduous Southeast subtype (MSSE) while the Western Region sites fall under the Moist Evergreen (ME) forest zones (Hall & Swaine, 1981). The ME forest zone is characterized by a semi-equatorial climate that has high rainfall (1500–1750 mm) and daily temperatures that range from 22°C to 34°C. Temperatures are high

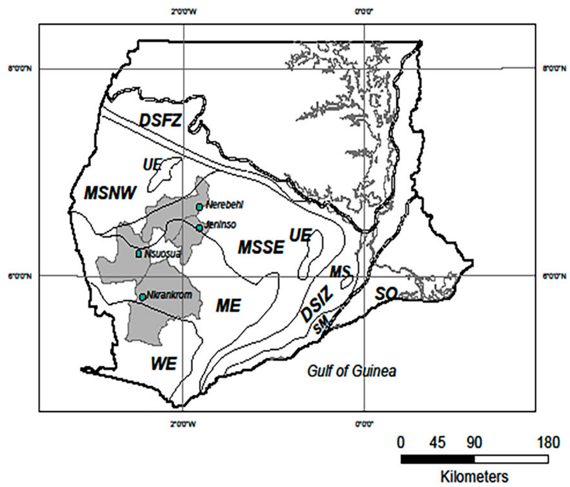

Figure 1. Map of Southern Ghana showing four shaded districts consisting of the study sites (•). Forest type boundaries are shown by broken line (———). Forest-type abbreviations: WE = Wet Evergreen; UE = Upland Evergreen; ME = Moist Evergreen; MSSE = Moist Semi-deciduous; NW = Northwest subtype; SE = Southeast subtype; DS = Dry Semi-deciduous; FZ = Fire Zone subtype; IZ = Inner Zone subtype; SM = Southern Marginal.

throughout the year, though March is generally the hottest month. Humidity is high, ranging from 70% to 90% for the monthly means. The MSSE forest zone is marked by moderate annual rainfall (1250–1500 mm) with uniformly high temperatures (mean monthly minimum and maximum of 27°C–31°C) and high relative humidity (Figure 1).

The soils of the forest zone are generally developed from rocks of the Birrimian system (middle Pre-Cambrian) (Adu, 1992), which consists mainly of argillaceous sediments metamorphosed into phyllites. The well-drained soils belong to the Forest Ochrosol (MSSE) and Forest Ochrosol-Oxysol Intergrade (ME) Great Soil Group of the Ghanaian soil classification system (Bramner, 1962) and are generally accommodated as Acrisols in the FAO-UNESCO Revised Legend (FAO–UNESCO, 1988) and as Ultisols ion Soil Taxonomy (OSD, 1998). These soils under natural conditions contain adequate nutrients that are tied-up with the organic layer in their top soils.

The Ashanti and Western regions were selected as they represent old and comparatively newer areas of cocoa cultivation in Ghana respectively, with the latter responsible for producing over 50% of the country's annual total production. Western Region is viewed as the last frontier for expansion of cocoa cultivation due to the presence of forest patches and extensive areas of protected forest. In comparison, the Ashanti Region landscape contains a more degraded forest environment, with more bush fallows, though it also contains gazetted forest reserves. In each of the four communities, at least 20 farmers representing the same number of cocoa farms were selected, using a systematic sampling approach that involved focus group discussions and individual interviews. Farmers were selected due to the presence of a variable number of shade trees on their cocoa farms. Besides, the age of cocoa was between 8 and 28 years which is the economically favourable age of cocoa trees (Obiri et al., 2007). Finally, farms were selected such that they were at least 100 m apart in each community.

