Influences of shading and fertilization on on-farm yields of cocoa in Ghana

Richard, Asare; Asare, Rebecca Ashley; Asante, Winston Adams; Markussen, Bo; Ræbild, Anders

Published in:
Experimental Agriculture

DOI:
10.1017/S0014479716000466

Publication date:
2017

Document version
Publisher's PDF, also known as Version of record

Expl Agric.: page 1 of 16

doi:10.1017/S0014479716000466

INFLUENCES OF SHADING AND FERTILIZATION ON ON-FARM YIELDS OF COCOA IN GHANA

By RICHARD ASARE†‡§§, REBECCA ASHLEY ASARE§¶, WINSTON ADAMS ASANTE††, BO MARKUSSEN‡‡ *and* ANDERS RÆBILD‡

†*International Institute of Tropical Agriculture, Private Mail Bag L-56, Legon, Ghana,* ‡*Department of Geosciences & Natural Resource Management University of Copenhagen, Denmark Rolighedsvej 23 DK-1958 Frederiksberg C, Copenhagen, Denmark,* §*Nature Conservation Research Centre, P.O. Box KN 925, Accra, Ghana,* ¶*Forest Trends, 1203 19th Street, NW, 4th Floor Washington, D.C., USA,* ††*Department of Silviculture and Forest Management, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana and* ‡‡*Laboratory of Applied Statistics, Department of Mathematical Sciences, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, OE, Denmark*

(*Accepted 14 June 2016*)

SUMMARY

Most cocoa farms in Ghana are cultivated in complex agroforest systems, with plant growth and cocoa productivity being affected. The objective of this study was to investigate how shade trees affect cocoa yield, temperature and soil nutrients in low-input cocoa systems. Establishing plots on 24 farms in four locations (districts) in Ghana, we assessed the influence of varying canopy cover and fertilization on cocoa yields. Results showed no relationship between canopy cover and cocoa yields in the light crop season (February to August). For the main crop season (September to January), there was an interaction between shade and yields: Yields were higher on no-shade plots than on shaded plots in two districts, whilst there were no differences at the two other districts possibly due to differences in precipitation and soil nutrient status. On the other hand, there was a positive effect of increased canopy cover on yields within the shaded plots. Soil nutrient analyses revealed no significant differences between shaded and no-shade plots and adequate levels of N, K^{+}, Fe^{2+}, Cu^{2+} and Zn^{2+} were recorded. However, soil contents of P, C, Mg^{2+} and Ca^{2+} were below recommended values. Peak temperatures recorded in the cocoa canopies were above the recommended range for this species. Although shade trees had a slight modifying effect on peak temperatures, the magnitude appeared too small to have any practical effects.

INTRODUCTION

Cocoa (*Theobroma cacao* L.) in Ghana and West Africa is grown in complex environments, in which multiple ecological, climatic and agronomic management factors can either limit or enhance growth and productivity (Cunningham and Arnold, 1962; de Almeida and Valle, 2007; Zuidema *et al.*, 2005). In Ghana, traditional or extensively managed smallholder plantations are established by sowing cocoa seeds and/or planting seedlings at random on completely cleared forest (primary or secondary) or fallow lands. In these systems, fertilizers and agrochemical

§§Corresponding author: Email: r.asare@cgiar.org

inputs are usually not applied or used in insufficient quantities (Baah *et al.,* 2011). Some cocoa farms, however, are managed more intensively, as evidenced by cocoa seedlings planted in rows, the regular application of fertilizer and pesticides, and/or the complete removal of shade trees (Gockowski *et al.,* 2013).

In its natural environment in the Amazon, cocoa evolved as an understory or sub-canopy tree species (Greenberg *et al.,* 2000), and is widely recognized as having the capacity to grow in a low light environment. However, the shade requirements of mature cocoa have been questioned (Cunningham and Arnold, 1962). Results of long-term trials on relationship between shade, fertilizer application and yield conducted in a forest environment in Ghana showed very high yields after shade removal in well-established cocoa plantations on fertilized soils (Ahenkorah *et al.* 1974; 1987; Cunningham and Arnold, 1962). Cunningham and Arnold (1962) argued that 'heavy shade is one of the greatest growth-limiting factors and the most vigorous growth and highest yields are only possible without shade' (p. 220). Later, research by Ahenkorah *et al.,* (1987) found that mean yield of heavily shaded cocoa (Amelonado) was approximately half that of no-shade cocoa, whilst the yield from a medium shade system was intermediate. Despite the economic gains that can be derived from increased yields, results from the fertilizer-shade trials also document numerous deleterious effects that offset the positive gains when eliminating shade over time. For example, the productive lifespan of no-shade, intensively cropped cocoa did not extend beyond 10 years; the point at which yields started to decline (Ahenkorah *et al.,* 1974). The most prominent negative effect was the increase in pest and disease damage (Ahenkorah *et al.,* 1987; Campbell, 1984). Faster weed growth and greater nutrient demands from the cocoa tree have also been observed (Ahenkorah *et al.,* 1974). Whilst eliminating shade may boost yield in the short term, a non-shaded cocoa system is not necessarily economically justified considering the negative effects associated with the lack of shade and the increased demand for agro-chemical inputs in order to maintain productivity. Besides, shade in cocoa plantation can provide considerable ecological and economic benefits, especially in cases of low input agriculture, where sustainability rather than maximization of productivity is of major interest (Beer, 1987).

Cocoa is exceptionally demanding in its soil requirements (Smith, 1975). For good growth, forest areas with deep, well-drained soils that vary from loamy sands to friable clays, red or reddish brown in colour, are preferred (Charter, 1953). Ahenkorah (1981) has documented the critical thresholds for some selected macro and micro nutrients for cocoa cultivation in Ghana. According to Afrifa *et al.,* (2009), the content of phosphorus (P) is very low compared to nitrogen (N) in most soils in Ghana. Especially the organic P content is important for the nutrition of cocoa (Appiah, 1975) as deficiency of soil P was reported as the main cause of decline in yields (Ahenkorah *et al.,* 1974). In recent times, however, the notion that P is the most limiting factor, and that N is not critical for cocoa yield in Ghana, has been challenged. Trials conducted by the Cocoa Research Institute of Ghana (CRIG) indicated high productivity when N is applied; hence, revising fertilizer recommendations to also incorporate N (Afrifa *et al.,* 2009). The effect of potassium (K) on cocoa yield in most experiments in

Ghana was found to be negligible (Ahenkorah *et al.,* 1982). Ahenkorah and company attributed this to high K buffering capacity of most soils in Ghana.

