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Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana

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ABSTRACT

Improving management practices of cocoa (*Theobroma cacao* L.) cultivation especially under future climate change requires knowledge of yield gaps and their determining factors. In this study, we assessed yield gaps and their determining factors through multiple regression modelling in smallholder cocoa agroforestry systems in Ghana along a climatic gradient. The studied zones referred to as dry, mid and wet with annual rainfall of 1200, 1200–1400 and 1400–2000 mm respectively, represent established "climate suitability zones" across the cocoa belt of West Africa, where 70% of the global cocoa is produced. Data was collected from 150 cocoa farmers and their plantation across the zones. Information about socioeconomic and management characteristics was collected through interviews. In each plantation, soil characteristics and cocoa plantation properties were recorded. Yield data for three consecutive years (2012/13–2014/15) and soil properties (0–30 cm layer) were analysed. Yield gap was estimated as the difference between attainable yield (AY) and actual farmers yield (FY) in each zone based on the approach of maximum farmer yields determined from survey. Average farmer and attainable yield of 211 and 645 kg ha^{-1} year^{-1} in the dry, 477 and 1174 kg ha^{-1} year^{-1} in the mid and 999 and 2125 kg ha^{-1} year^{-1} in the wet zone were recorded, respectively. Relative yield gaps were significantly larger in the dry (67%) than the wet zone (53%). In the dry zone with significantly older farmers (average age of 64), increasing labour cost (use of hired labour) significantly reduced yield gap. Contrary, increasing labour cost significantly increased yield gap in the mid zone where plantations were significantly larger. Yield gap increased significantly with increasing farmer age (54 years) in the mid zone but decreased significantly with farmer age (47 years) in the wet zone. Significant positive relationship between plantation size and yield gap was observed in both mid and wet zones. Soil available phosphorous (P) and fungicide use significantly reduced yield gap in the dry and mid zones. Finally, quantity of pesticide, proportion of hybrid cocoa plants and number of trainings received by farmers significantly reduced yield gap in the wet zone. In the dry zone, closing the yield gap against

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the climate risk might be unlikely. Transformation into more drought resistant systems such as cashew might be promising. However, in the mid and wet zones, labour availability for effective management of large plantations might be the major barrier for intensification, which needs to be addressed by intervention strategies.

1. Introduction

Global cocoa demand is projected to keep increasing up to 4.5 million tonnes by the end of 2020 whilst unstable production persist due to low productivity per unit area as well as climate variability (ICCO, 2017). Between 1980 and 2017, global land area under cocoa cultivation increased from 4.7 to 11.7 million ha while yield levels during the same period barely increased, 350 to 443 kg ha $^{-1}$ year $^{-1}$ (FAOSTAT, 2019). This emphasizes that global cocoa production increases have mainly relied on land expansion and therefore contributed to significant loss in tropical rainforest (Gockowski et al., 2013). Cocoa (*Theobroma cacao* L.*)* production plays a significant role in sustaining both the national economy and rural livelihoods especially for less resource endowed smallholder farmers in the producing countries. Several factors, in addition to climatic conditions, have been identified to co-determine cocoa production fluctuations across West Africa where 70% of global cocoa production occurs (Schroth et al., 2017). Observed and projected increase in spatiotemporal climate variability now contributes alongside the numerous challenges such as low soil fertility, increased pest and disease pressure, lack of quality planting material and inadequate extension services faced by smallholder cocoa farmers across West Africa (Noponen et al., 2014; Anim-Kwapong and Frimpong, 2004). The cocoa growing zones of West Africa are distributed along various climatic zones which have been categorized into different climate suitability zones for future cocoa production (Schroth et al., 2017; Schroth et al., 2016).

Categorization of the cocoa landscape into these climate suitability zones offers different options of yield improvement for climate change adaptation either through intensification measures adjusted to future climate or by expanding cultivation into climatically suitable areas (Schroth et al., 2017; Schroth et al., 2016). Expansion into climatically suitable zones and subsequent deforestation has been observed in Ghana and Ivory Coast where major production has shifted to the more climatically suitable forested zones in response to a changing climatic suitability for cocoa since the 1983/84 severe drought caused by an extreme El Niño event (Ruf et al., 2015; Mighty Earth, 2018). In these countries, shifts in cocoa production have occurred from the dry (zone 3) and intermediate or mid zones (zone 2) to the wetter forested zone (zone 1), resulting in a substantial loss of forest cover (Noponen et al., 2014; Ruf, 2011; Mighty Earth, 2018).