2.2. *Cocoa yield measurement*

In Ghana, there can be three possible methods for gathering on-farm cocoa yield data: (i) asking farmers to report their yield; (ii) obtaining yield records from official "Cocoa Passbooks", and (iii) directly recording the number of viable, harvested pods/tree and then weighing the dried beans from these pods after fermentation. Relying upon farmer self-reporting of annual farm yield can be highly inaccurate. Some reasons for these inaccuracies include farmer illiteracy, lack of farmer record keeping, and farmers' propensity to report yield based upon the average number of "bags" (approximately 64 kg) harvested from the farm. This is despite the fact that they do not sell their beans by the bag, but usually in smaller quantities and at multiple points in time over the course of the season. This method also requires knowledge of the area of the farm in order to be able to estimate the yield per hectare. When self-reporting is relied upon for both the area of the farm and the total cocoa harvest, the results can be highly unreliable, as work has shown that farmers tend to over-estimate the size of their farms (Hainmueller, Hiscox, & Tampe, 2011). Thus, one could argue that this method is perhaps only useful as a general or initial estimate.

The second method relies upon the Cocoa Passbook (CP), which is an officially dated record of the weight of dried cocoa beans that a farmer sells to a Purchasing Clerk (PC) at different points in the season. With each sale, the weight of the beans being sold is recorded by the PC into the farmer's CP. The farmer uses the CP to ensure that full payment is made, if money is not immediately available. It is also used to justify bonuses farmers receive from Ghana's Cocoa Board after the close of the cocoa season.

The third method demands that a researcher counts and records the number of viable pods harvested from the farm over the course of the season (approximately 4 months), and that the researcher directly weighs the dried beans coming off the farm after fermentation. Though highly accurate (Asare et al., 2017), this method is costly and labour intensive if data is to be collected from multiple farms over the full harvest period.

The method used for collecting yield data for four consecutive years, starting in the 2009/2010 season and ending in the 2012/2013 season in this research included a combination of the first and second methods. In order to do this, all of the farmers in this study and the PCs were trained by the research team on cocoa yield data keeping. Dry cocoa beans from each research delineated and measured farm (see next section) were measured by both the farmer and the PC and the weight recorded on a data sheet before entering it in the CP. The researcher then received the data sheet from the CP and results were crosschecked with farmers' CP after every harvest period.

During the same period, farmers' information on management was collected using a questionnaire in which farmers were asked questions about socio-economic and socio-cultural management factors, including land use type (was farm made on forest, fallow or already cropped land), history of farm (purchased, inherited, share cropped or tenancy), educational background, training experience in cocoa cultivation, fertilizer application, insecticide use, fungicide application, source of cocoa planting material and whether shade trees were planted or naturally regenerated. During the four-year period, application of fertilizer, insecticide or fungicide in a given year was registered as "yes or no" in the respective records, and treatment frequencies or amounts were not recorded. If there was any doubt about the yield data in a specific year (e.g. because the farmer had sold to a non-registered buyer or had neglected part of the harvest), data were omitted.

2.3. *Shade tree crown cover*

The selected farms were delineated such that they represented a single management regime. The area of each farm was recorded with a Garmin Global Positioning System by walking along the entire perimeter of the farm. All shade trees above the cocoa canopy and lying within the perimeter of the farm were identified and counted. Quantifying shade above integrated and closed cocoa farms is challenging, and a simplistic measure of the CC of shade trees was used as a proxy for shade cover [see Asare and Raebild (2016)]. For all shade trees, the diameter of the crown (CD) was measured four times across the crown spread from one tip to the other (Blozan, 2006). The average CD for the tree was calculated. The crown area (CA) of individual trees was calculated by the following formula:

$$\mathrm{CA} = \pi * \left(\frac{\mathrm{CD}}{2}\right)^2 \quad (1)$$

Where CA is expressed in m^2. The total CC for all the upper canopy trees was expressed as a percentage of farm area to ensure easy comparison between farms, using the following formula

$$\mathrm{CC} = \frac{\mathrm{TCA}}{Farmsize} 100\% \quad (2)$$

Where TCA is the total CA of all trees recorded per farm and farm size is expressed in m^2. Cocoa yield was expressed as the quantity of cocoa beans produced per annum in kg, divided by the farm size in ha.