In addition to rainfall, temperature has been identified as one of the most critical climatic factors for the growth and development of cocoa (Daymond and Hadley, 2004). In their projections, Anim-Kwapong and Frimpong (2008) predict an increase between 0.6 and 5.4 °C in mean annual temperature over the next 70 years in the moist evergreen (ME) and moist semi-deciduous forest zones of Ghana, which encompasses the cocoa growing belt. These authors contend that longer periods of drought and higher temperatures are causing fluctuations in productivity, and that farmers are already experiencing losses by tree desiccation and death. Hence, they recommend that farmers develop resilient shade grown cocoa systems (Anim-Kwapong and Frimpong, 2008; Nellemann, 2009) as it is believed that shade trees play a key role in regulating humidity and temperature fluctuations (Beer *et al.,* 1998). In cocoa plantations, the difference in temperature measured outside and inside canopy layers has been noted to be around 2 ± 0.5 °C, although higher differences were registered during summer weeks (de Almeida and Valle, 2009). In the Ghanaian context, the temperature in the cocoa growing system has been described mostly using standard weather data (Anim-Kwapong and Frimpong, 2008), which may represent the general scenario rather than the actual conditions in the cocoa environment (Bonaparte and Ampofo, 1977; de Almeida and Valle, 2007).

Despite the perceived role of shade trees in cocoa cultivation, there is limited – and to some extent contradictory – information on the ameliorating effect of canopy cover (CC) by shade trees on on-farm soil nutrients and temperature and how these may influence yields in smallholder plantations. Whilst a range of experiments has been conducted on-station, few studies aiming to measure key growing conditions and to understand the variation of cocoa yield on-farm have been developed (Isaac *et al.,* 2007; Koko *et al.,* 2013; Wade *et al.,* 2010) across West Africa. The objective of this paper therefore was to measure the effect of CC by shade trees on cocoa yields, soil nutrient contents and temperature in two main cocoa growing agro-ecological zones in Ghana in an effort to better understand the conditions affecting production at the farm level. Specifically, the research sought to answer the questions: (i) What is the variation in temperature and the status of soil nutrients in shaded and non-shaded cocoa farms?; and (ii) What is the relationship between CC of shade trees, fertilizer use and cocoa yields?

MATERIALS AND METHODS

Study area

The study was conducted in four cocoa growing communities in four administrative districts located in the Ashanti and Western regions of Ghana (Figure S1). Sites for the Ashanti Region (Amansie West and Atwima Nwabiagya) fall under the Moist Semi-Deciduous Southeast subtype (MSSE) whilst sites for the Western Region (Sefwi Wiawso and Wassa Amenfi West) fall under the ME forest zones (Hall and Swaine, 1981). The MSSE forest zone is characterized by moderate annual rainfall

(1250–1500 mm) with uniformly high temperatures (mean monthly minimum and maximum of 27 and 31 °C) and high relative humidity. 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 to 34 °C. Temperatures are high throughout the year, though March is generally the hottest month. The study area is characterized by two rainy seasons, the major occurring between April and July and peaking in May/June, and the minor occurring between September and October with a short dry period in August. Humidity is high, ranging from 70 to 90% for the monthly means.

Soils in these areas are generally developed from rocks of the Birimian system (middle Pre-Cambrian) (Adu, 1992). These consist 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 (Brammer, 1962) and are generally accommodated as Acrisols in the FAO-UNESCO Revised Legend (FAO, 1988) and as Ultisols in the US Soil Taxonomy (OSSD, 1998). These soils under natural conditions contain adequate nutrients that are tied-up within the organic layer in their top soils. According to the Soil Research Institute of Ghana, soils in the MSSE generally contain higher levels of available P, whilst soils in the ME have high N, available Ca^{2+} and organic matter content.

Experimental design and treatments

Data were collected from 11 and 13 farms in the Ashanti and Western regions, respectively. Age of the cocoa trees ranged between 8 and 28 years, often with several ages being present on individual farms. This range is considered to be the economically favourable age of cocoa trees (Obiri *et al.,* 2007). Farms in each region were selected such that they were at least 2 km apart in each community. These farms represent traditional cocoa systems in which cocoa seeds were sown on previously cleared forestlands with extremely variable CC of shade trees, spacing and age. On each farm, four circular plots of radius 10 m (341 m^2 area) were delineated, two with a tree in the middle forming a canopy above the cocoa trees and two without any shade trees in the plots. One shaded and one no-shade plot were fertilized (see later), leaving one shaded and one no-shade plot as controls. Hence, the experiment can be described as a full factorial design with two factors, shade/no-shade and fertilizer/no-fertilizer, replicated on the 24 farms (blocks). The shade trees comprised 22 different species with varying ecological classifications and guilds (Table S1).

Seventy nine percent of the trees were deciduous, shedding their leaves mostly in the dry period from November to April. Seventeen percent of the trees were non-pioneer light demanders and 74% were pioneers. The trees had varying CC for the various plots in the four locations (Table S2).

Plots were delineated on January 2012 and the circular plots included from 14 to 78 trees with an average of approximately 39 cocoa trees (equivalent to 1242 trees ha^{-1}). The boundaries of the plots were marked with nylon ropes to delineate them from other portions of the farms. Mature cocoa pods from the segregated plots were harvested every two weeks and pooled together to constitute one sample. The number of viable pods in each sample were counted, after which the beans were fermented in small heaps covered by banana leaves for 5–6 days as recommended by CRIG. The fermented beans were then dried and weighed. This was done in two crop seasons (2012/2013 and 2013/2014), with harvested pods during two 'light crop' periods (February to August) and two 'main crop' periods (September to January). Yield data recorded on plots were extrapolated to kg ha^{-1} for easy interpretation.