Further increase in cocoa production in the West African cocoa belt to meet global demand through land expansion is limited as land scarcity and strict regulation on cocoa deforestation (demand for deforestation free certified cocoa beans) currently persist (Mighty Earth, 2018; Gockowski et al., 2013). In this situation, narrowing the gap between attainable and actual yield through intensification can be an important means of reducing the pressure on the remaining forests and adapting to climate change (Hoffmann et al., 2020; Schroth et al., 2016). However, yield improvement can only be sustainable if ecological, economic and social dimensions are taken into consideration (Blaser et al., 2018). Such pathway has been coined as “sustainable intensification” (Garnett et al., 2013; Foley et al., 2011; Godfray et al., 2010). Sustainable intensification in cocoa production requires site- and season-specific management to ensure high resource-use efficiency (Noponen et al., 2014; Schroth et al., 2017). Arguably, such approach is knowledge- and often resource-intensive. Sustainable intensification of cocoa production will also require soil fertility improvement as recommended for other cropping systems (Cassman, 1999). Hence site-specific (climate suitability zone) information on yield gap (difference between attainable and actual farmer yields) and yield gap determining factors is a prerequisite for proper guidance on improving and sustaining production (van Ittersum et al., 2013; Cassman, 1999). Considering the existing variations in climatic conditions in the cocoa growing zones of West Africa (Schroth et al., (2016/17; Läderach et al., 2013), it is important to understand yield gaps along the established climate gradient to effectively identify the available scope for yield improvement. This is against the background that climatic variations and associated risk is a major constraint to intensify production (Hoffmann et al., 2017; Tittonell and Giller, 2013).

In this study, we used Ghana as a case study to understand how the established cocoa climate suitability zones across West Africa by Schroth et al., (2016/17) influence current cocoa yield gaps and to identify the determining factors that need to be considered for narrowing the yield gap. A previous study on cocoa yield gap in Ghana only focused on the national scale (Aneani and Ofori-Frimpong, 2013) without accounting for the variations caused by differences in climatic conditions. However, different zones in Ghana which align with the established climate suitability gradient across West Africa have been shown to exhibit different yield potentials according to surveys and model simulations (Abdulai et al., 2018; Zuidema et al., 2005). Although yield gap studies on some perennials e.g. oil palm (*Elaeis guineensis* Jacq.) (Hoffmann et al., 2017; Euler et al., 2016) or coffee (*Coffea arabica* L.) (Bhattarai et al., 2017; Wang et al., 2015) are limited due to minimal data availability, cocoa yield gap studies that even consider a climatic gradient, are virtually non-existent.

To this end, we hypothesized that, 1) cocoa yields and absolute yield gap values are highest in wet zone (climate suitability zone 1) due to less climate-induced risk compared to the dry zone (Suitability zone 3), and 2) relative yield gap (%) is highest in the climatically marginal zones due to less intensive crop management strategies that farmers

Table 1
Climate suitability zones across the cocoa production landscape of West Africa according to Schroth et al., 2017.

Climate suitability zone	Zone 1	Zone 2	Zone 3
Specific areas in West Africa	Include major production areas of Southern part of cocoa belts of Ghana and Côte d'Ivoire and parts of southern Cameroon	Northern parts of the cocoa belts of Liberia, Côte d'Ivoire, Ghana, Cameroon and most cocoa areas of Nigeria, Togo and Guinea	North-eastern part of the cocoa belt of Côte d'Ivoire; northern and north-western parts of Nigeria, northernmost parts of Ghana and Sierra Leone
Current and future suitability characteristics	High relative climatic suitability for cocoa for current and future (2050s)	Current climatic suitability sufficiently high and projected to remain broadly suitable for cocoa farming into the 2050s	Currently marginal climatic suitability and projected to drastically decline to almost unsuitable levels to support cocoa farming
Estimated land area	22.4 million hectares or 38% of the current cocoa belt	32.2 million hectares or 55% of the current cocoa belt	4.1 million hectares, or 7% of the current cocoa belt
Potential climate change adaptation strategies	Copping through intensification or expansion into new forest lands	Adjustment in cropping system through crop diversification	Change from cocoa to more drought tolerant crops

adopt as a means to reduce risk. The objectives of this study were to a) assess variations in cocoa yield gap across three different climatic zones corresponding to the established climate suitability impact zones as described in Table 1 and (b) identify major yield gap determining factors within the different zones.

2. Materials and methods

2.1. Study sites

The study grouped the current cocoa growing zones of Ghana into dry, mid and wet zones which aligns with the different climate suitability zones (Table 1). The zones are distinguished based on current annual rainfall amounts (Fig. 1) in conjunction with drought severity (including more factors than rainfall, i.e. temperature and evapotranspiration) during the annual dry Harmattan period (Table 2). Akumadan and Afrancho towns in the Offinso North district of the Ashanti region were selected to represent the dry zone. This zone has experienced change in vegetation type from moist semi-deciduous to forest savannah transition due to frequent fire influenced by the annually recurring longer dry Harmattan (Adjei-Nsiah and Kermah, 2012). The mid zone was located in five surrounding villages of Goaso in Asunafo North district of the Ahafo region. Subsequently, the wet zone in the moist evergreen forest type was located further south of the forest belt in five surrounding villages of Asankragua in the Amenfi West district of the Western region. The highly desaturated ferrallitic soils in the wet zone have been classified as unsuitable for cocoa cultivation due to high lack of available minerals unless fertilizers are applied (Anim-Kwapong and Frimpong, 2004).

2.2. Farmer survey and yield data collection

A total of 150 farmers with corresponding plantations, 50 per zone, were selected for the study. Combined approaches of farmer interview and on-farm inventory were employed in data collection from April to September 2014. Farmers from the dry and mid zones were randomly selected from the database of the Kuapa Kokoo farmers' cooperative union, the largest cocoa farmers union in Ghana. In the wet zone, farmers were selected from the Rainforest Alliance certification database managed by AgroEco-Louis Bolk Institute (AE-LBI) in the Western region of Ghana. Details on the sampling, data collection and descriptive statistics between the zones are presented in Abdulai et al. (2018). A structured questionnaire and "on-farm survey sheets" digitized on a smartphone was used to collect data using the Mobenzi Researcher ® platform (https://www.mobenzi.com/).

