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Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana

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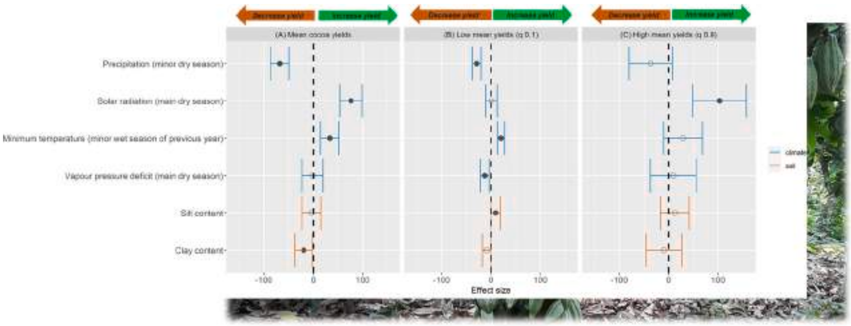
HIGHLIGHTS

- Interventions intended to improve yields & climate adaptation requires an understanding of yield drivers at farm level.
- Drivers of cocoa yield & its relevance for farms with different production levels were unraveled with unprecedented dataset.
- Cocoa farms with high yields are more sensitive to environmental conditions than farms with low yields.
- Climate effects on on-farm cocoa yields were stronger than soil effects, but management effects were most important.
- Good agricultural practices need to be in place before investing in additional climate adaptation practices.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Cocoa (*Theobroma cacao* L.) is one of the world's most important agricultural commodity crops with the largest share of global production concentrated in West Africa. Current on-farm yields in this region are low and are expected to decrease in response to climate change, through warming and shifts in rainfall. Interventions intended to improve yields and climate adaptation require an understanding of the main drivers of yields across farms.

OBJECTIVE: In this regard, we quantified the extent to which environmental (i.e., climate and soil) conditions drive cocoa yields and how this differs for farms achieving on average low- and high mean production levels

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Cocoa planting density
Shade tree density

based on an unprecedented dataset of 3827 cocoa farms spanning the environmental gradients of Ghana. We further quantified the relative importance of management practices based on a subset of 134 farms for which management information was available.

METHODS: We modelled on-farm annual cocoa yield as a function of environmental variables for the large dataset and cocoa yield per tree as a function of environmental and management variables for the subset farms using mixed-effects models. Differences in effects on yield between farms with low and high mean production levels were evaluated using quantile mixed-effects models.

RESULTS AND CONCLUSIONS: There was considerable variability in yields across farms, ranging from ~100 to >1000 kg ha^{-1} (mean = 554 kg ha^{-1}). Mixed-effects models showed that the fixed effects (i.e., environmental variables) only explained 7% of the variability in yields whilst fixed and random effects together explained 80%, suggesting that farm-to-farm variation played a large role. Explained variation in cocoa yields per tree of 134 farms in the subset increased from 10% to 25% when including management variables in addition to environmental variables. In both models, climate-related factors had a larger effect on yields than edaphic factors, with radiation of the main dry season and that of the previous year having the strongest effects on on-farm- and tree yields, respectively. The quantile regression analyses showed that productivity in high-yielding farms (90th percentile) was more strongly driven by environmental factors than in low-yielding farms (10th percentile).

In conclusion, agronomic management is the dominant determinant of on-farm cocoa yields in Ghana, more so than environmental conditions. Furthermore, high-yielding cocoa farms are more sensitive to environmental conditions than low-yielding ones.

SIGNIFICANCE: Our findings suggests that good agricultural practices need to be in place before investing in additional climate adaptation practices.

1. Introduction

Cocoa (*Theobroma cacao* L.) is one of the world's most important agricultural commodity crops with a great economic importance to producing countries and the confectionary industry. The crop is grown by nearly 6 million smallholder farmers on an estimated 10.2 million ha in over 60 countries in the humid tropics (Fairtrade Foundation, 2016; FAOSTAT, 2016). Globally, production is concentrated in West Africa, which supplies over 70% of global production with the main producing countries being Côte d'Ivoire and Ghana, and Nigeria and Cameroon becoming increasingly important (ICCO, 2018). Cocoa farming in this region is mainly low-input, with the majority of crops grown on farms with an average size of 3–4 ha (Aneani and Padi, 2016; Wessel and Quist-Wessel, 2015).

Current average yields of cocoa are very low, about 300–600 kg ha^{-1} (Wessel and Quist-Wessel, 2015), compared to potential water-limited yields of about 5000 kg ha^{-1} under rainfed conditions (Zuidema et al., 2005) and over 3000 kg ha^{-1} achieved in experimental trials (Appiah et al., 2000). Thus, the cocoa yield gap (i.e., the difference between potential and actual yields) is as large as 80–95%. Numerous factors have been found to limit cocoa yields, such as high incidence of pests and diseases (Akrofi et al., 2015; Mpika et al., 2011; Opoku et al., 2000), aging farms and trees (Nalley et al., 2014), planting material with low yield potential (Adomako and Adu-Ampomah, 2000; Edwin and Masters, 2005), loss of soil fertility due to inadequate soil nutrient management (Appiah et al., 2000; Baah et al., 2011) and planting density issues (Sonwa et al., 2018; Souza et al., 2009). There is also growing concern on climate change impacts on cocoa growing areas in West Africa with the potential to further reduce yields and negatively affect cocoa dependent livelihoods (Anim-Kwapong and Frimpong, 2008; Gateau-Rey et al., 2018; Läderach et al., 2013; Schroth et al., 2016). West Africa has been exposed to considerable droughts in the past (for instance in 1982/83 and recently in 2015/16) with concomitant cocoa yield reductions (Abdulai et al., 2018; Ruf et al., 2015).

Global climate models project further increases in temperature, shifts in rainfall with potential increase in the frequency and severity of climate extremes for this region (Niang et al., 2014; Serdeczny et al., 2017). Yet, limited knowledge exist (Black et al., 2020; Bunn et al., 2019; Läderach et al., 2013; Schroth et al., 2016) on the extent to which climate change will affect cocoa yield. Given the diverse agroecological conditions and production systems (e.g. ranging from intensive monospecific plantations to fully integrated agroforestry systems) under which cocoa is grown, it is relevant to improve our understanding of the extent to which environmental conditions drive yields and the relative role of management practices (for instance planting density (Souza et al., 2009), shade levels and fertilizer use (Asare et al., 2017; Asare et al., 2019) on yield, in order to improve current cocoa systems' ability to adapt to the projected climate changes and to further close cocoa yield gap.

In general, the magnitude of crop yield responses to changes in climate has been found to be influenced by soil characteristics, as the water and nutrient holding capacity of soils enables crops to either sustain or reduce growth during periods of adverse conditions (Folberth et al., 2016; Mäkinen et al., 2017). In West Africa, soils under cocoa farms are rather infertile, (van Vliet and Giller, 2017), exacerbated by continued nutrient mining after forest clearing (Hartemink, 2005). On nutrient limited soils, yields are not only low on average, but have also been reported to be relatively constant from year to year, thus insensitive to changes in climate (Descheemaeker et al., 2020; Masikati et al., 2019). Increasing nutrient inputs through soil fertility management technologies could increase average yields (Ahenkorah et al., 1987; Schroth and Krauss, 2006; Vanlauwe et al., 2010), but year-to-year variability might also increase as yield becomes less limited by nutrients and more by seasonal climate variation (Descheemaeker et al., 2020; Keating et al., 2010). Therefore, identifying the extent to which climate drives yields on farms with different overall mean production levels is needed to provide context-specific information on the challenges of different farmer groups. Such knowledge is relevant for developing tailormade strategies and provides background knowledge for sustainable intensification.