Soil nutrients

Soil sampling was conducted before the start of the experiment. At each farm, two composite soil samples consisting of equal portions of soil from the two no-shade plots at depths of 0–15 cm and 15–30 cm were taken. Similar samples were taken for the shaded plots. The soil samples were analysed at the Soil Science Laboratory of the CRIG. Soil pH was determined in a 1:2.5 soil–water suspension using a glass electrode and pH metre (van Reeuwijk, 2002). Organic carbon (C) was measured by the wet combustion method of Walkley and Black (1934). Total N was determined using the Kjeldahl method (Bremner, 1965). Available P was determined colourimetrically on an UV Visible Spectrophotometer by the Truog method (Truog, 1930). Exchangeable bases were determined by leaching the soil with 1 M ammonium acetate solution (Hanway and Heidel, 1952), and analysing the leachate by atomic absorption spectrometry (AAS) for potassium (K^{+}), magnesium (Mg^{2+}) and calcium (Ca^{2+}). Micronutrients including iron (Fe^{2+}), copper (Cu^{2+}) and zinc (Zn^{2+}) were determined by leaching the soil with Mehlich–3 extractant (Mehlich, 1984), and the leachate was analysed on AAS for the concentrations of those elements. After the soil analysis, *Asaase wura* fertilizer (NPK 0-22-18 +9 CaO, +7 S, +6 MgO) was broadcasted at a rate of 11.8 kg (equivalent to 375 kg ha^{-1}) on each of the fertilized plots in June 2012 and July 2013. This fertilizer formulation was used due to its recommendation by CRIG and was also preferred by farmers in previous surveys (Aneani and Ofori-Frimpong, 2013).

Determination of air temperatures and crown area

In order to determine the air temperature in the cocoa tree canopy, one farm was selected in each of the four districts except Wassa Amenfi West. Air temperature was measured at the highest point of the cocoa tree canopy in the middle of each plot. A calibrated Tinytag 2 Plus TGP-4017 temperature measuring device manufactured by Gemini Data Loggers Ltd (UK) was mounted above the cocoa canopy in the no-shade stands and above the cocoa canopy but under the shade trees in the shade tree stands. In total, four Tinytags were mounted on each farm in order to compare the air temperatures in the shaded and no-shade plots. The Tinytags were shielded in a 12 × 20 cm nursery pot, which was wrapped with aluminium foil. A nylon thread was used to tie it to a branch at the top of the cocoa canopy. The devices were set to record air temperature in intervals of 5 minutes from January to December 2013.

Finally, to estimate the CC provided by the shade trees on the plots, the crown area of each upper canopy non-cocoa tree within the plot was estimated by measuring the diameter of the crown (CD) in four different directions and calculating the average (Blozan, 2006). The diameter measurements were taken from one tip of the crown to the other. The crown spread was used to calculate the canopy area (CA):

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

The CC for the upper canopy trees was expressed as a percentage of the size of the plot and used as a proxy for shade cover per plot:

$$\mathrm{CC} = \left(\frac{\mathrm{CA}}{\mathrm{Plotsize}}\right) \times 100. \tag{2}$$

Data analysis

Cocoa yields from the light and main crops were analysed separately in an ANCOVA model with random effects. An optimal transformation of the response variable within the Box-Cox family (Box and Cox, 1964) was chosen in the maximal model, which consisted of the main effects of location (four levels: Atwima Nwabiagya, Amansie West, Wassa Amenfi West and Sefwi Wiawso), fertilizer (two levels: yes/no), shade (two levels: yes/no) and crown cover (continuous, 0 when shade = no), and the interactions between location and the three other main effects. The random effects were of year (two levels), farm (24 levels), subplot (96 levels), the interaction between location and year, the interaction between farm and year and the residual term, which may be interpreted as the interaction between subplot and year. In formula, the maximal model is

$$\begin{aligned} \mathrm{yield}^{\lambda} = {} & \alpha(\mathrm{location, shade}) + \beta(\mathrm{location, fertilizer}) + \gamma(\mathrm{location}) * (\mathrm{crown} \\ & - \mu_{\mathrm{location,shade}}) + \mathrm{A(year)} + \mathrm{B(location, year)} + \mathrm{C(farm)} + \mathrm{D(farm, year)} \\ & + \mathrm{E(subplot)} + \mathrm{F(subplot, year)}, \end{aligned}$$

in which the design parameter $\mu_{\mathrm{location,shade}}$ quantifies the mean CC in the four locations and shade conditions, i.e. these equal zero when shade = no and are given as estimates in the second part of Table 1 for shade = yes. The inclusion of these design parameters implies that the shade variable describes the difference between the no-shade subplots and the average of shaded subplots. The cocoa yield has substantial variation, and the different sources of variation were quantified using the random effects A to F above. Moreover, the inclusion of these random effects is necessary in order to achieve valid statistical inference on the systematic effects. Model selection was done keeping all the random effects, and selecting the best subset of the systematic effects using the Second-order Akaike Information Criterion (Burnham and Anderson, 2002). Significance tests of the systematic effects in the selected model was done using asymptotic chi-square tests on the likelihood ratio test statistic based

Table 1. Estimated variance components on random effects and significance tests and parameter estimates of selected systematic effects.

1. Estimated variance components on random effects					
Random effect		Estimated variance		Proportion of total variance	
Main crop					
Year		0.2177		2%	
Location: year		1.4605		12%	
Farm		4.0618		33%	
Farm: year		4.9329		40%	
Subplot: year		1.6176		13%	
Light crop					
Year		0.1459		40%	
Location: year		0.0440		12%	
Farm		0.0285		8%	
Farm: year		0.1083		30%	
Subplot		0.0006		0%	
Subplot: year		0.0359		10%	
2.	Significance tests and parameter estimates of selected systematic effects				
Effect	Estimate	95% confidence interval	LR-statistic	DoF	*P*-value
Location: shade			10.89	3	0.0123
Fertilizer	0.9897	[0.6323; 1.3479]	26.31	1	<0.0001
Crown cover	0.0176	[0.0011; 0.0344]	4.73	1	0.0366

on the maximum likelihood fits, and parameter estimates and post hoc analysis was done on the restricted maximum likelihood fits (Martinussen *et al*., 2012).