The questionnaire for cocoa farmer interviews was centred on characterization of variables including cocoa farmer socio-economics (e.g. farmer age, household size), cocoa plantation management (quantity of pesticide, fungicide, fertilizer use and hired labour) attributes as well as sources of planting material (proportion of hybrid and non-hybrids per plantation), accessibility of technical information for the farmer through training, and yield information from the 2012/13 cocoa season (Table 2). Interviews were conducted directly in the local Twi language to ensure accurate response. Pre-testing of the questionnaire preceded the data collection with translation and back-translation undertaken to verify understanding of the questions. Yield data for the subsequent 2013/14 and 2014/15 seasons were collected in June 2016 in a follow-up visit. Cocoa yields referred to the quantity of annual dried cocoa beans harvested per cocoa plantation area as reported by farmers and verified with their sale books. The farmer sales record book usually referred to as Cocoa Passbook has been found to be reliable as farmers require it to access their annual bonuses (Asare et al., 2018).

2.3. On-farm inventory and soil sampling

On-farm inventories were carried out on a randomly selected mature cocoa plantation of each farmer in case of more than one. Total cocoa plantation area was measured with GPS device. Shade tree canopy area was measured based on the methodology by Asare et al. (2017). Through the support of experienced forester, data was collected on number of shade trees (density), species identity (diversity), diameter at breast height (DBH) and the canopy area through complete inventory of the entire plantation as described in Abdulai et al. (2018). Cocoa tree density and DBH were recorded at the middle of the cocoa plantation on a fixed area transects of 40 m with cocoa trees selected within 10 m perpendicular distance and at 10 m interval as proposed by Nath et al. (2009). Incidence of mistletoe (*Tapinanthus bangwensis),* the parasitic pest on cocoa trees was also recorded for cocoa trees within the transect.

Soil samples from the top soil (0–30 cm depth) were taken from the mid-point and four coordinate points (at least 5 m from the boundary to avoid edge effect) of the cocoa plantation with an auger. The five samples were mixed thoroughly to form a composite sample from which a sub-sample was collected for analysis. Soil texture and chemical properties including pH, organic matter, total nitrogen (TN), soil organic carbon (SOC), exchangeable calcium (Ca), magnesium (Mg), and potassium (K), plant available phosphorous (P), cation exchange capacity (CEC) and base saturation (Table 4) were analysed at the laboratory of Soil Research Institute of Ghana (CSIR-SRI). Soil samples were dried at 105 °C, sieved through a 2 mm sieve and ground. Analysis followed standard methods as outlined in Blaser et al. (2017).

2.4. Statistical analysis

2.4.1. Yield gap and yield gap determining factors

Lobell et al. (2009) and van Ittersum et al. (2013) differentiated three methods to define attainable crop yield as a reference in yield gap

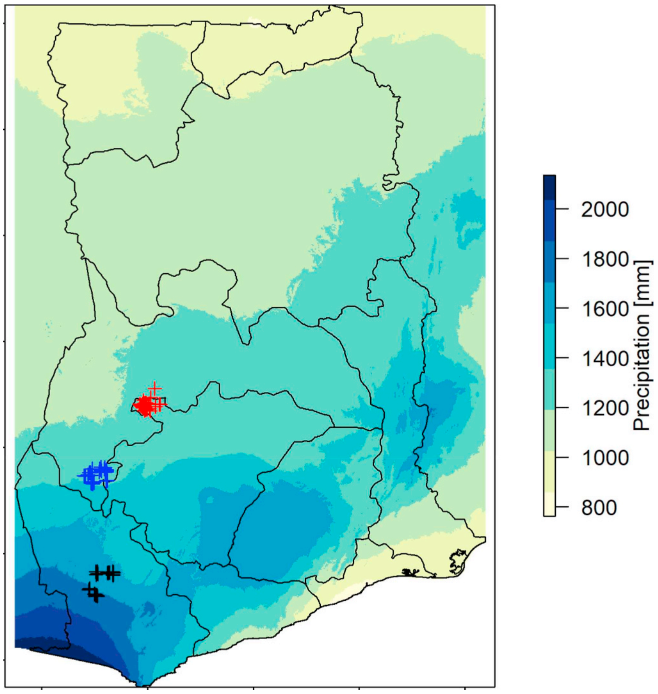

Fig. 1. Total annual rainfall (mm) across the studied zones. Lines indicate regions within Ghana. Rainfall values derived from WorldClim data ((www.worldclim.org; Hijmans et al., 2005) are calculated means of 1950–2000. Dry, mid and wet zones denoted by red, blue and black colours respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Characteristics of the studied zones (dry, mid, wet).