In this study, we analyse effects of environmental (i.e., climate and soil) conditions on yields for 3827 cocoa farms in Ghana and assess how these effects differ between farms achieving on average low and high yields. We also explore the role of management practices, i.e., cocoa- and shade-tree density, fertilizer-use and farm age on yield using a subset of 134 cocoa farms for which information on management was available. Such knowledge is quintessential for developing long-term planning of cocoa adaptation strategies to climate change and for reducing cocoa yield gaps. We address the following questions (1) What environmental conditions drive cocoa yields and what is their relative importance? (2) Are effects of environmental conditions stronger for farms that achieve on average relatively high compared to low yields? (3) To what extent do management practices influence cocoa yields?

We expect environmental variables to drive cocoa yield with positive effects of water availability and radiation and negative effects of stressful climatic conditions such as high climatic water deficit (CWD).

Furthermore, we expect that climate effects will be stronger for farms with high yields as they are less limited by other factors such as soil nutrients. Finally, we expect positive effects of cocoa planting density and fertilizer use and negative effects of high shade tree density.

2. Materials and methods

2.1. Study area

The study was conducted in Ghana, the world's second largest cocoa-producing country after Côte d'Ivoire located in West Africa (Latitude: 7.9528 Longitude: −1.0307). In Ghana, climate is highly variable and follows a pronounced gradient with arid conditions in the north and humid conditions in the south (MOFA, 2016). Cocoa is grown in the southern part of the country. In this study, we focus on a dry-to-wet gradient based on rainfall (Fig. 1 and Table 1) from 2012 to 2019 for which period cocoa yield data was available.

The annual cocoa production cycle in Ghana follows a distinct seasonal pattern of rainfall (Asomanin et al., 1971). Peaks of leaf flushing, flower production and pod setting occur during the major wet season (Adjaloo et al., 2012; Asomanin et al., 1971). There are two harvest seasons; the 'main crop', which is harvested during the minor wet season through to the main dry season (i.e. September to January with peaks in November or December) and the 'light-crop' with relatively lower yields harvested during the main wet season with peaks in April or May (Ali, 1969; Asomanin et al., 1971).

Table 1
Characteristics of the dry, moist, and wet zones in Ghana where cocoa is grown.

	Dry	Moist	Wet
Wet season (months)	MJ = April to July, MN=September to October	MJ = March to July, MN=September to November	MJ = March to July, MN=September to November
Dry season (months)	MJ = November to March MN = August	MJ = December to February MN = August	MJ = December to February MN = August
Mean annual temperature (°C)	27–30 °C	25.5–30 °C	27–30 °C
Agroecological zone	forest/savanna transition	deciduous forest	rain forest
Dominant vegetation type	dry semi-deciduous	moist & dry semi-deciduous	moist & wet evergreen
Dominant soil types	acrisol, alfisol	acrisol, alfisol, oxisol	acrisol, alfisol, oxisol

MJ = Major season MN = Minor season.
Sources: (Abdulai et al., 2020; Asare-Nuamah and Botchway, 2019; FAO, 2005; Stanturf et al., 2011; MOFA, 2016).

2.2. Cocoa yield data

Cocoa yield data across Ghana for the period 2012/2013 to 2018/2019 seasons (excluding for 2014/2015) was obtained from farmers, cocoa companies AgroEcom Ghana Ltd. and Mondelez International 'Mapping Cocoa Productivity' project data (Daymond et al., 2017), and published data (Blaser et al., 2018). A total of 3827 farms (i.e., 4015 yield data points) for which the location was known was obtained. The data set includes: 758 records in the dry zone, 2011 records in the moist zone and 1246 records in the wet zone. With this large sample size our study covered the full range of environmental conditions in the cocoa growing region of Ghana (Fig. 1). For a subset of 134 farms (i.e., 267 data points) data on management (cocoa and shade trees per hectare, fertilizer use and farm age) and average annual cocoa yield per tree was

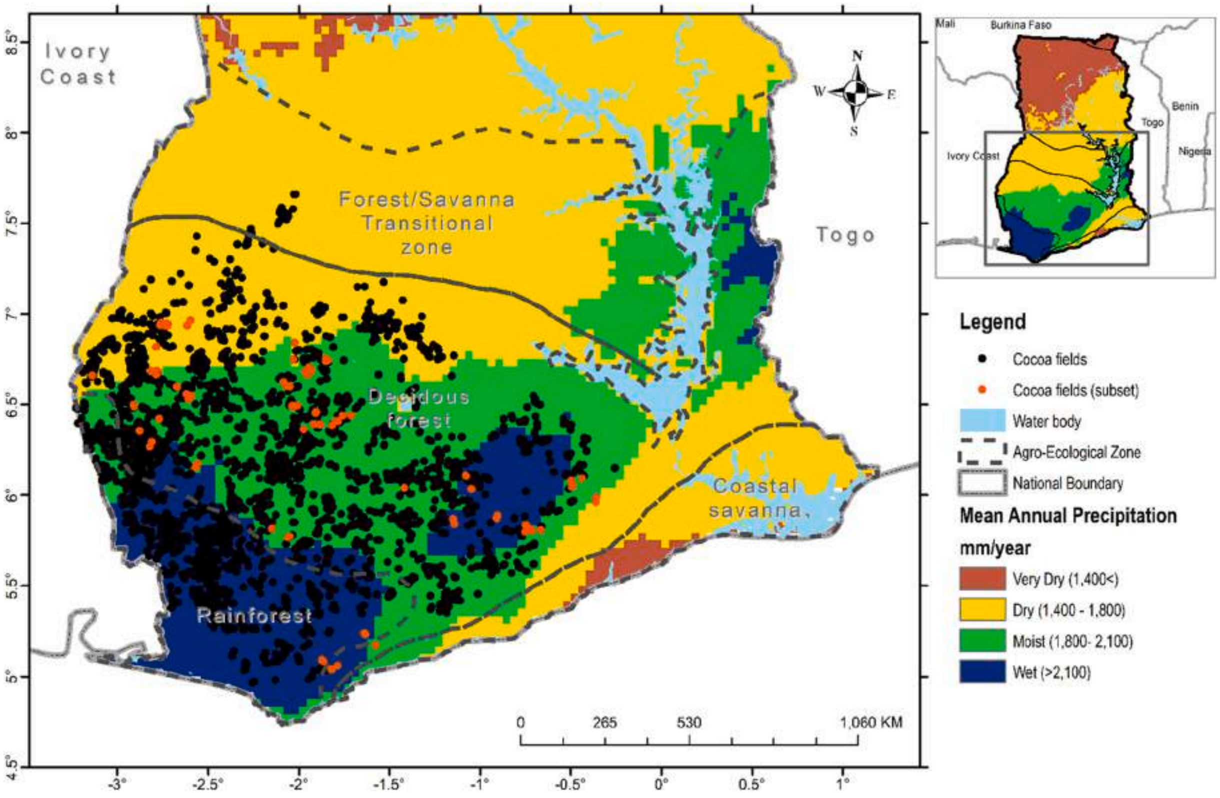

Fig. 1. Mean annual precipitation (mm) distribution across southern Ghana, based on Terraclimate data (Abatzoglou et al., 2018). Rainfall values are calculated means of 2012–2019 on a 4-km resolution. Black circles indicate the locations of the included cocoa farms and red circles indicate a subset of cocoa farms for which more detailed data on management were available. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

available (Fig. 1). We defined cocoa yield as the quantity of dried beans (i.e., assuming, 28 pods give 1 kg of dried beans and 1 bag is 64 kg) harvested per year (annual cocoa cropping season; March of a given year – February of the next year, e.g., the yield for 2017/2018 refers to March 2017 – Feb 2018), per unit cocoa plantation area (ha). We verified datasets for outliers and excluded those extreme values that were considered impossible e.g., extremely high (>7000 kg ha), or low or negative values.

Different approaches were used for collecting cocoa production records and measuring field size to estimate yield. For cocoa production, 93% of records were collected through farmer reports with verification from sale books usually referred to as cocoa passbooks (Asare et al., 2019) and 7% using pod counts. Most (86%) of the field size information was obtained using GPS measurements and 14% through farmer estimates.