With respect to air temperature, the minimum, maximum and mean temperatures were calculated for each day and sensor. For each of these three values, the average, minimum and maximum temperatures were calculated, resulting in nine variables for each sensor (Table S3). Analysis of variance tests were performed to determine significant differences of soil chemical properties and air temperature between the locations and treatments (Table S3). These variables were then subjected to two-way analysis of variance according to a model with the effects of location (three or four levels: Atwima Nwabiagya, Amansie West, Sefwi Wiawso and Wassa Amenfi West in the case of soil nutrient analyses) and shade (two levels: yes/no): $Y = \alpha(\text{location}) + \beta(\text{treatment})$, where the tests showed significant differences between locations and pairwise comparisons were made using Tukey's Studentized range test ($P < 0.05$). In all cases, model assumptions were validated by plots of residuals against predicted values, and by normal quantile plots of residuals.

RESULTS

Cocoa yields in relation to canopy cover and fertilization

Cocoa yields were extremely variable, ranging from an average of 1204 ± 489 kg ha^{-1} year^{-1} in Wassa Amenfi West to 386 ± 210 kg ha^{-1} year^{-1} in Amansie

West. The average yields across all farms were 219 ± 214 kg ha^{-1} year^{-1} for the light crop and 674 ± 474 kg ha^{-1} year^{-1} for the main crop (mean ± s.d.).

The model for the main crop selected by the Akaike Information Criterion is

$$\begin{aligned}\text{yield}^{0.4} = {} & \alpha(\text{location, shade}) + \beta(\text{fertilizer}) + \gamma^{*}(\text{crown} - \mu_{\text{location, shade}}) \\ & + \text{A(year)} + \text{B(location, year)} + \text{C(farm)} + \text{D(farm, year)} \\ & + \text{F(subplot, year)}.\end{aligned}$$

Here, the random effect of subplot is removed since the corresponding variance component was estimated to 0. The R-square value of the selected model is 0.32, which shows that the main crop is difficult to predict by the systematic factors. The unexplained variation is decomposed in the variance components as shown in Table 1.

Thirty three percent of the unexplained variation may be attributed to differences between farms not accounted for by the location. The remaining part may be attributed to annual variation, where the largest part comes from annual variation within farms (40%). The annual variation within subplots (13%) also includes the residual variation, and is presumably also due to error in recording yields in the main crop. Significance tests and parameter estimates for the selected systematic effects are shown in Table 1. There is a highly significant positive effect of fertilizer, a borderline significant positive effect of the size of the CC in the shaded subplots and a significant interaction between location and shade. The latter means that the contrast between the no-shade and the typical shaded subplots is different in the four investigated locations.

As shown in Figure 1, there are significant negative effects of shade in Atwima Nwabiagya ($P = 0.0382$) and Amansie West ($P = 0.0040$), but no effect of shade in Wassa Amenfi West ($P = 0.7551$) and Sefwi Wiawso ($P = 0.4832$). It is important to recall that the model includes two different terms describing the shade: The factor shade (yes/no), which illustrate a negative effect in the two sites mentioned above, and the covariate crown cover, which shows increasing yields with increasing levels of crown cover within the shaded plots. The covariate means that for large crown covers, yields are increased above the level of the no-shade plots, except in the case of the low-yielding location of Amansie West, which consisted of five shaded plots instead of six due to disease on one shade tree that resulted in sudden loss of all leaves on the tree.

Fertilizers resulted in an increase of 14.5% in the main crop yield ($P < 0.0001$) when compared to unfertilized plots (953 ± 65 vs. 832 ± 65 kg ha^{-1}) (mean ± s.e.).

The model for the light crop selected by the Akaike Information Criterion is

$$\begin{aligned}\text{yield}^{0.2} = {} & \beta(\text{location, fertilizer}) + \text{A(year)} + \text{B(location, year)} + \text{C(farm)} \\ & + \text{D(farm, year)} + \text{E(subplot)} + \text{F(subplot, year)}\end{aligned}$$

In particular, there is no systematic relation between the light crop yield and shade. The R-square value of the selected model is 0.16, showing that only a small fraction