	Dry	Mid	Wet
Mean temperature (°C)	27–30	25.5–30	27–30
Mean annual rainfall (mm)	100–1200	1200–1400	1400–2000
Dry season (months)	Nov. – Mar. (4–5)	Nov.– Feb (3–4)	Nov. – Feb (3–4)
Dominant soil types	Acrisol, Alfisol	Acrisol, Alfisol, Oxisol	Acrisol, Alfisol, Oxisol
Agro-ecological zone	Savannah Transition	Moist Semi-deciduous	Moist Evergreen

Sources: (MOFA, 2017; Anim-Kwapong and Frimpong, 2004; Adjei-Nsiah and Kermah, 2012).

analysis. The standard approach commonly employed to assess attainable yield under irrigated (potential) and rainfed (water-limited) growth conditions in yield gap studies is the use of crop simulation modelling. However, with a few exceptions, crop models for tropical perennials do not exist. For cocoa, Zuidema et al. (2005) developed such model, but it is still far from being sufficiently tested and validated. The second approach for assessing attainable yield is through well-designed field or potential growth trials, where ample water and nutrients are provided at all times and biotic stresses are minimised as much as possible to estimate potential yield. In determining water-limited yield, nutrients are still provided according to needs, and biotic stresses are minimised. However, for cocoa such field trial data are not available. The third approach, which we applied, was to use maximum yields recorded by farmers. This method is well-established and is the only option in the absence of potential growth trials. It has the advantage that recorded yields have indeed been shown to be attainable by farmers applying best practices (Hoffmann et al., 2017; Wang et al., 2015).

Yield gap was estimated as the difference between attainable yield (AY) and actual farmers yield (FY) in each climatic zone based on the approach of maximum farmer yield determined from the survey (Lobell et al., 2009). Attainable yield was defined as the three-year average yield from the 10% best performing farmers within a zone. Using average yield data over a minimum of three consecutive years is necessary to capture inter-annual variability to some extent and eliminate carry-over effects in perennials (Hoffmann et al., 2017). Yield gap was further expressed as percentage of the attainable yield. Yield gap determining factors were identified and estimated per zone by multiple linear regression models. All statistical analyses were undertaken by using the R software (R core team, 2017). Yield gap determining factors considered for the multiple regression analysis were categorized into socio-economic, plantation inputs management, plantation and soil characteristics (Table 3 & 4).

Correlation analysis was conducted for all independent variables with GGally R package from which a correlation matrix was plotted with accompanying R^2. Variable pairs with R^2 value of > 0.6 which represent variance inflation factor (vif) of more than 2.5 were considered collinear according to Allison (2012). Variance inflation factor (vif) quantifies how much the variance of each predictor is inflated due to the presence of high collinearity with other predictors. Only one variable among highly collinear independent variables was included in the full model (Table 5) to avoid the effect of collinearity (Quinn and Keough, 2002), prior to the stepwise regression. Stepwise multiple regression analysis according to Crawley (2005) was performed to identify the most parsimonious model that explains most of the variation in the yield gap response variable. The most parsimonious model was selected as the model with the lowest Akaike information criterion (AIC) value after further manual checks. The selected model was checked for normality and heteroscedasticity and improved by transformation of either the dependent or independent variables when necessary. All variables as stated in Tables 3 and 4 were considered in the regression analysis with the exception of soil K in the wet zone. Soil K showed unrealistic agronomic relationship with yield gap (i.e. increasing K significantly increased yield gap) and could only be considered as random rather than causal. The recorded soil K value for the wet regions was also much lower compared to the established threshold for cocoa cultivation (Table 4). Under such high rainfall condition of the wet zone, K effect could be better evaluated through plant analysis since most part of K are stored in cocoa and shade tree biomass rather than in soils (van Vliet and Giller, 2017).

3. Results

3.1. Yield gap and variability across climatic zones

The three-year mean annual cocoa yield from 2012/13 to 2014/15 significantly increased along the climatic gradient from the dry to wet zone (Fig. 2). The dry zone recorded significantly lower average farmer yield (FY) of 211 kg ha^{-1} yr^{-1} and attainable yield (AY) of 645 kg ha^{-1} yr^{-1} followed by the mid zone with FY of 477 and AY of 1174 kg ha^{-1} yr^{-1}. The wet zone recorded the highest average FY of 999 and AY of 2125 kg ha^{-1} yr^{-1}. This resulted in significantly higher absolute yield gap when going from the dry to wet zones. Absolute yield gap from the dry, mid and wet zones were 434, 697 and

Table 3

Descriptive statistics of variables collected across the zones (dry, mid, wet). Different letters indicate significant difference in the means (SD) among the zones at $p \leq .05$ with Tukeys HSD test in standard ANOVA.