2.3. Climate and soil data

Monthly climate data for the period 2011–2019 with a spatial resolution of 4 km covering the study area was obtained from the Terraclimate database (Abatzoglou et al., 2018). We included minimum and maximum temperature (°C), average precipitation (mm), downward surface shortwave radiation (W/m^2), actual and reference evapotranspiration (ET_0; mm), vapour pressure and vapour pressure deficit (kPa) as well as climatic water deficit (CWD; mm). CWD is defined as the absolute difference between reference and actual evapotranspiration, and more positive values indicate drier conditions. CWD was included as it better represents climatic stress than temperature and precipitation alone. For all climate variables, we analyse annual totals starting from March of a given year to February of the next year, based on the cocoa cropping season in Ghana.

Soil properties were obtained from the ISRIC/SoilGrids database (Hengl et al., 2017), at a depth of 0–30 cm with a spatial resolution of 250 m. We included, sand (g 100 g^{-1}), clay (g 100 g^{-1}) and silt (g 100 g^{-1}) content.

2.4. Statistical analyses

We assessed how, and to what extent, environmental conditions influenced cocoa yields by modelling annual cocoa yield (kg ha^{-1}) as a function of climatic and soil variables using linear mixed-effects models (MEMs) (Zuur et al., 2009). For climate, we considered all four seasons in this study defined as, main wet season (March–June), minor dry season (July–August), minor wet season (September–November), main dry season (December–February). To account for possible lag effects of climatic variables on cocoa yields, we considered both the seasons of the previous and the current year. To identify for each climate variable in which season it most strongly influenced yield, we first performed for each climatic variable linear regression between annual cocoa yield and the climatic variable for each of the seasons separately. We selected for each climate variable the season that was included in the best model (i.e., lowest Akaike Information Criterion; AIC).

We included all selected environmental variables in the model as fixed effects (Table 2). All continuous explanatory variables were standardized by subtracting the mean value of the variable and dividing it by the standard deviation. This allowed for direct comparison of the relative importance of explanatory variables (Gelman and Hill, 2006). A larger standardized coefficient means that the variable is more important. We included a random intercept for each farm to account for non-independence of data points from the same farm. We evaluated collinearity of explanatory variables using the variance inflation factor (VIF). We excluded variables with the highest VIF until none of the included variables had a variance inflation factor > 3. Based on this procedure, actual and reference evapotranspiration, maximum temperature, vapour pressure, climate water deficit and sand content were excluded from the final model. Conditional and marginal R^2 were calculated to evaluate variation explained by fixed effects alone and fixed effects and random effects together, respectively (Nakagawa and Schielzeth, 2010).

Table 2
Selected predictors for the mixed-effects model based on AIC and collinearity tests for the full dataset based on 3874 farms and for the subset of 134 farms.

Predictors	Unit	Min	Max	Range	Mean ± SD
Full data predictors					
Precipitation (minor dry season)	mm	36.5	167	130.5	90.4 ± 29.5
Downward surface shortwave radiation (main dry season)	W m^2	194	239	45	216 ± 10
Minimum temperature (minor wet season of previous year)	°C	19.5	23.9	4.4	22.6 ± 0.7
Vapour pressure deficit (main dry season)	kPa	0.6	2.4	1.8	1.5 ± 0.3
Silt content	g 100 g^{-1} (%)	7.7	32.7	25	20 ± 4.5
Clay content	g 100 g^{-1} (%)	14	35.7	21.7	26.8 ± 2.9
Subset data predictors					
Downward surface shortwave radiation (main dry season of previous year)	W m^2	203	228	25	217 ± 8.4
Minimum temperature (main dry season)	°C	20.1	23.7	3.6	21.7 ± 0.5
Maximum temperature (main dry season of previous year)	°C	30.7	33.7	3	32.6 ± 0.6
Climate water deficit (minor wet season)	mm	0	11.7	11.7	2.7 ± 4.1
Silt content	g 100 g^{-1} (%)	12	32	20	24 ± 4.4
Clay content	g 100 g^{-1} (%)	18	32	14	26 ± 2.5
Cocoa planting density	trees ha	276	3626	3350	1211 ± 440
Shade tree density	trees ha	0	178	178	15.9 ± 26.5
Farm age	years	8	58	50	22.4 ± 9.4
Fertilizer use	yes/no	–	–	–	–

We used a quantile mixed-effects model to analyse how effects of environmental conditions differed between farms with low and high yields. In the quantile mixed-effects model, we included the same climate and soil variables as fixed effects as in the final mixed-effects model described above, and we also included a random intercept per farm.

Finally, to assess the relative importance of management practices in explaining variability in cocoa yields, we performed a separate analysis for a subset of 134 farms for the period 2012–2017 (excluding 2014/2015) for which data on management was available. We compared a mixed-effects model with climate and soil variables only, with a model that also included management practices. The management variables included the number of cocoa and shade trees per hectare, fertilizer (use vs. no use) and farm age. Because yield per ha is estimated by multiplying average yield per tree with the number of cocoa trees per hectare, we used cocoa yield per tree instead of per hectare as response variable and included planting density as explanatory variable. However, to evaluate the effects of number of cocoa trees on yield at the hectare-level we also performed a log-log simple regression (log(cocoa yield per tree) ~ -1*log(cocoa planting density), i.e., a log transformation of cocoa yield per tree $\sim$1/cocoa planting density, to test whether yield per hectare is independent of cocoa planting density). If the slope of cocoa planting density is larger (less negative) than -1, it indicates that hectare-yield would increase with cocoa planting density, the opposite holding if the slope is smaller than -1. Following the model selection procedure for the full data set, we selected the seasons of the climate variables based on a comparison of regression models between yield per tree and climate variables for the different seasons using AIC. Again, we excluded variables with the highest VIF, and excluded, precipitation, actual and reference evapotranspiration, vapour pressure and vapour pressure deficit, and sand content.

All analyses were performed using R statistical software (R Core Team, 2018). Mixed-effects models were performed with the “lmer” function of the lme4 package (Bates et al., 2015). The “lqmm” function of the lqmm package in R was used to perform the quantile mixed-effects model (Geraci and Bottai, 2014).

3. Results

3.1. Variability of farm level cocoa yields across the rainfall gradient

Over the six-year timespan included in our dataset (2012–2019), strong inter-annual variability in cocoa yields across the rainfall gradient and individual farms was observed (Fig. 2). Annual mean yields per rainfall zone and year varied from ~300 to 700 kg ha^{-1} whilst that of individual farms ranged from ~100 kg ha^{-1} to >1000 kg ha^{-1}. Annual mean yields were highest in 2012–2016 for all rainfall zones and lower in later years. For instance, from 2015/2016 to 2018/2019 mean yields declined from ~650 to ~400 kg ha^{-1} in the dry zone, and from ~700 to ~300 kg ha^{-1} in the moist and wet zones, respectively.

Relatively small differences in yields were observed between rainfall zones, with highest mean yields in the wet zone, 568 kg ha^{-1}, followed by the moist zone, 559 kg ha^{-1} and the dry zone with a lower mean yield of 522 kg ha^{-1}. Within rainfall zones, strong variation in cocoa yields was observed particularly in the moist and wet zones.

3.2. Effects of environmental conditions on on-farm cocoa yield

Effects of environmental conditions on annual cocoa yields were found to be generally weak. The climatic and soil variables (i.e., fixed effects), together explained only 7% (marginal R^2 of 0.07) of the variation in annual mean cocoa yields in Ghana. Whilst the variance explained by the fixed and random (i.e., farm-to-farm variation) effects together was 80% (conditional R^2 of 0.80). Thus, variation in cocoa yield was largely driven by farm-to-farm variation in other variables than those tested as fixed effects, suggesting that effects of management related factors predominated.

Effects of climatic variables were stronger than soil effects (Fig. 3A). The main dry season solar radiation had the strongest effect, with a significant, positive effect on annual mean cocoa yield. Minimum temperature of the previous year minor wet season was the next most influential with a significant, positive effect on yield, whilst minor wet-season precipitation, had a significant negative effect. Vapour pressure deficit of the main dry season was included in the final model, but it had no significant effect on yield.