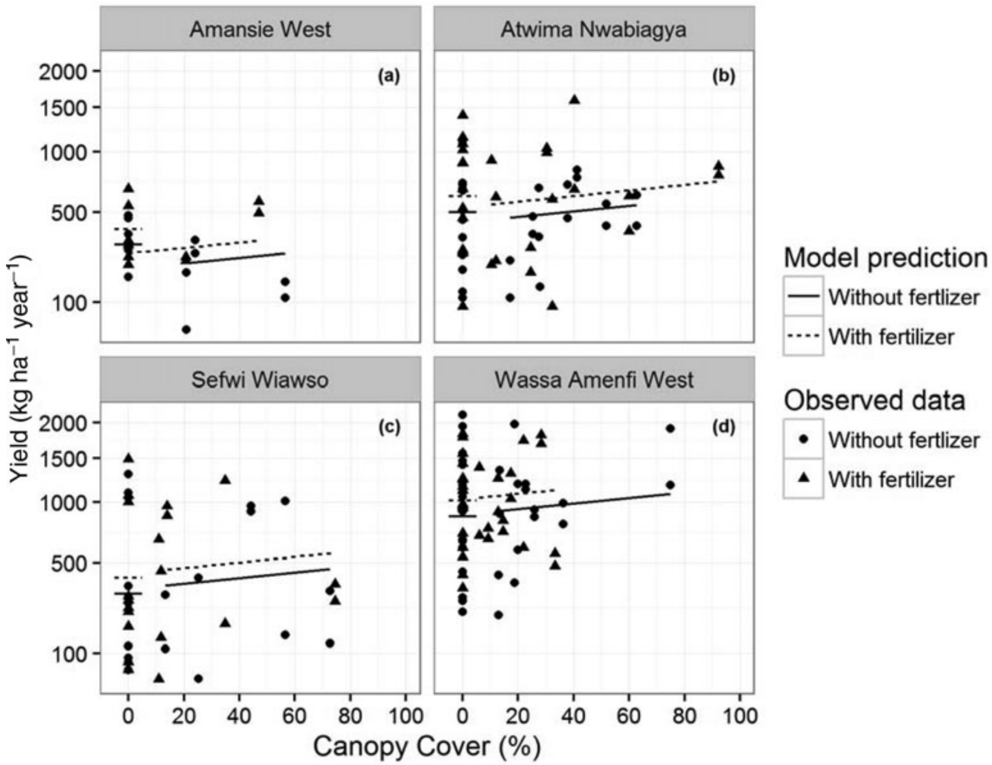

Figure 1. Canopy cover and yield of cocoa (triangles = with fertilizer, crosses = without fertilizer) in (a) Amansie West; (b) Atwima Nwabiagya; (c) Sefwi Wiawso and (d) Wassa Amenfi West. The lines show the model predictions (full lines = with fertilizer, dashed line = without fertilizer). These model lines are drawn inside the range of the canopy cover in the four districts and two fertilizer regimes, but for visualization extended around cover = 0% for the subplots without shade.

of the light crop is predicted by the systematic factors. The unexplained variation was decomposed in the variance components as shown in Table 1. As for the main crop, we see that there was some variation between farms not accounted for by the location (8% of the total unexplained variation), but besides this most of the unexplained variation may be ascribed to annual variation. In contrast to the main crop, most of the unexplained variation of the light crop is jointly over all farms, namely 40% annually over all locations and 12% within the four locations. The interaction between location and fertilization was significant ($P = 0.0365$). A fifth power back transformation shows only a significant effect ($P = 0.0006$) of fertilizer in Amansie West.

Across all treatments, Wassa Amenfi West had the highest mean yield for the main crop at 1012 ± 62 kg ha^{-1}, followed by Antwima Nwabiagya (582 ± 54 kg ha^{-1}), Sefwi Wiawso (483 ± 73 kg ha^{-1}) and Amansie West (313 ± 43 kg ha^{-1}), respectively. For the light crop, Antwima Nwabiagya had the highest mean yield

Table 2. Variability of soil chemical properties (Mean ± SE) within 0–30 cm on cocoa farms in Amansie West, Atwima Nwabiagya, Wassa Amenfi West and Sefwi Wiawso districts in Ghana.

Soil chemical characteristics	Locations/districts				†Soil nutrient thresholds in Ghana
	Amansie West	Atwima Nwabiagya	Wassa Amenfi West	Sefwi Wiawso	
pH	5.94 ± 0.04^{a}	5.64 ± 0.06^{a}	4.98 ± 0.02^{b}	6.01 ± 0.09^{a}	5.6–7.2
Total N (%)	0.12 ± 0.005^{a}	0.14 ± 0.005^{a}	0.12 ± 0.008^{a}	0.13 ± 0.004^{a}	0.09
C (%)	1.14 ± 0.05^{ab}	1.36 ± 0.04^{a}	1.05 ± 0.05^{b}	1.12 ± 0.05^{ab}	2.03
Available P ($\mu g\ g^{-1}$)	1.66 ± 0.23^{a}	5.27 ± 0.29^{b}	7.17 ± 0.49^{bc}	8.28 ± 0.61^{c}	20
K^{+} (meq 100 g^{-1})	0.25 ± 0.01^{a}	0.43 ± 0.24^{b}	0.28 ± 0.007^{a}	0.33 ± 0.01^{ab}	0.25
Mg^{2+} (meq 100 g^{-1})	1.94 ± 0.06^{a}	1.44 ± 0.12^{a}	0.66 ± 0.06^{b}	1.53 ± 0.09^{a}	1.33
Ca^{2+} (meq 100 g^{-1})	6.75 ± 0.23^{a}	6.36 ± 0.30^{a}	2.84 ± 0.11^{b}	7.08 ± 0.40^{a}	7.5
Zn^{2+} (mg kg^{-1})	2.73 ± 0.11^{a}	2.65 ± 0.12^{a}	2.16 ± 0.06^{a}	5.70 ± 0.31^{b}	1.33
Cu^{2+} (mg kg^{-1})	2.70 ± 0.22^{a}	3.62 ± 0.14^{a}	0.91 ± 0.07^{b}	3.01 ± 0.18^{a}	1.33
Fe^{2+} (mg kg^{-1})	19.48 ± 0.36^{a}	27.23 ± 0.63^{b}	34.78 ± 0.66^{c}	22.49 ± 0.23a	1.33

Values with different letters (a–d) in each row represent statistical differences ($P < 0.05$) according to Tukeys HSD test ($n = 112$).
†Soil nutrient thresholds for Cocoa cultivation in Ghana [Adopted from Ahenkorah (1981)].

(326 ± 18 kg ha^{-1}), followed by Sefwi Wiawso (188 ± 30 kg ha^{-1}), Wassa Amenfi West (183 ± 17 kg ha^{-1}) and Amansie West (73 ± 19 kg ha^{-1}) (mean ± s.d.), respectively.

Effect of canopy cover and soil nutrients

Analyses of variance showed no significant differences in the soil nutrient content between shaded and no-shade plots. However, there were differences between locations (Table 2). Soils in Wassa Amenfi West had significantly lower pH levels compared to the other three districts, with Sefwi Wiawso recording the highest pH. There were no significant differences in total soil N between locations, but Wassa Amenfi West had the lowest levels of total C. Available P was very low in Amansie West, with the highest values recorded in Sefwi Wiawso. K^{+} was high in both Atwima Nwabiagya and Sefwi Wiawso, whilst Mg^{2+} and Ca^{2+} levels were low in Wassa Amenfi West with Amansie West and Sefwei Wiawso recording the highest levels in Mg^{2+} and Ca^{2+}, respectively. Sefwi Wiawso had the highest levels of Zn^{2+}, whilst Cu^{2+} levels were low in Wassa Amenfi West. Fe^{2+} was high in Wassa Amenfi West and low in Amansie West.