	Dry	Mid	Wet
Socioeconomics			
Farmer age (years)	64 (19)^{a}	54 (14)^{b}	47 (11)^{b}
Household size	11 (8)^{a}	7 (3)^{b}	8(3)^{b}
Training (days year^{-1})	4(5)^{a}	2 (3)^{ab}	6(6)^{ac}
Labour cost (GHS ha^{-1} year^{-1})	166 (230)^{a}	131(164)^{a}	148(183)^{a}
Cocoa income (%)	50 (30)^{a}	80 (20)^{b}	80(20)^{b}
Non-cocoa income (%)	50 (30)^{a}	20 (10)^{b}	20(10)^{b}
Input management			
Fungicide (sachets ha^{-1})	43 (85)^{a}	22(26)^{a}	21(47)^{a}
Pesticide (liters ha^{-1})	4.5 (10.0)^{a}	2.7(1.9)^{a}	9.9(46.2)^{a}
Organic fertilizer (kg ha^{-1})	0(0)^{a}	39(86)^{b}	71(121)^{b}
Inorganic fertilizer (kg ha^{-1})	2 (13)^{a}	20(73)^{b}	42(103)^{b}
Plantation characteristics			
Plantation size (ha)	1.0(1.0)^{a}	1.7(1.1)^{b}	1.0(0.7)^{a}
Cocoa plantation age (years)	17(11)^{a}	21(8)^{a}	16(9)^{a}
Cocoa plant DBH (cm)	9.4(2.6)^{a}	9.9(2.4)^{a}	12.1(2.5)^{b}
Cocoa plant density (trees ha^{-1})	1576(534)^{a}	1620(461)^{a}	1738(395)^{a}
Shade cover (%)	27(16)^{a}	13(8)^{b}	18(11)^{b}
shade trees density (trees ha^{-1})	49(33)^{a}	23(14)^{b}	34(24)^{b}
Shade tree diversity (species ha^{-1})	22.4(15.2)^{a}	10.8(6.5)^{b}	15.5(8.0)^{b}
Shade tree basal area (m^{2})	4.2(3.6)^{a}	7.0(5.7)^{b}	4.1(5.7)^{a}
Mistletoe incidence (%)	13.8(25.6)^{a}	14.6(18)^{a}	18.4(18)^{a}
Proportion of hybrid and non-hybrid (farmer own selected) cocoa plants per plantation			
Hybrid	7.3(3.5)^{a}	3.4(4)^{b}	2.7(3.9)^{b}
Non-hybrid	2.7(3.5)^{a}	6.7(4)^{b}	7.5(4.0)^{b}

DBH refers to diameter at breast height.

Table 4

Mean and standard deviation (SD) of soil characteristics **(0–30 cm depth)** among zones (dry, mid, wet). Different letters indicate statistical differences ($p < .05$: Tukeys HSD test in standard ANOVA).

Soil property	Dry	Mid	Wet	Threshold*
pH	6.9 (0.40)^{a}	6.8 (0.47)^{a}	5.3 (0.31)^{b}	5.6–7.2
Soil organic C%	1.32 (0.45)^{a}	1.64(0.53)^{b}	1.71(0.41)^{b}	2.03
Total N%	0.12(0.03)^{a}	0.14(0.05)^{b}	0.15(0.04)^{b}	0.2
Soil OM%	2.3(0.8)^{a}	2.8(0.9)^{b}	2.9(0.7)^{b}	≥3%
Ca (cmolc kg^{-1})	8.46(4.34)^{a}	10.23(7.15)^{a}	3.93(2.34)^{b}	7.5
Mg (cmolc kg^{-1})	2.34(1.14)^{a}	3.16(1.89)^{b}	1.56(0.92)^{c}	2.0
K (cmolc kg^{-1})	0.23(0.09)^{a}	0.22(0.10)^{a}	0.18(0.09)^{a}	0.25
P (ppmP)	11.11(5.14)^{ab}	13.74(8.88)^{b}	8.72(3.60)^{a}	20
CEC (cmolc kg^{-1})	11.22(5.12)^{a}	13.85(8.84)^{ab}	9.22(3.56)^{ac}	3–15
% Base Sat.	98.81(1.06)^{a}	98.78(1.47)^{a}	93.67(3.56)^{b}	< 35
Sand (%)	58.90(11.32)^{a}	41.55(8.97)^{b}	31.81(9.09)^{c}	
Clay (%)	12.31(4.95)^{a}	12.74(4.18)^{a}	12.42(4.52)^{a}	
Silt (%)	28.79(11.36)^{a}	45.71(9.38)^{b}	55.77(8.53)^{c}	

* Ranges and threshold values of soil chemical properties relevant for cocoa cultivation (van Vliet and Giller, 2017; Asare et al., 2017

1126 kg ha^{-1} yr^{-1}, respectively. Highest relative yield gap (in percentage) of 67% for the dry zone was not significantly different from the mid zone with 59%. However, the wet zone, with 53% yield gap, was significantly different from the dry zone (Fig. 2).

3.2. *Yield gap determining factors across the zones*

In the dry zone, quantity of fungicide applied and labour cost were management related variables that significantly correlated with the yield gap. However, the relationship between yield gap and quantity of fungicide applied was influenced by an “outlier”, which however was kept upon doubling checking with the farmer, proven to be a true yield value. Negative relation of decreasing yield gap with increasing plant available P content, proportion of sand (almost all soils in the zone were sandy loam) and cocoa plant density was observed in the dry zone. In the mid zone, positively significant correlation between yield gap and farmer age was revealed. Among the plantation characteristics, increasing plantation size significantly related to yield gap increase (Table 6). With respect to the soil variables, significant positive relationship between plant available P in the soil and the yield gap was observed. Whilst higher quantities of applied fungicide significantly related to yield gap reduction, labour cost showed a negative relationship. For the wet zone, farmer age and the number of trainings received by farmers were important socioeconomic variable that showed a significant negative correlation with yield gap: the older the farmer and the more training received, the smaller the yield gap. Yield gap significantly increased with increasing plantation size and decreased with increasing plantation age and proportion of hybrid planting material in the plantation (Table 6).