2.4. *Statistical analysis*

Cocoa yield was analyzed in a linear mixed effect model where *Yield*, representing annual production of dry cocoa beans per ha (measured four times in four years), was used as the dependent variable. The fixed effects consisted of *District* location of the farms (4 levels: Atwima Nwabiagya, Amansie West, Wassa Amenfi West, Sefwi Wiawso), *FarmSize* (continuous, centralized at the average farm size within districts), total number of shade trees on farm *TreeTotal* (continuous), shade tree *Density* (continuous, expressed per ha), CC of shade trees (continuous), title of farm land *LandTitle* (3 levels: purchased, inherited and sharecropping), land use type *LandUse* (3 levels: forest, long fallow, short fallow), sources of planting materials *SeedT* (4 levels: own seeds, hybrid seeds from approved source, both own seeds and seeds from approved sources and, unknown), *Training* (no/yes), *Gender* (male/female), *Fertilizer* (no/yes), *Fungicide* (no/yes), as well as 2-way interactions between CC and *Fertilizer*, and between *District* and *Training*. The dependent variable was power transformed (Box & Cox, 1964), and this analysis showed that the best normality of the residuals was achieved by taking *Yield* to the third root. The study involves repeated measurements within farms and it is necessary to model the correlation between measurements. Since only four measurements were taken on each farm the correlation was modelled by random effects. Five different sets of random effects were tried as shown in Table 1.

The correlation structure with the lowest value of the *Second order Akaike Information Criterion* (AICc) (Burnham & Anderson, 2002) was used for the further analysis. This is a model with the random effects of *Year*, *Farm* and *District* nested within *Year.* The statistical assumptions underlying this model were validated by residual and normal quantile plots. Two of the 84 farms had missing values for the covariate *Fungicide*. To use the observations for these farms all four combinations of possible yes/no values were tried, and the combination achieving the lowest AICc value was used. Doing this allows all farms to be used in a best subset model selection based on the AICc, where the missing values are inserted in order to favour the selection of *Fungicide*. If this covariate is not selected in the final model, the insertion of the missing values has no implication. After selection of the fixed effects by AICc, significance tests on the selected effects were done by likelihood ratio test, estimates were found by restricted maximum likelihood, and confidence intervals were computed by parametric bootstrap.

Since the focus of this study is to investigate the effect of CC on *Yield*, the statistical analysis was completed by investigating the relations between CC and other

Table 1. Selection of random effects by AICc (Second order Akaike Information Criterion) in a model containing all the fixed effects.

Random effects	No. parameters	AICc
District within *Year*, *Year* within *District, Farm*	45	1210.21
District within *Year, Farm*	35	1183.57
Year within *District, Farm*	35	1188.47
District nested in *Year*, *Year, Farm*	27	1178.24
Year, Farm	26	1211.63

Note: The random effect *District* within *Year* means an arbitrary correlation structure between the four districts, which are independent across the four years, and similarly for *Year* within *District*. The random effect *District* nested in *Year* means a random effect of the 16 combinations of *District* and *Year*.

explanatory variables from the selected model in separate univariate analyses. For statistically valid models, CC was logarithmic transformed in these analyses.

3. Results

Farm sizes ranged from 0.12 ha to 8.8 ha. All farms had trees, but in varying numbers, resulting in shade tree densities ranging from 2.1 to 66.7 trees ha^{-1}, and CC above the cocoa trees varying from 1.0% to 34%. CA of shade trees positively correlate with diameter at breast height (DBH) with different species having different canopy sizes. In total 1042 shade trees were recorded on a total farm area of 127.7 ha, 96% of which were a result of natural regeneration. The shade trees comprised 90 species from 30 families with 49 species appearing in both agro-ecological zones (see Asare & Raebild, 2016). The most occurring species included timber species like *Terminalia superba* Engl. & Diels, *T. ivorensis* A. Chev., *Newbouldia laevis* (P. Beauv.) Seem. ex Bureau, *Milicia excelsa* (Welw.) C.C.Berg, *Ficus exasperata* P. Beauv., *Antiaris toxicaria* Lesch., *Amphimas pterocarpoides* Harms, *Albizia zygia* (DC.) J.F.Macbr., and *Morinda lucida* Benth. Fruit trees such as *Persea Americana* Mill, *Cola nitida* (Vent.) Schott & Endl., and *Ricinodendron heudelotii* (Baill.) Pierre ex Heckel were also found. Analysis showed that tree diversity on the farm plots increased with increasing farm size, but measure of evenness was unaffected by farm size even though it varied significantly between districts.