Effect of canopy cover on temperature

Air temperatures were recorded from January 30 to December 18, 2013. There was a wide temperature variation recorded in the cocoa canopy ranging from 14.7 to 45.4 °C across shaded and no-shade plots (Figure 2). Mean values for the sites were significantly different, but all between 25 and 26 °C. Maxima daily air temperatures were recorded in the main dry season (November–March), whilst the minima were recorded at the end of the main rainy season (August) and at one occasion in

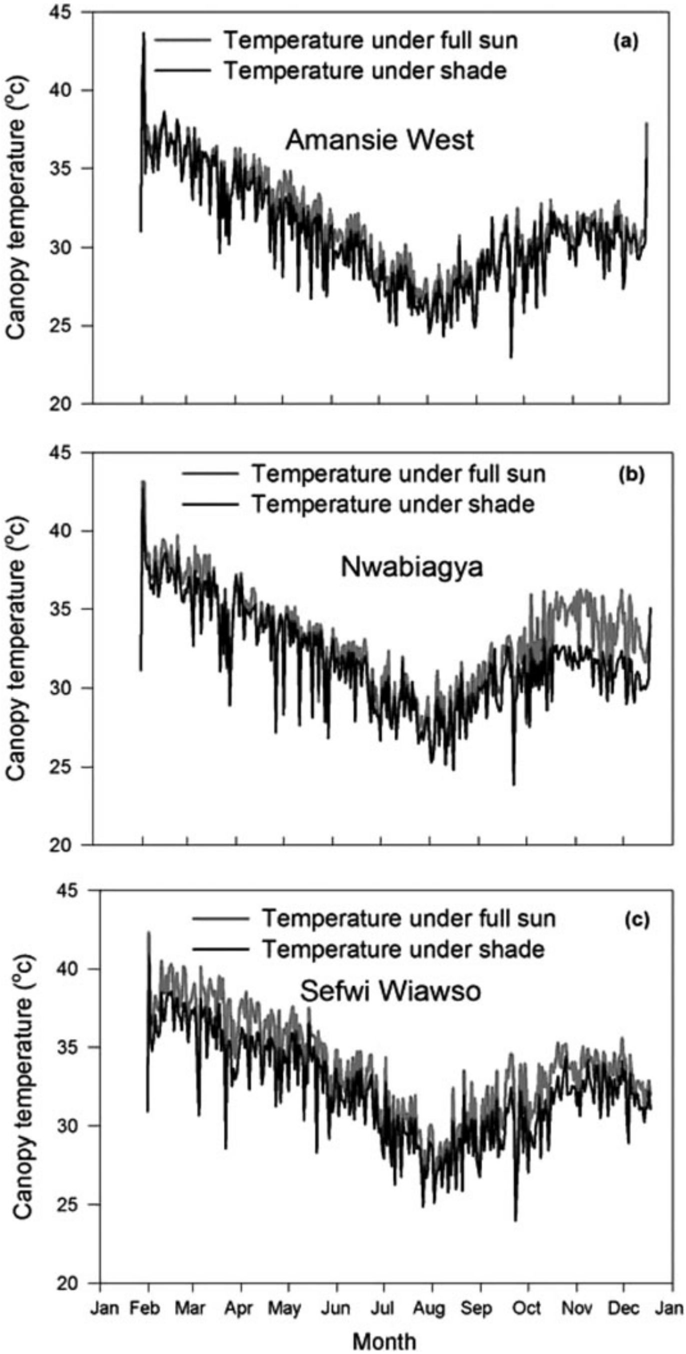

Figure 2. Average daily maximum temperatures within shaded and unshaded plots in (a) Amansie West; (b) Atwima Nwabiagya and (c) Sefwi Wiawso: $n = 2$.

September. There were also significant differences between location for the lowest daily mean air temperature, the lowest maximum, the highest minimum and the absolute minimum, but differences were small and within 1–2 °C (Table S3). The analyses showed significant effects of shade on the lowest daily mean ($P = 0.023$), the highest minimum air temperature ($P = 0.02$) and the absolute minimum ($P = 0.0298$). However, differences were always less than 1 °C and mostly less than 0.5 °C. Maximum air temperatures were not significantly affected by shade.

DISCUSSION

The effect of canopy cover on cocoa yields, soil nutrients, air *temperature at the plot level*

Our results illustrate the complexity of analysing cocoa yields in agroforestry systems. Not only did results vary between sites and seasons; the statistical analysis also revealed an apparent paradox in the relationship between shade and yield. Looking at the main crop, an increasing crown cover resulted in higher yields in the shaded plots. However, for the two locations in the Ashanti region, non-shaded plots on average had higher yields than the shaded plots, indicating a negative effect of the shade trees on yields. We can only speculate on the reasons for this, but it seems logical to assume that it is related to competition between cocoa and shade trees. Below ground competition for water and/or nutrients could reduce yields although other studies have indicated that roots from cocoa trees and shade trees occupy different soil layers and thus may access different resources (Isaac *et al.,* 2014; Moser *et al.,* 2010). Reduced irradiation due to shade from the canopy trees may have a negative effect through reduced photosynthesis, but also a positive effect through reduction of photoinhibition. The effect of reduced radiation is thus probably dependent on the position in the canopy, leaves in the deep shade being more likely to experience light limitations, whilst leaves at the top of the canopy may experience less photoinhibition. It is interesting to note that the reduced yields of shaded plots were only found in the Ashanti region, which has lower precipitation than the Western region, and was especially pronounced in Amansie West, which also had a very low soil P-status. In the two locations in the Western Region, results were easier to interpret as inclusion of shade cover seemed to have positive net effects on yields. It is possible that this is due to the improvement of nutrient uptake by cocoa trees under shade trees as documented by Isaac *et al.* (2007), which ensure the long-term sustainability of shaded cocoa systems alluded to by Obiri *et al.* (2007). The shade tree species composition was fairly similar between regions and does not seem to be able to explain differences between regions (Table S1).