For soil variables, we observed significant, negative effect of clay content on yield whilst the effect of silt content was not significant.

3.3. Effects of environmental conditions on farms with different production levels

The role of environmental conditions in determining cocoa yields varied amongst farms with different overall mean yields. In most cases, effects of the environmental variables including radiation, minimum temperature, vapour pressure deficit and silt content were stronger for high-yielding (i.e., at the 0.9 yield quantile) farms than for low-yielding

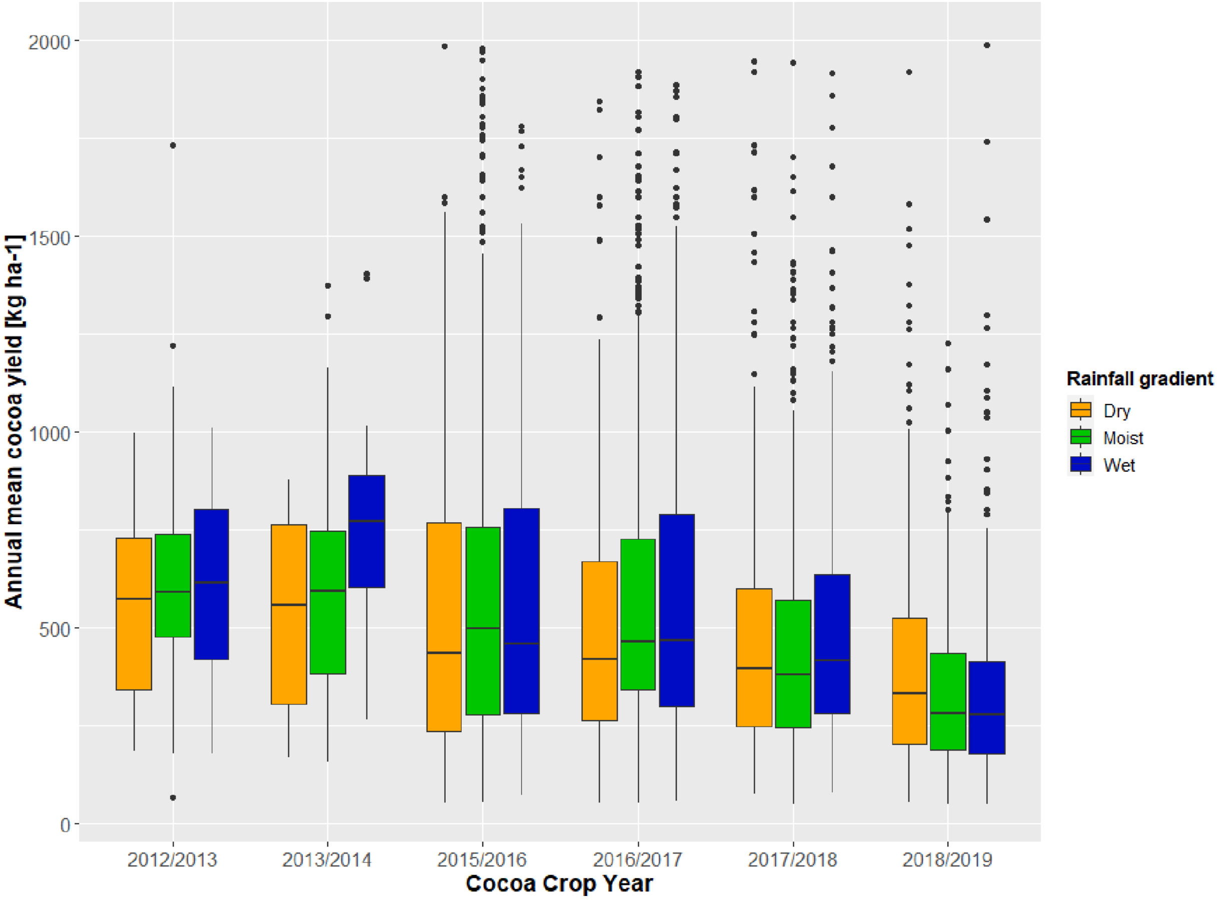

Fig. 2. Variation in on-farm cocoa yields in Ghana across a rainfall gradient. Cocoa crop year: March of a given year – February of the next year.

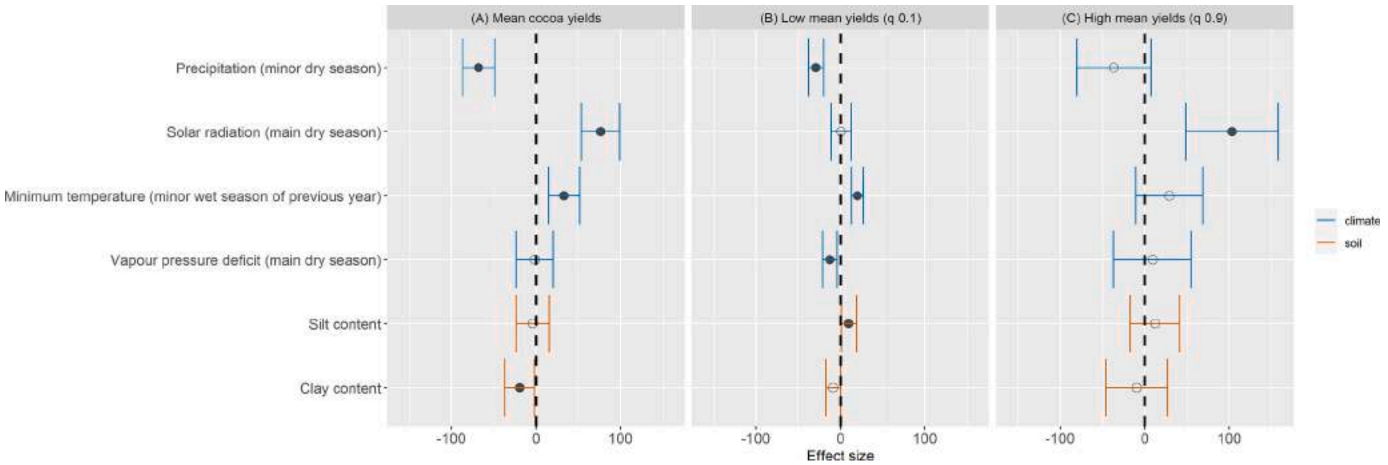

Fig. 3. Mixed-effects model results of annual yield as a function of environmental conditions (A) and quantile mixed effect model results of the 0.1 and 0.9 annual yield quantile as a function of environmental variables (B and C). Filled circles indicate significant effects, while open circles indicate non-significant effects. Standardized coefficients with 95% confidence intervals are included.

(i.e., at the 0.1 yield quantile) farms (Fig. 3B, C). This indicates that high-yielding farms could be more sensitive to changes in environmental conditions, particularly climatic ones.

Amongst environmental variables, the effect of dry-season solar radiation was strong, with significant, positive, effect on high yielding farms. However, the effect of all other environmental variables were not significant. On the other hand, for the low-yielding farms, minimum temperature of the minor wet season of the previous year and silt content had significant positive effects on yield, while precipitation of the minor dry season and vapour pressure deficit of main dry-season had significant negative effects.

3.4. *Effects of management on cocoa yield*

The effect of management practices on cocoa yield per tree was stronger than that of environmental conditions based on a subset of 134 (for 2012–2017 crop seasons, 2014/2015 not inclusive) cocoa farms across Ghana for which data on management practices were available.