Of the 84 farmers, 35% had received a form of training in cocoa cultivation, and approximately 30% were women, almost all of whom had inherited their farm lands from their spouses or family. In terms of previous land use, 56% of the farms were cultivated on old fallows, 23% on land that had been forested, and 21% on short fallow or cropped land. A high frequency of farmers used agrochemicals, with 60, 80 and 99% of farmers using fertilizers, fungicides and insecticides, respectively. Because of the high percentage using insecticides, this parameter was not included in the statistical analysis.

In the statistical analysis of yield, the best model retained the main effects of *District*, *Farmsize*, *CC*, *LandUse*, *Training*, and *Fertilizer*:

$$Yield^{1/3} = \alpha(District) + \beta*(Farmsize - \mu_{District}) + \gamma*\mathrm{CC} + \delta(LandUse) + \varepsilon(Training) + \zeta(Fertilizer) + A(Farm) + B(District, Year) + C(Year) + error$$

The corresponding estimates, confidence intervals, and *P*-values for the fixed effects are given in Table 2. In this model, the average farm size within the districts are $\mu_{\text{Atwima Nwabiagya}} = 1.802$, $\mu_{\text{Amansie West}} = 1.086$, $\mu_{\text{Wassa Amenfi West}} = 1.941$, $\mu_{\text{Sefwi Wiawso}} = 0.899$, calculated as raw means from the data. The introduction of these parameters implies that the parameters α can be interpreted as the cubic root of the yield of an averaged sized farm in the corresponding district, without shade, with *LandUse* = forest, without training, and without fertilizer.

The model shows highly significant positive effects of CC on yields ($\gamma = 0.07$, $p < 0.0001$), of training ($\varepsilon = 0.73$, $p = 0.0052$) and of fertilizer application ($\zeta = 64$, $p = 0.0088$). Moreover, *LandUse* = forest gives the highest yields.

Estimates for the variance components are given in Table 2. We see that 56% of the total unexplained variation can be attributed to the error term, which can be interpreted as the year to year variation within the individual farms. The remaining part of the total unexplained variation is almost equally split as variation between farms (21.3%) and year to year variation within the four districts (22.0%).

The relations between tree CC and the other selected explanatory variables (Farmsize, LandUse, Training and Fertilizer) showed that only *Farmsize* was confounded with CC ($P < 0.0001$).

The estimated relation between these variables is given by the equation

$$\mathrm{CC} = 6.29*Farmsize*\exp(-0.70)$$

This indicates that smaller farms in general have larger CC than larger farms. Based on the estimates in Table 2 we see that smaller *Farmsize* and larger CC both imply higher *Yield*. Thus, the positive effect of CC and the negative effect of farm size are confounded, which is also seen as

Table 2. Estimates, confidence intervals, *p*-values and variance components in the selected model.

Effect	Parameter	Estimate	95% Confidence interval	*P*-value
1. Estimates, confidence intervals, and *p*-values in the selected model				
District	α (Atwima Nwabigya)	6.25	5.18; 7.30	0.0048
	α (Amansie West)	6.03	5.02; 7.11	
	α (Wassa Amenfi West)	7.91	6.77; 8.98	
	α (Sefwi Wiawso)	7.83	6.73; 9.03	
Farmsize	β	−0.17	−0.34; −0.01	0.0305
CC	γ	0.07	0.04; 0.11	<0.0001
LandUse	δ (Long fallow)-δ(Forest)	−0.16	−0.69; 0.40	0.0147
	δ (Short fallow)-δ(Forest)	−0.91	−1.60; −0.19	
Training	ε(yes)-ε(no)	0.75	0.18; 1.31	0.0052
Fertilizer	ζ(yes)-ζ(no)	0.64	0.15; 1.13	0.0088
2. Estimates for the variance components in the selected model				
Random effect	*Variance component*	*Proportion of total variation*		
Farm	0.6110	21.3%		
District nested in *Year*	0.6321	22.0%		
Year	0.0090	0.3%		
error	1.6225	56.4%		

a positive correlation between the estimates for β and γ (ρ = 0.431). To investigate this confounding scenario, we estimated models without *Farmsize* and without CC. Removing *Farmsize* increases AICc by 2.49 relative to the best model, which means that doing this has good support in the data. Removing CC increases AICc by 14.52, which means that this has no support in the data (Burnham & Anderson, 2002). A graphical display of the fit of the