4. Discussion

4.1. *Yield gap and variability across climatic zones*

The survey supported the study hypothesis that yields and associated absolute yield gap values increase along the climate suitability gradient but relative yield gap (%) was clearly highest in the low rainfall marginal climate suitability zone. The low farmer yield and high relative yield gap (%) in the marginal climatic zone (suitability zone 3) is an indication of farmers producing far below their potential yields. This phenomenon is attributed to lack of agricultural intensification, considered as some kind of risk management strategy in response to the existing marginal suitability conditions associated with drought and fire risks (Abdulai et al., 2018; Menapace et al., 2013; Adjei-Nsiah and Kermah, 2012). This observation corroborates the description of the dry zone (climate suitability zone 3) by Schroth et al. (2017) as currently marginal for cocoa production. As a result, already now cocoa production in the dry zone is gradually being replaced by short rotation annual crops and drought tolerant tree crops (such as cashew: *Anacardium occidentale* L.) which appear to be less vulnerable to current and projected future climatic risks (Abdulai et al., 2018; Schroth et al., 2017; Asante et al., 2016; Adjei-Nsiah and Kermah, 2012). Since cocoa as a perennial tree crop is vulnerable to heat and drought stress and also requires more time to establish than annuals (Carr and Lockwood, 2011), it is therefore difficult to adapt production to climatically risky conditions of the dry zone (climate suitability zone 3). Hence, cocoa cannot, unlike annual crops benefit from being aligned with season-specific practices in conjunction with seasonal weather forecasts (Hoffmann et al., 2018). Thus such season-specific crop management is difficult to achieve.

Average farmer yields and attainable yields in the mid and wet zones recorded for this study are higher compared to the yield levels usually reported by the cocoa sector and even higher than found in most of the scientific literature (Aneani and Ofori-Frimpong, 2013). According to Aneani and Ofori-Frimpong (2013), cocoa plantation management activities in Ghana are mostly undertaken by the farmers themselves. Therefore, older farmers tend to have lower cocoa productivity as they are usually unable/lack the capital to afford hired labour to complement their own efforts. With significantly older cocoa farmers in the dry zone compared to the mid and wet zones (Table 3), farmer age is therefore perceived as an important socioeconomic factor that influenced cocoa yields along the climate suitability gradient (Abdulai et al., 2018). Higher fertilizer use in the mid and wet zones compared to the dry zone is another contributing factor for the observed yield difference among the zones. Tailored application of NPK fertilizer is considered a major means required to improve current cocoa productivity and to ensure sustainable intensification (Hoffmann et al., 2020). The wet zone (high climate suitability, zone 1) is the leading cocoa production zone in the West African cocoa belt (Schroth et al., 2017; Gockowski et al., 2013). The highest yield in this climatically suitable (absence of drought risk) wet zone under such soil condition in this study could therefore be attributed to the effect of high fertilizer use (Table 3). With fertilizer application, yields even up to 4000 kg ha^{-1} year^{-1} have been observed in this zone by Ruf (2011).

4.2. *Yield gap determining factors across the zones*

Observation of significant reduction in yield gap with increasing labour cost in the dry zone where farmers are much older (average age of 64) could be attributed to the fact that, their cocoa productivity depend on their ability to employ labour (Dormon et al., 2004). But in the mid zone, increasing labour cost significantly increased the yield gap which could be rather attributed to the combined effect of plantation size (larger plantations in the mid zone (Table 3)) and inefficient plantation management as emphasized in other smallholder yield gap studies in oil palm (Euler et al., 2016). Increasing yield gap with increasing farmer age as observed in the mid zone can therefore be attributed to lack of sufficient labour for the significantly larger cocoa plantations by relatively older farmers (average farmer age of 54) (Table 3) (Dormon et al., 2004). In the wet zone, the opposite trend of increasing yield gap with decreasing farmer age was observed. Such age effect in the wet zone can be attributed to lack of sufficient experience in cocoa cultivation by much younger farmers (average age of 47) who might even be keeping larger cocoa plantations. The relationship of increasing cocoa plantation size with increasing yield gap in the mid and wet zones could also be attributed to lack of sufficient labour to effectively undertake management practices such as timely weeding, pruning and spraying. Also the inability to financially invest in labour, fertilizer, fungicides and pesticides as reported by Aneani and Ofori-Frimpong (2013) could be a contributing factor.

Table 5
Zone specific (dry, mid, wet) stepwise multiple regression model construction for identification of yield gap (YG) determining variables. Full model established after collinear variables were identified through a multicollinearity test.