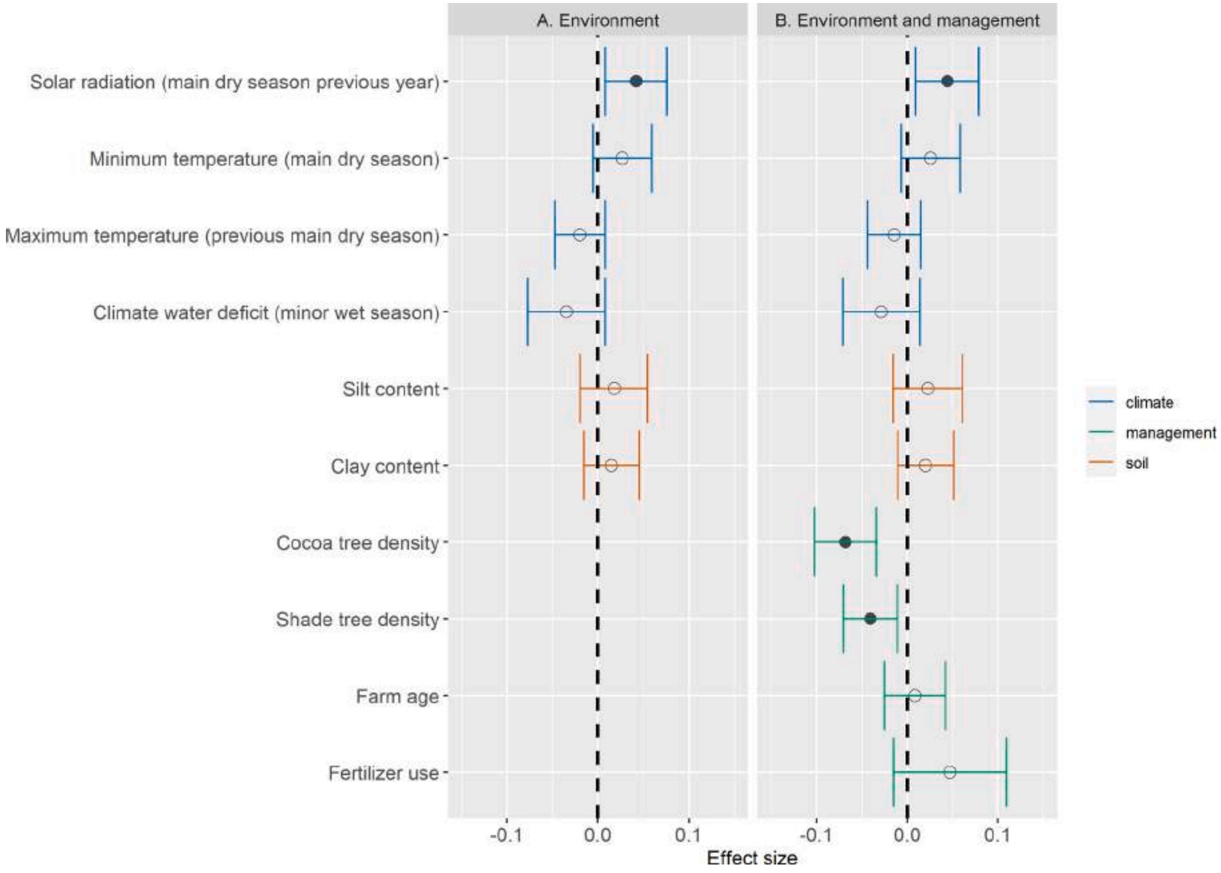

Fig. 4. Mixed-effects model results of annual cocoa tree yield as a function of environmental and management conditions. The size of the fertilizer use coefficient is not comparable since it is a categorical variable. Filled circles indicate that the variable is significant, whilst open circles indicate that the variable is not significant. Standardized coefficients with 95% confidence intervals are included.

When only environmental variables (Fig. 4A) were used as fixed effects for the subset of 134 farms, 10% (marginal R^2 of 0.10) of the variability in cocoa tree yields was explained by environmental conditions and fixed and random effects together explained 55%. By including management (Fig. 4B), the fixed effects (i.e., environment and management variables), explained 25% (marginal R^2 of 0.25) of the variation in cocoa yield, and similarly the fixed and random effects together explained 55%. Thus, here a relatively large share of the total explained variance is due to the fixed effects.

In this model, management variables had the strongest effects on yield, followed by climate and then soil (Fig. 4). Amongst the management variables, cocoa planting density (Fig. 5a) had the strongest influence, with a significant negative effect on cocoa yield per tree. However, when yields per tree were plotted against plant density after log-transforming both variables and using simple regression, the slope was −0.36 and significantly larger than −1, which indicates that cocoa yield per hectare increase with cocoa planting density. Shade tree density (Fig. 5b) was the next most influential variable in the mixed-effect model with a significant, but weak, negative effect on yield. For shade tree density, excluding farms with >100 shade trees per hectare resulted in a non-significant effect on yield, though there was still a negative trend.

Amongst environmental variables, solar radiation of the previous dry season (Fig. 5c) was the most influential variable with significant positive effects on cocoa yield per tree. Effects of climate water deficit of the minor wet season, minimum temperature of the main dry season, maximum temperature of the previous year main dry season, silt content, clay content, fertilizer use, and farm age were not significant.

4. Discussion

4.1. Climate effects on cocoa yields were stronger than soil effects, but variability in management was high

Generally, our results supported the hypothesis that environmental conditions drive cocoa yields but, surprisingly, the degree to which they influenced yields in Ghana was lower than expected. Environmental variables only explained 7% (Fig. 3A) of the variation in yields of the full dataset and 10% (Fig. 4A) of the variation in yields of the subset of 134 farms in Ghana, which is a very small portion of the total variance explained when both environment and farm-to-farm variation is considered (i.e.,80% and 55% of the variation in yields for the full dataset and subset of 134 farms respectively). This suggests that management-related factors strongly drive on-farm yields. A huge variability in management has been observed across cocoa growing areas (Daymond et al., 2017; van Vliet and Giller, 2017). The weak effect of environment on cocoa yields found here may explain the relatively small differences in annual mean cocoa yields observed between rainfall zones. On the other hand, the strong yield variation within the rainfall zones may also be due to the huge variability in management. This points to a significant opportunity for many farmers to increase yields through improved management independent of environmental conditions.