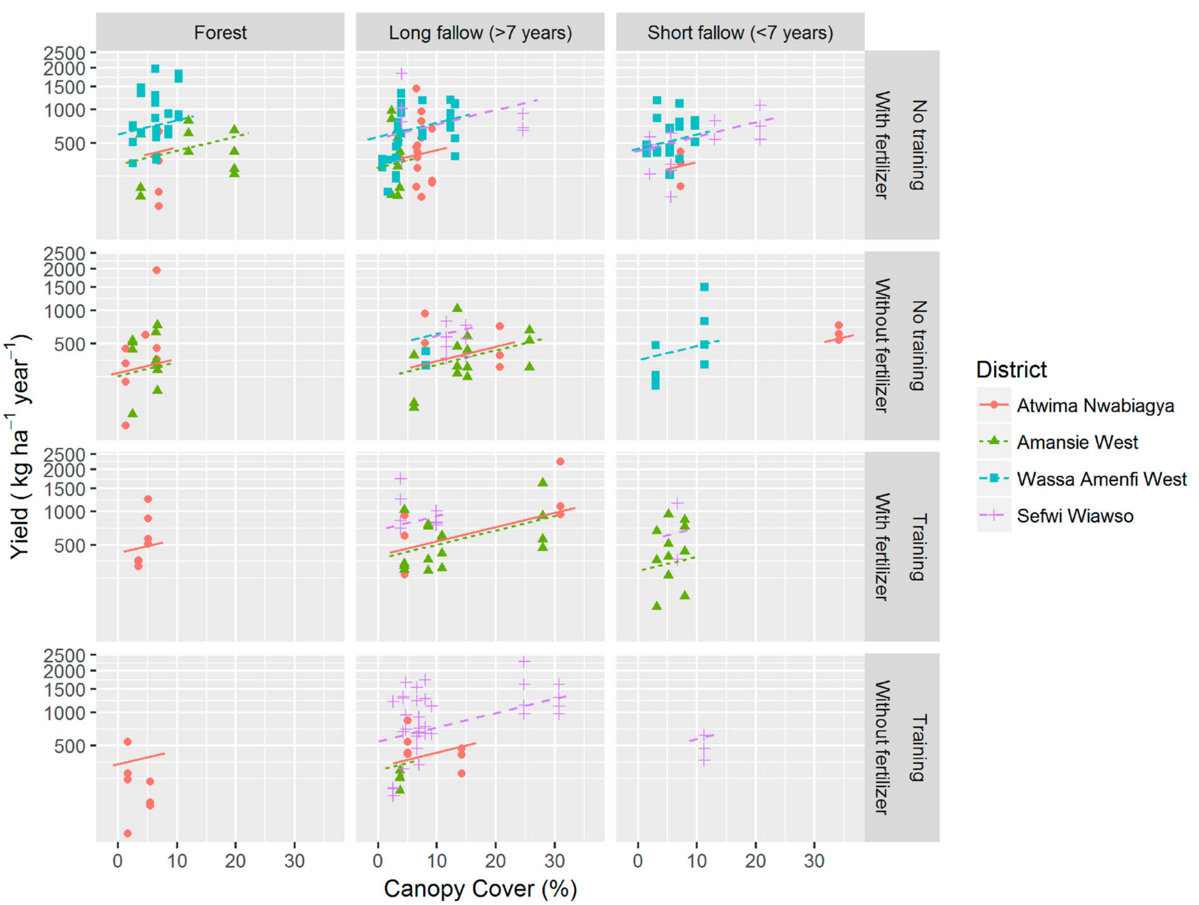

Figure 2. Observed yields (points) against canopy cover separated over Fertilizer and Training (in the rows) LandUse (in the columns), together with model predictions (lines) from the selected model with Farmsize.