Shade appeared to have no effect on yields in the light crop. The light cropping season coincides with a dry period, in which many of the shade trees shed their leaves. Of the shade tree species located within the sampled plots the majority are deciduous pioneers that typically shed leaves in the dry seasons as a strategy to avoid moisture loss by evapotranspiration during the driest months of the year. Hence, cocoa trees in shaded and no-shade plots may experience the same light climate during the light crop, whilst during the main cropping season, most trees would be foliated. The data suggest that when all trees have leaves in the wetter months there is a positive impact on cocoa yields, as represented on Figure 1. In any case, there is a need to more fully elucidate the responses of cocoa to shade and competition. In our study, we have ignored that different shade trees may be more or less compatible with the cocoa trees. Taking the analysis to species level, thus considering guilds and ecological characteristics of the species must be one of the next steps in improving cocoa agroforestry. Likewise, it would seem that simple experiments with suspended shade nets above the cocoa canopy could help in separating the effects of below-ground competition from the effects of shade. Finally, extrapolating the studies to the farm scale may help to elucidate whether there is an overall effect of tree density or CC on yields.

Variability between plots

In order to explore the role of fertilizer application on cocoa yields, it is important to understand the baseline soil conditions and how they relate to the recommended soil nutrient minimum thresholds (Ahenkorah, 1981). We found no effect of shade cover on soil nutrient levels, which is partly consistent with studies by Isaac *et al.* (2007) who found no effect of shade on nutrients like N in Ghana. Discussions with farmers on the study plots indicated that cocoa farm fertilization was done in an inconsistent manner over the previous years, depending on access and cost. This falls in line with Appiah *et al.* (1997), who found that cocoa in Ghana is mainly produced by small-scale farmers using few fertilizers, and with Ogunlade *et al.* (2009), who reported that most Nigerian Cocoa farmers do not use fertilizers. Hence, it is no surprise that the baseline soil information (Table 2) shows mixed and low availability of nutrients.

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

Cocoa is growing around the world in temperatures ranging from 18 to 21 °C mean minimum and 30 to 33 °C mean maximum (Wood and Lass, 2008). The overall maximum air temperatures recorded in our study were above 40 °C, with the highest temperatures of 43 and 42 °C found in Nwabiagya and Amansie West, respectively. High air temperatures are cause for concern given that high transpiration rates, as a result of high temperatures, produces water stress, which can reduce productivity in cocoa (Anim-Kwapong and Frimpong, 2008; Daymond and Hadley 2004). However, differences in air temperature between shaded and no-shade plots were small; suggesting that the CC provided by shade trees play only a minor role in moderating air temperature in the cocoa canopy. Based on these preliminary results, cocoa agroforestry may not be the only solution to the higher temperatures projected for the cocoa growing belt of Ghana by Anim-Kwapong and Frimpong (2008). However, it should be emphasized that the dataset is limited to three farms, and that increasing the sample size and expanding to other regions may produce clearer results. It should also be acknowledged that shade trees differ widely in the CC that they provide (Asare and Ræbild, 2016) meaning that some species may have larger effects on air temperatures than others.

CONCLUSION

These on-farm experiments showed that increased CC of shade tree had a positive effect on cocoa yield in some locations and a negative effect in other ones. Although this does not provide sufficient clarity on the effect of shade trees across different locations, the findings indicate that a reassessment of the long standing paradigm that shade trees limit cocoa productivity is necessary. More work is required to explain the relationship between CC of shade trees and cocoa yields, especially at the farm level.

Even though the air temperature results confirm some buffering effects of CC on cocoa farm plots, they also show that CC alone is inadequate in ameliorating the microclimate for cocoa. The extreme air temperatures reaching up to 43 °C in the cocoa canopy widely exceed the recommended temperatures for cocoa.

The baseline soil nutrient results showed no effect of CC on soil nutrients, but P, C, Mg^{2+} and Ca^{2+} were below recommended levels. Even though fertilizer was applied at the recommended rates, it did not produce the dramatic increments documented by other authors. There is a need for fertilizer recommendations to take into consideration targeted nutrient deficiencies, in order to ensure efficiency in application across locations.

Acknowledgements. We wish to gratefully thank the management of the International Institute of Tropical Agriculture and the Cocoa Research Institute of Ghana for support and collaboration obtained for this work.

SUPPLEMENTARY MATERIALS

For supplementary material for this article, please visit http://dx.doi.org/(10.1017/S0014479716000466)

REFERENCES

Adu, S. V. (1992). *Soils of the Kumasi Region, Ashanti Region, Ghana*. Memoir. Accra, Ghana: Soil Research Institute.

Afrifa, A., Ofori Frimpong, K., Acquaye, S., Snoeck, D. and Abekoe, M. (2009). Soil nutrient management strategy required for sustainable and competitive cocoa production in Ghana. Paper presented at the 16th International Cocoa Conference, Bali.

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

Ahenkorah, Y., Akrofi, G. and Adri, A. (1974). The end of the first cocoa shade and manurial experiment at the cocoa research institute of Ghana. *Journal of Horticultural Sciences* 49:43–51.

Ahenkorah, Y., Halm, B., Appiah, M. and Akrofi, G. (1982). Fertilizer use on cacao rehabilitation projects in Ghana. In: Proceedings of the 8th International Cocoa Research Conference, Cartagena, Colombia, 18 23 Oct 1981., 1982. Cocoa Producers' Alliance, pp. 165–170.

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

Aikpokpodion, P. (2010). Nutrients dynamics in cocoa soils, leaf and beans in onto state, Nigeria. *Journal of Agricultural Sciences* 1(1):1–9.

Aneani, F. and Ofori-Frimpong, K. (2013). An analysis of yield gap and some factors of cocoa (theobroma cacao) yields in Ghana. *Sustainable Agricultural Research* 2(4):117–127.

Anim-Kwapong, G. J. and Frimpong, E. B. (2008). Climate change on cocoa production. In *Ghana climate change impacts, vulnerability and adaptation assessments*, 263–314 (Ed J. Allotey and L. Mensah). Environmental Protection Agency. Accra, Ghana.

Appiah, M. (1975). Organic phosphorus and phosphatase activity in cocoa soils of Ghana. *Ghana Journal of Agricultural Science* 8:45–50.