The magnitude of climate effects on cocoa yields was larger than soil

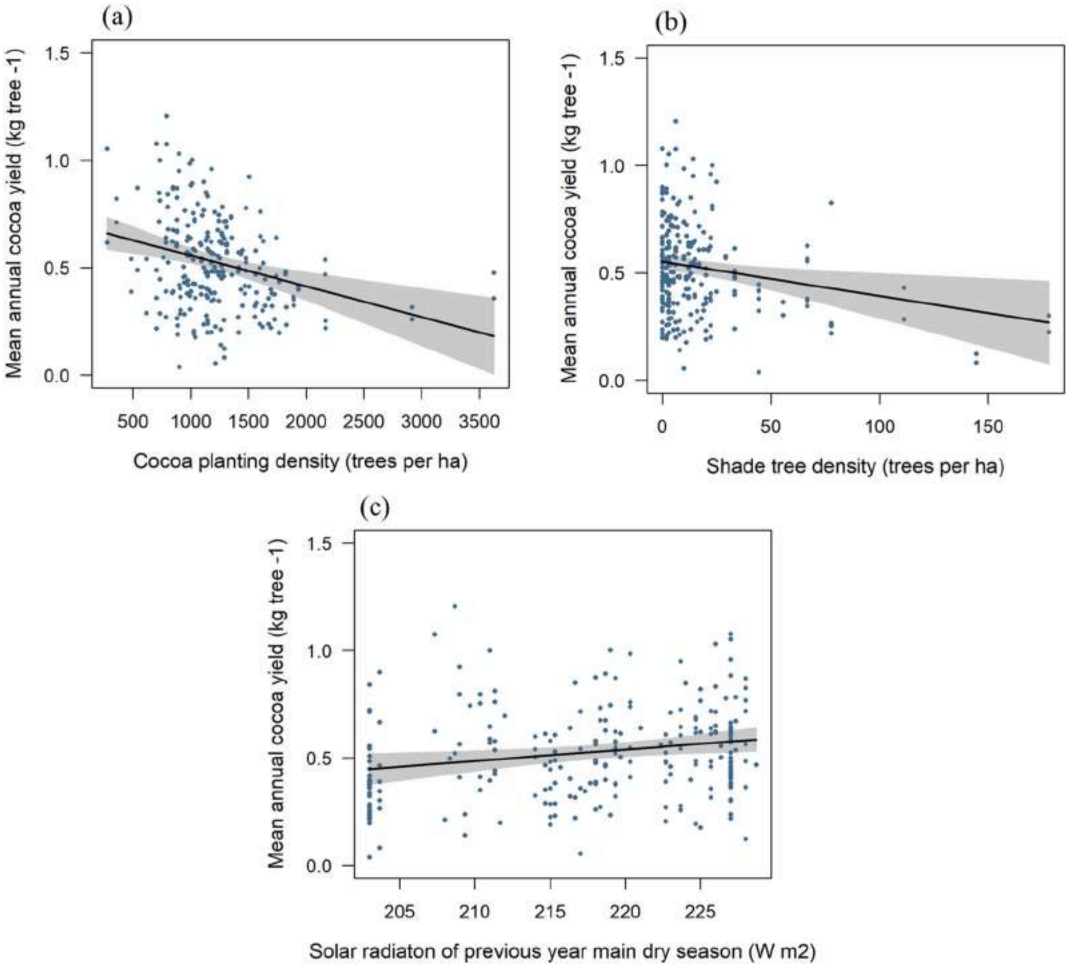

Fig. 5. Relationship between annual cocoa yield per tree and (a) cocoa and (b) shade tree density and (c) Solar radiation (previous main dry season), based on subset of 134 farms from 2012 to 2017. Predictions include the use of fertilizer (use vs. no use), other predictors were kept constant at the mean.

effects, suggesting that yields are more sensitive to changes in climatic conditions. Radiation in the main dry season of the current and previous year were the most prominent environmental variables that significantly increased yields at the hectare and tree level, respectively. Radiation affects yields mainly through photosynthesis (Baligar et al., 2008; Jaimez et al., 2018; Zuidema et al., 2005)., and previous studies have reported significant increases in photosynthesis rates under high light conditions (i.e., beyond the cocoa light saturation point of ~400 μmol m^{-2} s^{-1} to ~1000 μmol m^{-2} s^{-1}) when soil water and nutrients are not limiting (Balasimha et al., 1991; Baligar et al., 2008; Jaimez et al., 2018). On the one hand, increases in yields under high light conditions, such as experienced during the dry season, may be due to the increased carbohydrate production resulting from higher assimilation rates (Owusu, 1980). On the other hand, the positive effect of high radiation of the main dry season on yield could also be a consequence of lower humidity levels which reduces incidence of diseases such as black pod (Akrofi et al., 2015; Mpika et al., 2011). More data on pest and disease incidence in relation to spatial and temporal weather variation is thus needed to quantify effects on yields. With a crop growth model it was shown that solar radiation and precipitation together explained 70% of the variation in simulated water-limited potential cocoa yield (Zuidema et al., 2005). The strong positive relationship between cocoa yield and minimum temperature of the minor wet season of previous year at the field level is not fully understood. One possible explanation could be that temperature has significant effects on pod development and final pod size (Daymond and Hadley, 2008). The observed negative relationship between precipitation of the minor dry season and yield may be related to high humidity levels favouring diseases during pod development. The effects of precipitation on pods may be to some extent dependent on the developmental pod stage. Precipitation has been reported to be beneficial at initial stages of pod development possibly because of its effect on assimilation rates, but becomes less positive with maturity, as damp conditions can lead to an increase in disease incidence (Ali, 1969; Bridgland, 1953) which may reduce yields. The observed positive effect of radiation on cocoa yields supports our hypothesis. However, our data do not indicate that precipitation has a positive effect on cocoa yields as we hypothesized. Negative effects of stressful climatic conditions such as high climatic water deficit (CWD) on yield were also not significant. Amongst soil variables, a negative relationship was found between clay content and yields. Clayey soils have a large moisture holding capacity, and contain more nutrients than sandy soils (Feller and Beare, 1997). However, water and nutrient release to plants was found to be slower, and water and nutrients were therefore not readily available for plant use (Wessel, 1971; Wood, 1985). Zuidema et al. (2005) suggested that loamy soils will give best yields especially under sub-optimal rainfall conditions.

4.2. Cocoa farms with high yields are more sensitive to changes in environmental conditions than farms with low yields

We found that farms with high yields were more sensitive to environmental conditions than farms with low yields (Fig. 3B,C), which suggests low-yielding farms are more nutrient limited (i.e., no or insufficient fertilizer management) and hence less affected by changes in climate (Descheemaeker et al., 2020; Masikati et al., 2019). This illustrates that climate effects become more important when other limiting factors are removed, in this regard, supporting our hypothesis. The dependence of climate effects on overall production levels suggests that there is a need for a diversified climate adaptive strategy that is tailored to the management level of the crop. For instance, on low-yielding farms good agricultural management practices needs to be put in place before investing in additional climate adaptation practices whilst on high-yielding farms, management practices that can facilitate better adaptation of cocoa to the local climatic conditions may be needed.

Amongst the evaluated variables, the strong positive effect of radiation on yields highlights the importance of light availability for increasing yields. On low-yielding farms, yields were more sensitive to precipitation, minimum temperature, vapour pressure deficit, and silt content. To the best of our knowledge, this is the first study to report such differential effects of environmental conditions on cocoa yields for low- vs high-yielding farms.

4.3. Management effects were stronger than climate and soil effects

Based on yield data for a subset of 134 farms over a four-year period, we assessed the relative importance of environmental conditions and management practices (cocoa- and shade-tree density, fertilizer-use, and farm age) on cocoa yield per tree. Without considering management factors, the general results were consistent with the results of the full (3827 farms) dataset. However, by including the management factors a large part (25%) of the variability in cocoa yield per tree was explained (Fig. 4). This indicates the importance of improved management practices to increase yields.

Management practices influenced yield; average tree-level yield decreased with increasing cocoa planting density, however, at the hectare-level yield increased with increasing cocoa planting density. Cocoa planting density has consistently been identified as a significant yield determining factor, and at the plot level increases in cocoa yields with increasing planting densities have been reported (Abdulai et al., 2020; Daymond et al., 2017; Somarriba et al., 2018; Sonwa et al., 2018; Souza et al., 2009). A decreasing average yield per tree with increasing planting densities is likely explained by plant intra-specific competition similar to results reported for coffee (Paulo and Furlani Jr., 2010), or increased disease incidence (Sonwa et al., 2018).

Cocoa yields are significantly reduced with increasing shade tree density supporting our hypothesis, but when farms with more than 100 shade trees per hectare were removed from the analysis, the effect on yield became non-significant. This indicates that the effect of shade tree density is not strong, and that the relationship might be non-linear. A curvilinear relationship is usually found between cocoa yield and shade tree canopy cover (Blaser et al., 2018), however, here we only use shade tree density and therefore cannot make a direct comparison between yield and shade-level. Moreover, the number of shade trees can lead to very different competition effects depending on the shade tree species composition. Shade cover or basal area are better predictors of shading. Our results support the hypothesis that plot level yield increases with cocoa planting density, however, tree level yield decreases.

We found no significant effects of fertilizer use and farm age on cocoa yields, which is agrees with findings reported by Aneani and Ofori-Frimpong (2013). The lack of significant fertilizer effects in our analyses might be due to poor information about quantity and timing of fertilizer application, which is important for determining the effects of fertilizer on yield. In addition to the management practices we included, other factors such as pest and disease control, and planting material, amongst others, could also have important yield implications. Unfortunately, data on such factors were not available.

5. Conclusion

Our results clearly illustrate the enormous yield variability that exists between farms within rainfall zones in Ghana and suggest that there is a significant opportunity for farmers to increase yields through improved agronomic management. The effects of agronomic management, particularly cocoa planting density, on on-farm cocoa yields, are considerably stronger than effects of environmental conditions. Nevertheless, our results also showed that the effects of environmental conditions on on-farm yield became more prominent with increasing yields suggesting that the less cocoa yield is limited by management the more sensitive it is to environmental conditions. Hence, effects of future climate change on cocoa yields may depend on the level of management, which means that sustainable intensification plays a key role in climate adaptive strategies.