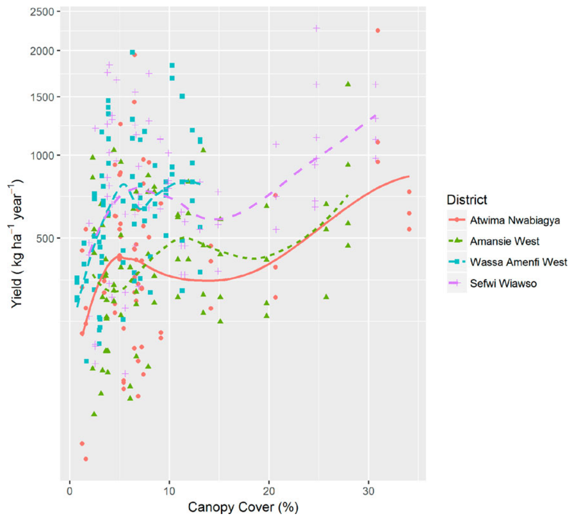

Figure 3. Observed yields (points) against canopy cover designated by districts together with model predictions (lines) from the selected model.

model without *Farmsize* against the observed data is given in Figure 2, showing a substantial amount of biological variation. As a final confirmation, likelihood ratio tests showed significant effects of CC, farm location, fertilizer, land use and training experience on yields. On the contrary, there were no significant differences in the effect of gender, history of land ownership, fungicide application and sources of cocoa planting materials on average cocoa yield.

Between the periods from 2009 to 2013, the average annual yield of cocoa was recorded to be 618 kg ha^{-1} /ha across four districts in the two regions, with the highest yields observed in the 2009/2010 season. At the district level, Sefwi Wiawso had the highest average annual yield of 807 kg ha^{-1}, followed by Wassa Amanfi West at 716 kg ha^{-1}, Nwabiagya at 497 kg ha^{-1}, and Amansie West at 430 kg ha^{-1}. There was a tremendous variation in yield between farms, with individual farm yields ranging between 15 and 2275 kg ha^{-1} year^{-1}. There was also a significant difference between trained and untrained farmers (Table 2). Yields were highly variable between years and the ranking between districts with respect to yield changed from year to year. The yields of farmers using fertilizer (627 ± 41 kg ha^{-1}) were on average 7% higher than farmers that were not using fertilizer (586 ± 57 kg ha^{-1}). In addition, the average yields for land use types were 581 kg, 666 kg and 536 kg ha^{-1} year^{-1} for forest, long fallow and short fallow land respectively. In general, there was a positive effect of CC on yields within the districts as shown in Figure 3.

4. Discussion

4.1. *Relationship between CC and yield*

Results from a recent study in the same cocoa agroforestry systems, showed that cocoa trees under shade trees have lower yields compared to full sun cocoa, but also that yields under shade trees increase with increasing amounts of shade at plot level (Asare et al., 2017). The interpretation given by the authors implied that there is a positive effect of shade on yields, but that competition from shade trees for water and nutrients may have a negative effect. The question was, what would the aggregate effect of shade trees be for the whole field? With the present study, which shows a positive correlation between shade cover and yield at field level, we have evidence to support that larger CC from shade trees results in increasing yields. Smaller yields under shade trees thus seem to be offset by positive effects of shade on the rest of the field.