Dry	*Full model for stepwise regression after testing for multiple collinearity* Step(lm(yg~farmer.age + household.size + gender + cocoa.tree.density + plantation.age + plot.size.ha(shade.tree.basal.area) + shade.cover (shade.tree.species.diversity + density) + total.N(organic.carbon + OM) + pH(base.saturation) + available.P(Ca + Mg + CEC) + Soil.K + clay + sand (silt) + cocoa.DBH + mistletoe + pesticide + fungicide + labour.cost + hybrid.material(non-hybrid.materials) + training.days.yr,data),direction = “both”) *Parsimonious model after stepwise regression* m < −lm(yg~cocoa.tree.density + ph + available.P + sand + fungicide + labour.cost) Further manual simplification did not improve model AIC value Transformation to improve normality and heteroscedasticity (random variance of residuals) lm(yg~log(cocoa.tree.density) + pH + available.P + log(sand) + fungicide + log(labour.cost + 1)) Residual standard error: 127.6 on 42 degrees of freedom, Multiple R-squared: 0.4674, Adjusted R-squared: 0.3913 F-statistic: 6.144 on 6 and 42 DF, *p*-value: 0.00011
Mid	*Full model for stepwise regression after testing for multiple collinearity* step(lm(yg~farmer.age + household.size + gender + cocoa.tree.density + plantation.age + plot.size.ha + shade.cover (shade.tree.species.diversity + density) + shade.tree.basal.area.m2 + total.N(organic.carbon + OM) + pH(base.saturation) + available.P(Ca + Mg + CEC) + Soil.K + clay + sand (sand) + cocoa.DBH + mistletoe + pesticide + fingicide + labour.cost + hybrid.material(non-hybrid.materials) + training.days.yr,data), direction = “both”) *Parsimonious model after stepwise regression* m < −lm(yg~farmer.age + household.size + plot.size.ha + pH + available.P + Soil.K + fungicide + labour.cost) Further manual simplification did not improve model AIC value. Model fulfilled normality and heteroscedasticity (the variance of residuals are random) condition Residual standard error: 209 on 41 degrees of freedom Multiple R-squared: 0.4697, Adjusted R-squared: 0.3662 F-statistic: 4.539 on 8 and 41 DF, p-value: 0.0005194
Wet	*Full model for stepwise regression after testing for multiple collinearity* Step(lm(yg~farmer.age + household.size + gender + cocoa.tree.density + plantation.age + plot.size.ha(shade.tree.basal.area) + shade.cover(shade.tree.species.diversity + density) + total.N(available.P + OM + organic.carbon + Ca + CEC) + pH(base.saturation) + mg + clay + sand(silt) + mistletoe + pesticide + fingicide + labour.cost + hybrid.material(non-hybrid.materials) + training.days.yr,data)direction = “both”) *Parsimonious model after stepwise regression* mf < lm(yg~farmer.age + household.size + plantation.age + plot.size.ha + total.N + pesticide + hybrid.material + training.days.yr) Model fulfilled normality and heteroscedasticity condition Residual standard error: 410.7 on 41 degrees of freedom Multiple R-squared: 0.4676 Adjusted R-squared: 0.3638 F-statistic: 4.502 on 8 and 41 DF, p-value: 0.0005558

NB: variables in parentheses represent multiple collinear variables and are represented in the full model by variables outside the parentheses.

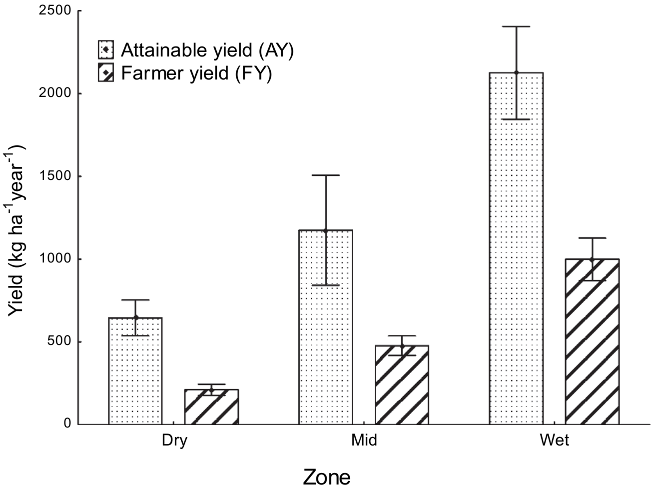

Fig. 2. Attainable yield (AY) and average farmer yield (FY) along a climatic gradient in Ghana. Average farmer yield (FY) defined as the mean yield of the sampled 50 plantations, and the attainable yield (AY) determined by the 10% best performing (highest yielding) plantations per zone. Columns represent the mean and whiskers indicate 95% confidence intervals.

Table 6

Yield gap response to the different variables tested in a multiple regression model for each zone. Significance level · $p < .1$ * $p < .05$. ** $p < .01$. *** are marked.