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

Asare, R. and Ræbild, A. (2016). Tree diversity and canopy cover in cocoa systems in Ghana. *New Forests* 47:287–302. DOI 10.1007/s11056-015-9515-3.

Baah, F., Anchirinah, V. and Amon-Armah, F. (2011). Soil fertility management practices of cocoa farmers in the eastern region of Ghana. *Agriculture and Biology Journal of North America* 2(1):173–181.

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

Beer, J., Muschler, R., Kass, D. and Somarriba, E. (1998). Shade management in coffee and cacao plantations. *Agroforestry Systems* 38:139–164.

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

Bonaparte, E. and Ampofo, S. The cacao microclimate. (1977). In Proceedings of the 5th International Cocoa Research Conference, 210–215. Ibadan: CRIN.

Box, G. E. P. and Cox, D. R. (1964). An analysis of transformations (with discussion). *Journal of the Royal Statistical Society* 26:211–252.

Brammer, H. (1962). Soils of Ghana. In *Agriculture and Land Use in Ghana*, 88–126 (Ed B. Wills). Oxford University Press, London.

Bremner, J. M. (1965). Total nitrogen. In *Methods of Soil Analysis*, Part 2 edn. 1149–1178 (Ed C. A. Bremner Black,). Madison: American Society of Agronomy.

Burnham, K. P. and Anderson, D. R. (2002). *Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach*. 2nd ed. New York: Springer-Verlag.

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

Charter, C. (1953). Cocoa soils. Good and bad. WACRI Report, Tafo, Ghana.

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

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

de Almeida, A. A. F. and Valle, R. R. (2007). Ecophysiology of the cacao tree. *Brazilian Journal of Plant Physiology* 19(4):425–44.

de Almeida, FA-A. and Valle, R. R. (2009). Cacao: ecophysiology of growth and production. In *Ecophysiology of Tropical Tree Crops*, 37–70 (Ed F. DaMetta). New York: Nova Science Publishers.

(1988). UNESCO soil map of the world, revised legend. *World Resources Report* 60:138.

Gockowski, J., Afari-Sefa, V., Sarpong, D. B., Osei-Asare, Y. B. and Agyeman, N. F. (2013). Improving the productivity and income of Ghanaian cocoa farmers while maintaining environmental services: what role for certification?. *International Journal of Agricultural Sustainability* 11(4):331–346.

Greenberg, R., Bichier, P. and Angón, A. C. (2000). The conservation value for birds of cacao plantations with diverse planted shade in Tabasco, Mexico. *Animal Conservation* 3(2):105–112.

Hall, J. B. and Swaine, M. D. (1981). Distribution and ecology of vascular plants in a tropical rain forest. *Forest Vegetation in Ghana*, 71–100, Netherlands: Springer.

Hanway, J. and Heidel, H. (1952). Soil analysis methods as used in Iowa state college soil testing laboratory. *Iowa Agriculture* 57:1–31.

Hartemink, A. E. (2005). Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. *Advances in Agronomy* 86:227–253.

Isaac, M. E., Anglaaere, L. C., Borden, K. and Adu-Bredu, S. (2014). Intraspecific root plasticity in agroforestry systems across edaphic conditions. *Agriculture, Ecosystems & Environment* 185:16–23.

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

Koko, L. K., Snoeck, D., Lekadou, T. T. and Assiri, A. A. (2013). Cacao-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. *Agroforestry Systems* 87(5):1043–1052.

Martinussen, T., Skovgaard, I. M. and Sorensen, H. (2012). A first guide to statistical computations in R. Samfundslitteratur, Frederiksberg C Denmark.

Mehlich, A. (1984). Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Communications in Soil Science & Plant Analysis* 15(12):1409–1416.

Moser, G., Leuschner, C., Hertel, D., Hölscher, D., Köhler, M., Leitner, D. and Schwendenmann, L. (2010). Response of cocoa trees (Theobroma cacao) to a 13-month desiccation period in Sulawesi, Indonesia. *Agroforestry Systems*, 79(2):171–187.

Nellemann, C., MacDevette, M., Manders, T., Eickhout, B., Svihus, B., Prins, A. G., Kaltenborn, B. P. (Eds). (2009). *The environmental food crisis: the environment's role in averting future food crises: A UNEP rapid response assessment.* United Nations Environment Programme, GRID-Arendal. Birkeland Trykkeri AS, Norway. www.grida.no

Obiri, B. D., Bright, G. A., McDonald, M. A., Anglaaere, L. C. and Cobbina, J. (2007). Financial analysis of shaded cocoa in Ghana. *Agroforestry Systems* 71(2):139–149.

Ogunlade, M. O. and Aikpokpodion, P. O. (2006). Available phosphorus and some micro-nutrient development, contents of cocoa soils in three cocoa growing ecological zones of Nigeria. In: Proceedings of 15th International Cocoa Research Conference 2006. San José, Costa Rica, 9–14 October 2006, pp. 675–678.

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

OSSD. (1998). Keys to soil taxonomy. *United States Department of Agriculture, Natural Resources Conservation Service. Official Soil Series Description*, 8th ed. Washington, DC: World Soil Resources Staff, Natural Resources Conservation Service.

van Reeuwijk, L. P. (2002). *Procedures for soil analysis*, 6th edn. Technical paper, vol 9. International Soil Reference and Information Centre. Wageningen, Netherlands.

Smith, D. (1975). Effects of potassium topdressing a low fertility silt loam soil on alfalfa herbage yields and composition and on soil K values. *Agronomy Journal* 67(1):60–64.

Truog, E. (1930). The determination of the readily available phosphorus of soils. *Agronomy Journal* 22(10):874–882.

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

Walkley, A. and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37(1):29–38.

Wood, G. A. R. and Lass, R. (2008). *Cocoa.* 4th ed. 38–58, Cornwall Great Britain: John Wiley & Sons. Blackwell Science Ltd.

Zuidema, P. A., Leffelaar, A. F., Gerritsma, W., Mommer, K. and Anten, N. P. R. (2005). A physiological production model for cocoa (Theobroma cacao): model presentation, validation and application. *Agricultural Systems* 84:195–225.