Hence, compared to farms with no shade trees, yields at 34% CC would be approximately doubled (Figure 2). With respect to making recommendations on optimizing CC, these findings fall in line with the Ghana Cocoa Board's recommendation of 30%–40% CC for improved yields under cocoa agroforestry systems (Anim-Kwapong, 2006), which has also been confirmed in studies by Vaast and Somarriba (2014). However, achieving this coverage will depend on what species, stage of maturity, and density of trees as analysis have shown that the CA of a tree species is dependent on its DBH (Asare & Raebild, 2016). It must be stated here that even though it may not be biologically plausible that the yield keeps on increasing with increasing CC, however, within the observed data range with CC up to a level of approximately 30% we do not see a decrease in yield with CC. This is substantiated by recent findings of Andres et al. (2018) who found increased number of pods up to a level of 30%–50% shade, after which yields declined. Although this may seem to be at odds with the common perception that shade results in decreasing yield, we find that there is no conflict between this study and previous findings from controlled or semi-controlled experiments (e.g. Ahenkorah et al., 1987; Cunningham & Arnold, 1962). These studies were carried out under high-input conditions and showed higher yields in open systems than in shaded cocoa systems. Even though farmers in our study applied fertilizer and other agrochemical inputs, the quantities applied by small-scale farmers are usually below the recommended doses needed to optimize yields in full-sun grown cocoa (Appiah, Sackey, Ofori-Frimpong, & Afrifa, 1997). Instead, farmers tend to apply low amounts of fertilizer (Baah, Anchirinah, & Amon-Armah, 2011) with irregular use of fungicides and insecticides, meaning that natural maintenance of soil fertility as well as pest and disease control by non-chemical means become more important. These natural processes may be more prominent in a diverse system with emergent shade trees. Indeed, Beer, Muschler, Kass, and Somarriba (1998) suggested that shade can be beneficial under low input scenarios. Specific to Ghana, Isaac, Timmer, and Quashie-Sam (2007) documented an increase in nutrient uptake by cocoa trees under shade. One important question is therefore at what CC threshold will yield begin to decline?

Management and the level of shade are often correlated, exemplified by the study of Wade et al. (2010) in the Eastern Region of Ghana. Here, higher yielding, more intensively managed farms had significantly lower shade levels than farms with low productivity, extensive management and a multi-strata shade system. In our study, we were able to separate different management strategies from the shade level, thus eliminating confounding effects and showing a positive effect of shade. However, it is also possible that the effect of shade in the Eastern region is indeed negative, as farming practices here tend to be different from practices in the Ashanti and Western Regions that were included in our study. Cocoa has been cultivated for a longer time in the Eastern region, and consequently there is a possibility that the soils are significantly more degraded. The Western and Ashanti regions present newer areas of cocoa production where management practices have improved and taken advantage of modern technical know-how on cocoa production.

Still, further research on-farm, applying multi-year and multi-location approaches is needed to clarify the role of shade trees in low input systems. Such research could also include the effects of specific shade tree species on cocoa productivity, as species are likely to interact differently with cocoa. In our study, we used an appropriate measure for yield as determined from both farm records and CP confirmation with an accurate determination of the farm size. We believe that the combination of these two methods should be applied more intensively in the future to achieve reliable farm-based yield data.

If other studies confirm our findings that the average yield increases with increasing CC on farm it may have important practical implications in terms of recommendations to farmers, extension strategies aimed at increasing yields, and enhanced environmental sustainability on-farm. Though not endorsed by the Ghana Cocoa Board or the Cocoa Research Institute of Ghana, the wide-spread perception of a negative relationship between shade cover and yield has led to a gradual elimination of shade trees in cocoa growing systems (Padi & Owusu, 1998) across the cocoa landscape over the past decades, which has led to a decline in tree cover on farms (Asare & Raebild, 2016). This research now questions whether there is a risk that the loss of tree cover has negatively affected the production of cocoa beans, as compared to the positive effect that some farmers and experts might have assumed. While encouraging farmers to maintain or increase CC may also result in other environmental benefits, it is important to note that the CC and per hectare tree density recorded in this study is substantially lower than what has been recorded in the *Cabruca* systems of Bahia, Brazil, which have been noted for improving the environmental integrity of the cocoa landscapes and maintaining high levels of biodiversity in terms of forest tree species (Sambuichi et al., 2012).