		Estimate	Std. error	t value	Pr(> |t|)	
Dry	(Intercept)	1791.26	656.44	2.73	0.0092	**
	Cocoa plant density (trees ha^{-1}) (log)	−130.48	60.72	−2.15	0.0375	*
	Soil pH	114.14	63.39	1.80	0.0790	.
	Available P (ppmP)	−12.73	5.17	−2.46	0.0180	*
	Sand (%) (log)	−242.24	112.14	−2.16	0.0365	*
	Fungicide (sachets ha^{-1})	−0.95	0.23	−4.09	0.0002	***
	Labour cost (Ghana cedis ha^{-1}) (log)	−17.65	8.32	−2.12	0.0398	*
Mid	(Intercept)	−923.45	575.05	−1.61	0.1160	
	Farmer age (years)	6.48	2.41	2.69	0.0104	*
	Household size	13.44	9.97	1.35	0.1852	
	Plantation size (ha)	96.28	28.84	3.34	0.0018	**
	Soil pH	142.21	83.73	1.70	0.0970	.
	Available P (ppmP)	−12.06	4.87	−2.48	0.0175	*
	Soil K (cmolc kg-1)	685.35	392.67	1.75	0.0884	.
	Fungicide (sachets ha^{-1})	−3.43	1.46	−2.35	0.0234	*
	Labour cost (Ghana cedis ha^{-1})	0.56	0.21	2.68	0.0106	*
Wet	(Intercept)	1516.88	418.49	3.63	0.0008	***
	Farmer age (years)	−14.21	6.29	−2.26	0.0293	*
	Household size	32.63	22.46	1.45	0.1539	
	Plantation age (years)	−16.20	7.60	−2.13	0.0391	*
	Plantation size (ha)	237.32	96.42	2.46	0.0181	*
	Total Nitrogen	2640.82	1774.34	1.49	0.1443	
	Pesticide (liters ha^{-1})	−42.67	30.13	−1.42	0.1643	
	Hybrid seedlings (%)	−53.02	16.24	−3.27	0.0022	**
	Training received (days year $^{-1}$)	−26.36	11.56	−2.28	0.0278	*

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

Cocoa planting density has been identified as important yield determining factor in cocoa agroforestry system (Somarriba et al., 2018). This density effect therefore explains the significant relationship of increasing cocoa planting density with decreasing yield gap in the dry zone. The significant reduction in yield gap with increasing cocoa plantation age in the wet zones could be attributed to the fact that, the plantations in the wet zone are still in their active productive years (average age of 16 years) compared to those in the mid zone (average age of 22) which are close to the current cocoa rotation age of 25 years (Ruf, 2011).

In the marginal climate suitability zone (dry) and the medium climate suitability zone (mid), it was expected that fungicide application will be low compared to the wet zone since the black pod disease (*Phytophthora palmivora* and *megakarya*) is more prevalent in the more humid zones (Anim-Kwapong and Frimpong, 2004). This was not the case as the high rate of fungicide use in the dry zone was due to high relative humidity during the rainy seasons in combination with less intensive plantation management practices including removal of diseased pods, pruning of dense cocoa and companion tree (Abdulai et al., 2018). Furthermore, fungicides were acquired through a government subsidy program (Cocoa Pests and Diseases Control Programme (CODAPEC) usually at no cost, and therefore application rates are dependent on the prevalence and not the farmer's ability to purchase the fungicide for application. Low cocoa farmer population in the dry zone therefore implied accessibility to large quantity of the supplied fungicide per farmers compared to the mid and wet zones.

Furthermore, an increase in the proportion of hybrid cocoa trees per plantation resulted in significant reduction in yield gaps in the wet zone. Hybrid cocoa trees are improved planting materials developed through intensive breeding programmes by the Cocoa Research Institute of Ghana (CRIG) (Asare et al., 2010). The hybrid cocoa planting materials are characterized by high yield of approximately 50% higher than planting materials selected by farmers on their own (Asare et al., 2010). According to Binam et al. (2008), accessibility to technical information through trainings (contacts with extension agents) is an important factor for improving technical efficiencies among cocoa farmers across West Africa. The significant relationship of decreasing yield gap with increasing the number of trainings received by farmers in the wet zone is therefore explained by the effect of training frequencies (extension contacts) on cocoa farmers' technical efficiency.

Among the soil characteristic variables, high available P in the soil significantly reduced the yield gap in the dry and mid zones. Higher P response to cocoa yield than N and K has been observed under less intensively managed and old age cocoa plantations (van Vliet and Giller, 2017). Therefore, the importance of P on yield gap in the low input management systems (e.g. the lower fertilizer applications) and older age cocoa plantations in the dry and mid zones respectively (Table 4) should be emphasized. The negative relationship between proportions of sand on yield gap has also been observed by Hoffmann et al. (2020) whereby some of the highest yielding cocoa plots were found on sandiest soils. In such sandy loam soils as observed in the dry zone, cocoa plants benefit from good drainage, aeration and develop deeper rooting depth to reduce drought stress (van Vliet and Giller, 2017).

5. Conclusion

This study highlights the large variations in smallholder farmer cocoa yield gaps and yield gap determining factors across three different climate suitability zones in West Africa. Low cocoa yield under marginal climate suitability zone could be attributed to farmers not willing to intensify their management due to both, socioeconomic (e.g. older farmers, labour availability and cost) and climatic (long dry spells and high drought risk) constraints. There is scope for yield improvement by closing the yield gap through sustainable intensification in the climatically suitable regions to compensate for the potential future cocoa production losses expected from the climatically marginal zones across the West African cocoa belt. Important factors for yield improvement to avoid potential deforestation in the climatically suitable wetter zones include accessibility to training on good agricultural practices, availability of quality planting materials (access to hybrid cocoa seeds) and cultivation of optimum plot size to ensure high input use and management efficiency. Improvement in soil fertility, especially available P through effective use of fertilizer is strongly recommended.

Considering the observed yield gap values and future climate change projections, it will be both economically and environmentally prudent to focus management intensification in the mid and wet zones as proposed by Schroth et al. (2017). In the currently marginal zones, crop diversification and future transformation from cocoa to other tree crops such as cashew need further research across the West African cocoa cultivation belt.

Data availability

All data generated or analysed during this study are readily available upon request.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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