Declaration of Competing Interest

The author declare that they have no conflict of interest.

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References

Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A., Hegewisch, K.C., 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Sci. Data 5 (1), 170191. https://doi.org/10.1038/sdata.2017.191.

Abdulai, I., Vaast, P., Hoffmann, M.P., Asare, R., Graefe, S., Jassogne, L., Graefe, S., 2018. Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Glob. Chang. Biol. 24 (1), 273–286. https://doi.org/10.1111/gcb.13885.

Abdulai, I., Hoffmann, M.P., Jassogne, L., Asare, R., Graefe, S., Tao, H.-H., Rötter, R.P., 2020. Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana. Agric. Syst. 181 (October 2019), 102812. https://doi.org/10.1016/j.agsy.2020.102812.

Adjaloo, M.K., Oduro, W., Banful, B.K., 2012. Floral phenology of upper Amazon cocoa trees: implications for reproduction and productivity of cocoa. ISRN Agronomy 2012, 1–8. https://doi.org/10.5402/2012/461674.

Adomako, B., Adu-Ampomah, Y., 2000. Reflections on the yield of upper Amazon cocoa hybrids in Ghana with reference to breeding for cocoa swollen shoot virus resistant varieties. Cocoa Growers' Bull. 33–45.

Ahenkorah, Y., Halm, B.J., Appiah, M.R., Akrofi, G.S., Yirenkyi, J.E.K., 1987. Twenty Years' results from a shade and fertilizer trial on Amazon cocoa (Theobroma cacao) in Ghana. Exp. Agric. 23 (1), 31–39. https://doi.org/10.1017/S0014479700001101.

Akrofi, A.Y., Amoako-Atta, I., Assuah, M., Asare, E.K., 2015. Black pod disease on cacao (Theobroma cacao, L) in Ghana: spread of Phytophthora megakarya and role of economic plants in the disease epidemiology. Crop Prot. 72, 66–75. https://doi.org/10.1016/j.cropro.2015.01.015.

Ali, F.M., 1969. Effects of rainfall on yield of cocoa in Ghana. Exp. Agric. 5 (3), 209–213. https://doi.org/10.1017/S0014479700004452.

Aneani, F., Ofori-Frimpong, K., 2013. An analysis of yield gap and some factors of cocoa (Theobroma cacao) yields in Ghana. Sustain. Agricult. Res. 2 (4), 117. https://doi.org/10.5539/sar.v2n4p117.

Aneani, F., Padi, F., 2016. Baseline farmer survey of smallholder cocoa farming Systems in Ghana. Sustain. Agricult. Res. 6 (1), 13. https://doi.org/10.5539/sar.v6n1p13.

Anim-Kwapong, G.J., Frimpong, E.B., 2008. Vulnerability of Agriculture to Climate Change- Impact of Climate Change on Cocoa Production. Cocoa Research Institute of Ghana, New Tafo Akim. Retrieved from. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.494.4508&rep=rep1&type=pdf.

Appiah, M., Ofori-Frimpong, K., Afrifa, A., 2000. Evaluation of fertilizer application on some peasant cocoa farms in Ghana. Ghana J. Agric. Sci. 33 (2) https://doi.org/10.4314/gjas.v33i2.1869.

Asare, R., Asare, R.A., Asante, W.A., Markussen, B., Ræbild, A., 2017. Influences of shading and fertilization on on-farm yields of cocoa in Ghana. Exp. Agric. 53 (3), 416–431. https://doi.org/10.1017/S0014479716000466.

Asare, R., Markussen, B., Asare, R.A., Anim-Kwapong, G., Ræbild, A., 2019. On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana. Clim. Dev. 11 (5), 435–445. https://doi.org/10.1080/17565529.2018.1442805.

Asare-Nuamah, P., Botchway, E., 2019. Understanding climate variability and change: analysis of temperature and rainfall across agroecological zones in Ghana. Heliyon 5 (10), e02654. https://doi.org/10.1016/j.heliyon.2019.e02654.

Asomanin, E.J.A., Kwakwa, R.S., Hutcheon, W.V., 1971. Physiological studies on an Amazon shade and fertilizer trial at the cocoa research institute, Ghana. Ghana J. Agric. Sci. 4, 47–64.

Baah, F., Anchirinah, V., Amon-Armah, F., 2011. Soil fertility management practices of cocoa farmers in the eastern region of Ghana. Agric. Biol. J. N. Am. 2 (1), 173–181. https://doi.org/10.5251/abjna.2011.2.1.173.181.

Balasimha, D., Daniel, E.V., Bhat, P.G., 1991. Influence of environmental factors on photosynthesis in cocoa trees. Agric. For. Meteorol. 55 (1–2), 15–21. https://doi.org/10.1016/0168-1923(91)90019-M.

Baligar, V.C., Bunce, J.A., Machado, R.C.R.R., Elson, M.K., 2008. Photosynthetic photon flux density, carbon dioxide concentration, and vapor pressure deficit effects on photosynthesis in cacao seedlings. Photosynthetica 46 (2), 216–221. https://doi.org/10.1007/s11099-008-0035-7.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. *67* (1) https://doi.org/10.18637/jss.v067.i01.

Black, E., Pinnington, E., Wainwright, C., Lahive, F., Quaife, T., Allan, R.P., Vidale, P.L., 2020. Cocoa plant productivity in West Africa under climate change: a modelling and experimental study. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abc3f3.

Blaser, W.J., Oppong, J., Hart, S.P., Landolt, J., Yeboah, E., Six, J., 2018. Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat. Sustain. 1 (5), 234–239. https://doi.org/10.1038/s41893-018-0062-8.

Bridgland, L.A., 1953. Study of the relationship between cacao yield and rainfall. Papua and New Guinea. Agricultural Gazette 8:7–14 (1972). In: Fordham, R. (Ed.), The water relations of cacao. In: Proceedings of the 4th International Cocoa Research Conference. In Proceedings of the 4th International Cocoa Research Conference, pp. 320–325.

Bunn, C., Läderach, P., Quaye, A., Muilerman, S., Noponen, M.R.A., Lundy, M., 2019. Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. Clim. Services 16. https://doi.org/10.1016/j.cliser.2019.100123.

Daymond, A.J., Hadley, P., 2008. Differential effects of temperature on fruit development and bean quality of contrasting genotypes of cacao (Theobroma cacao). Ann. Appl. Biol. 153 (2), 175–185. https://doi.org/10.1111/j.1744-7348.2008.00246.x.

Daymond, A.J., Acheampong, K., Prawoto, A., Abdoellah, S., Addo, G., Adu-Yeboah, P., Hadley, P., 2017. Mapping cocoa productivity in Ghana, Indonesia and Côte d'Ivoire. In: 2017 International Symposium on Cocoa Research (ISCR), Lima, Peru, 13–17 November 2017. Lima, Peru, pp. 13–17.

Descheemaeker, K., Reidsma, P., Giller, K.E., 2020. Climate-smart crop production: understanding complexity for achieving triple-wins. In: Climate change and agriculture. https://doi.org/10.19103/AS.2020.0064.14.

Edwin, J., Masters, W.A., 2005. Genetic improvement and cocoa yields in Ghana. Exp. Agric. https://doi.org/10.1017/S0014479705002887.

Fairtrade Foundation, 2016. Commodity briefing: Cocoa. Retrieved from. https://www.fairtrade.org.uk/wp-content/uploads/legacy/Cocoa-commodity-briefing-6May16.pdf.

FAO, 2005. Fertilizer Use by Crop in Ghana (Rome).

FAOSTAT, 2016. Food and Agricultural Organization of the United Nation Statistics Data. Retrieved from http://www.fao.org/faostat/en/#data/QC on August 22, 2018.

Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. In: Geoderma. https://doi.org/10.1016/S0016-7061(97)00039-6.

Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L.B., Obersteiner, M., Van Der Velde, M., 2016. Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. Nat. Commun. 7 https://doi.org/10.1038/ncomms11872.

Gateau-Rey, L., Tanner, E.V.J., Rapidel, B., Marelli, J.-P., Royaert, S., 2018. Climate change could threaten cocoa production: effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. PLoS One 13 (7), e0200454. https://doi.org/10.1371/journal.pone.0200454.

Gelman, A., Hill, J., 2006. Data Analysis Using Regression and Multilevel/Hierarchical Models. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press, Cambridge.

Geraci, M., Bottai, M., 2014. Linear quantile mixed models. Stat. Comput. 24 (3), 461–479. https://doi.org/10.1007/s11222-013-9381-9.

Hartemink, A.E., 2005. Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: A review. In: Advances in Agronomy, Vol. 86. Academic Press, pp. 227–253. https://doi.org/10.1016/S0065-2113(05)86005-5.

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Kempen, B., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12 (2), e0169748. https://doi.org/10.1371/journal.pone.0169748.

ICCO, 2018. Quarterly Bulletin of Cocoa Statistics, *Vol.* XLIV. International Cocoa Organization, London. No. 2, Cocoa year 2017/18.

Jaimez, R.E., Amores Puyutaxi, F., Vasco, A., Loor, R.G., Tarqui, O., Quijano, G., Tezara, W., 2018. Photosynthetic response to low and high light of cacao growing without shade in an area of low evaporative demand. Acta Biol. Colombiana *23* (1), 95–103. https://doi.org/10.15446/abc.v23n1.64962.

Keating, B.A., Carberry, P.S., Bindraban, P.S., Asseng, S., Meinke, H., Dixon, J., 2010. Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci. https://doi.org/10.2135/cropsci2009.10.0594.

Läderach, P., Martinez-Valle, A., Schroth, G., Castro, N., 2013. Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. Clim. Chang. 119 (3–4), 841–854. https://doi.org/10.1007/s10584-013-0774-8.

Mäkinen, H., Kaseva, J., Virkajärvi, P., Kahiluoto, H., 2017. Shifts in soil–climate combination deserve attention. Agric. For. Meteorol. 234–235, 236–246. https://doi.org/10.1016/j.agrformet.2016.12.017.

Masikati, P., Descheemaeker, K., Crespo, O., 2019. Understanding the role of soils and management on crops in the face of climate uncertainty in Zimbabwe: A sensitivity analysis. In: The Climate-Smart Agriculture Papers. Springer International Publishing, pp. 49–64. https://doi.org/10.1007/978-3-319-92798-5_5.

MOFA, 2016. Agriculture in Ghana Facts and Figures - 2015 (Accra).

Mpika, J., Kebe, I.B., N'Guessan, K.F., 2011. Isolation and identification of indigenous microorganisms of cocoa farms in Côte d'Ivoire and assessment of their antagonistic effects Vis-À-Vis Phytophthora palmivora, the causal agent of the Black pod disease. In: Biodiversity Loss in a Changing Planet. InTech. https://doi.org/10.5772/23123.

Nakagawa, S., Schielzeth, H., 2010, November 1. Repeatability for Gaussian and Non-Gaussian Data: A Practical Guide for Biologists. John Wiley & Sons, Ltd., Biological Reviews https://doi.org/10.1111/j.1469-185X.2010.00141.x.

Nalley, L.L., Dixon, B.L., Popp, J.S., 2014. An optimal phased replanting approach for cocoa trees with application to Ghana. Agric. Econ. 45 (3), 291–302. https://doi.org/10.1111/agec.12065.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K. J. (Eds.), Climate Change 2014: Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 1199–1266. https://doi.org/10.1017/CBO9781107415386.002.

Opoku, I.Y., Appiah, A.A., Akrofi, Y., Owusu, G.K., 2000. Phytophthora megakarya: a potential threat to the cocoa industry in Ghana. Ghana J. Agric. Sci. 33, 237–248.

Owusu, J.K., 1980. Light requirements of cocoa: a review. In: Proceedings of the Int. Conf. on Cocoa and Coconuts. Kuala Lumpur, Malaysia, June 21 24, 1978, pp. 112–121.

Paulo, E.M., Furlani Jr., E., 2010. Yield performance and leaf nutrient levels of coffee cultivars under different plant densities. Sci. Agric. 67 (6), 720–726. https://doi.org/10.1590/S0103-90162010000600015.

R Core Team, 2018. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Ruf, F., Schroth, G., Doffangui, K., 2015. Climate change, cocoa migrations and deforestation in West Africa: what does the past tell us about the future? Sustain. Sci. 10 (1), 101–111. https://doi.org/10.1007/s11625-014-0282-4.

Schroth, G., Krauss, U., 2006. Biological soil fertility management for tree-crop agroforestry. In: Uphoff, N. (Ed.), Biological Approaches to Sustainable Soil Systems. CRC Press, Boca Raton, pp. 291–303. https://doi.org/10.1201/9781420017113.ch20.

Schroth, G., Läderach, P., Martinez-Valle, A.I., Bunn, C., Jassogne, L., 2016. Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation. Sci. Total Environ. 556, 231–241. https://doi.org/10.1016/j.scitotenv.2016.03.024.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Reinhardt, J., 2017. Climate change impacts in sub-Saharan Africa: from physical changes to their social repercussions. Reg. Environ. Chang. 17 (6), 1585–1600. https://doi.org/10.1007/s10113-015-0910-2.

Somarriba, E., Orozco-Aguilar, L., Cerda, R., López-Sampson, A., 2018. Analysis and design of the shade canopy of cocoa-based agroforestry systems. In: Achieving sustainable cultivation of cocoa. Burleigh Dodds Science Publishing, pp. 469–500. https://doi.org/10.19103/AS.2017.0021.29.

Sonwa, D.J., Weise, S.F., Schroth, G., Janssens, M.J.J.J., Shapiro, H.-Y.Y., 2018. Structure of cocoa farming systems in west and Central Africa: a review. Agrofor. Syst. 93 (5), 2009–2025. https://doi.org/10.1007/s10457-018-0306-7.

Souza, C.A.S., dos Dias, L.A.S., Aguilar, M.A.G., Sonegheti, S., Oliveira, J., Costa, J.L.A., 2009. Cacao yield in different planting densities. Braz. Arch. Biol. Technol. 52 (6), 1313–1320.

Stanturf, J.A., Warren, M.L., Polasky, S.C., Goodrick, S.L., Armah, F., Nyako, Y.A., 2011. Ghana Climate Change Vulnerability and Adaptation Assessment. USAID, Ghana.

van Vliet, J.A., Giller, K.E., 2017. Mineral nutrition of cocoa: A review. In: Advances in Agronomy, Vol. 141. Academic Press Inc, pp. 185–270. https://doi.org/10.1016/bs.agron.2016.10.017.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Sanginga, N., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric. 39 (1), 17–24. https://doi.org/10.5367/000000010791169998.

Wessel, M., 1971. Fertiliser requirements of cacao (Theobroma cacao L.) in South Western Nigeria. In: Communication 61. Koninklijk Instituut voor de Tropen. Amsterdam.

Wessel, Marius, Quist-Wessel, P.M.F., 2015. Cocoa production in West Africa, a review and analysis of recent developments. NJAS - Wageningen J. Life Sci. 74–75, 1–7. https://doi.org/10.1016/j.njas.2015.09.001.

Wood, G., 1985. Environment. In: Cocoa. Blackwell Science Ltd, Oxford, UK, pp. 38–79. https://doi.org/10.1002/9780470698983.ch3.

Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L., Anten, N.P.R., 2005. A physiological production model for cocoa (Theobroma cacao): model presentation, validation and application. Agric. Syst. 84 (2), 195–225. https://doi.org/10.1016/j.agsy.2004.06.015.

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer New York, New York, NY.