Nonetheless, the potential positive impact on yield at field or farm level alters discussions about trade-offs between productivity and ecosystem services in shaded systems that conserve biodiversity and carbon stocks. This is particularly relevant with regards to REDD+ and CSA programmes; suggesting a possible win-win situation in terms of increasing yields and increasing CC to promote mitigation and adaptation to climate change (*cf.* Asare et al., 2014; Wade et al., 2010). It seems necessary to more actively promote cocoa agroforestry and to change the current messaging (both formal and informal) to farmers about the economic and ecological value of shade trees in cocoa farms.

4.2. *Other variables*

Fertilizer use was widespread amongst respondents (60%) compared to other results from Ghana (Nunoo, Nsiah Frimpong, & Frimpong, 2014). The positive influence of fertilizer on cocoa yield, however, is relatively small, especially considering that most cocoa experts promote the use of inorganic fertilizers. Although we did not systematically record the amount of fertilizers, the overall impression is that farmers were applying low levels of fertilizer (*cf.* Appiah et al., 1997; Asare et al., 2017). A more detailed investigation would have to be carried out to clarify this, recording fertilizer amounts applied for every year.

In the absence of the required doses of fertilizers, the natural maintenance of soil fertility becomes more important, and low cocoa yields on short fallow/cropped lands in the four districts suggests that the soils of recently cropped land are exhausted in terms of nutrients, resulting in lower yields. Interestingly, there were no significant difference between yields of cocoa planted on previously forested and long fallow lands, raising the question as to the real yield value of the perceived forest rent over a long time as suggested by Ruf and Zadi (1998).

The two districts in the Western Region attained higher average yields than the farms located in districts in the Ashanti Region. A study by Vigneri (2007) attributed the high yields to favourable rainfall conditions in the Western region. A better understanding of the variations in yields between different agro-ecological zones could also have implications for Ghana's REDD+ efforts. For example, if high cocoa yields, above the national average, make the Western Region more attractive to cocoa farming than other areas, this could serve as a potential threat to forests as the Western Region contains the highest density of forest reserves and national parks across the high forest zone.

Many variables that are commonly assumed to be important, including gender, use of fungicide, the cocoa seed source (indicating a hybrid cocoa tree or not) and the land tenure arrangement (history of the land), had no significant impact on yields. Gender issues have received limited attention with respect to cocoa farming in West Africa, though Asare and Raebild (2016) found that gender had a significant impact on farm size, with female farmers having farms that were on average 0.92 ha smaller than men's farms. Since gender had no significant influence on yield, the interpretation must be that female farmers are likely to obtain less income from cocoa farming due to the smaller size of their farms.

Land and tree tenure are commonly cited as factors affecting decisions about shade tree management (Asare & Raebild, 2016). This is contradicted by the absence of a significant relationship between yields and whether the cocoa farm is inherited ($n = 65$), purchased ($n = 8$) or under a sharecropping arrangement locally known as *abunu* ($n = 13$). From a policy point of view, it seems that there is a need for better understanding the socio-economic and ecological management factors that affect yield.

The limited impact of agrochemicals and cocoa seed source on yields questions whether the farmers applied the required quantities (fertilizer, pesticide, fungicide and planting materials) at the appropriate times of year for them to have the intended effect. An alternative approach could be to help farmers maximize their efforts through training in good management practices, which was found to have a positive effect on yields. Such practices could include planting or retaining shade trees. However, it is important to note that there was a very considerable variation in yield between the different farms, ranging from very low to very high yields. A targeted analysis of high yielding farms is likely to lead to a better understanding of how high yields may be attained under low and high input management systems.

5. Conclusions

A sustainable, climate-smart cocoa policy that fosters increased productivity, resilience from climate-change and climate-change mitigation requires a better understanding of the relationship between CC and cocoa yield as it is realized on smallholders' farms. This study has shown that shade trees, fertilizers and training have significant positive effects on farmers' yields, but also that there is a tremendous variation between farms and regions that to some extent is due to previous land use. We propose that interventions in the cocoa value chain be revisited, and that more focus is given to promotion of shade trees, as they seem to increase cocoa yields and at the same time provide numerous ecosystem and societal services.

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Supplemental data

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