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Influences of climate variability on cocoa health and productivity in agroforestry systems in Ghana

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ABSTRACT

The susceptibility of cocoa to harsh climatic conditions is evident in cocoa growing areas in Ghana, and climate distribution models show reduced cocoa suitability to climate change. We assessed how cocoa health and productivity were affected by varying climate conditions for 4 years in 23 cocoa farms along a gradient of low rainfall/high temperature in the north to high rainfall/low temperature in the south of Ghana's cocoa belts. Twenty cocoa trees per farm (in total 460) were observed and scored for their canopy condition, flower intensity, and damaged pods due to mirids, cocoa shield bugs, and black pod disease (BPD). Harvested pods and extracted dried cocoa beans were evaluated to ascertain yield/productivity. Insect pest damages to pods were on average 2.3 ± 0.8, 2.2 ± 1.0, and 3.0 ± 0.7 pods tree^{-1} year^{-1} in the south, middle and north, respectively. The healthiest and highest yielding trees were in the rainy south at 0.99 ± 0.02 kg dry beans tree^{-1} followed by the middle (0.84 ± 0.02 kg) and the north (0.60 ± 0.01 kg). BPD infection was highest in the south at 1.1 ± 1.1 pods tree^{-1} year^{-1}, followed by the middle (0.7 ± 0.8), and the north (0.4 ± 0.6). Within sites variability in rainfall and temperature was not found to affect yields significantly. The variability in cocoa performance and occurrence of pests and diseases observed within sites may thus be caused by farm management practices that are key to the enhancement of productivity at site level. We recommend regular pruning of cocoa and shade trees to increase aeration and prevent BPD in high rainfall areas, and an increase in shade tree components in dry regions for insect pest management in cocoa systems.

1. Introduction

Cocoa (*Theobroma cacao* L.) belongs to the family Malvaceae, and is predominantly grown in Central and South America, Asia, and Africa under varied agro-ecological and climatic conditions (Franzen and Mulder, 2007; Marita et al., 2001). The crop originates from South America and is cultivated for its seeds (beans), which are the main raw material for chocolate. Cocoa is commonly grown together with forest and/or fruit trees, and food crops for shade and economic benefits in agroforestry systems (Lachenaud et al., 2007; Thomson et al., 2020). In West Africa, the crop has two annual fruiting peaks, the light and major crop periods, based on the amount and pattern of precipitation (Almeida & Valle, 2007; Wood, 1985).

More than two thirds of global cocoa production originate in West Africa, where monthly rainfall is becoming more erratic alongside increasing temperature (Ruf, 2011; Tscharntke et al., 2011). Annual optimal rainfall for cocoa ranges between 1500 and 3000 mm (Abdulai et al., 2020), while annual maximum and minimum temperature ranges are at 30–32° C and 18–21^0 C, respectively (Wood, 1985). These two climatic factors influence tree performances (Adjaloo et al., 2012; Daymond & Hadley, 2008; Medina & Laliberte, 2017), and the occurrences of pests and disease which contribute to lower yields in cocoa (Abdulai et al., 2020; Babin et al., 2010; Mahob et al., 2015).

High rainfall correlates with high on-farm humidity which promotes

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fungal black pod disease caused by *Phytophthora palmivora* and *Phytophthora megakarya* (Akrofi et al., 2015). The disease is highly destructive with attacks on both developing and ripening cocoa pods, causing up to 60–100% production losses if the disease is not managed (Adeniyi, 2019; Akrofi, 2015; Ndoumbe-Nkeng et al., 2004; Lass, 1985). The disease peaks in May – June, which coincides with high rainfall volumes and humidity (Akrofi, 2015; Opoku et al., 2000). Management of black pod disease has been through fungicide applications, and phytosanitary practices including the removal of infected pods and pruning of both cocoa and shade trees to enhance aeration. The introduction of Cocoa Pest and Disease Control Programme (CODAPEC) since 2001 by the Ghana Cocoa Board has helped in tackling the disease situation through mass fungicide spraying of cocoa farms (Adjinah & Opoku, 2010). According to Kolavalli and Vigneri (2011), the programme among other interventions has resulted in yield increments from 210 kg ha^{-1} $year^{-1}$ to over 404 kg ha^{-1} $year^{-1}$ since its implementation.

Temperature on the other hand is known to play an important role in the incidence and severity of insect pests in cocoa. For example, the incidence of mirids (*Sahlbergella singularis* Hagl. and *Distantiella theobroma* Distant, Heteroptera: Miridae), and shield bugs (*Bathycoelia thalassina*, H.S, Hemiptera: Pentatomidae) are exacerbated under high temperatures (Babin et al., 2010; Mahob et al., 2015). Large populations of mirids are often observed between August and January (Mahob et al., 2015; Oluyole et al., 2013). Mirids affect cocoa production by piercing young and soft tissues of stems, branches, pods, and killing host cells while producing unsightly necrotic lesions that cause up to 40% yield losses (Anikwe & Otuonye, 2015). Their feeding on shoots leads to the death of terminal buds and leaves, leading to cocoa dieback in most severe instances. They are usually found in open areas of cocoa canopies where many fresh shoots (chupons) and pods are produced. The cocoa shield bugs mostly attack cocoa pods leading to early ripening of young pods, and subsequent yield reduction. So far, the two insects have been managed mainly through application of insecticides (Adu-Acheamong et al., 2015).

Shade trees have the potential to reduce high temperature conditions in cocoa-agroforestry systems (Mahob et al., 2015; Thomson et al., 2020; Vaast & Somarriba, 2014). By reducing temperatures, shade trees can reduce production costs through decreasing insect populations and reducing requirements for pesticide application. Furthermore, income derived from timber, fruits and nuts (e.g. Cola nuts, *Cola nitida*) from shade trees may enhance revenue diversification (Asare et al., 2019). Nonetheless, earlier studies by Ahenkorah et al. (1987) and Cunningham and Arnold (1962) observed higher yield under light shade or no shade conditions combined with high soil fertility supported by fertilizer and other agrochemichal inputs. Babin et al. (2010), Dumont et al. (2014), and Graefe et al. (2017) have expressed concerns about the potential role of some shade trees as alternative host to pests. Many studies have examined how cocoa productivity is influenced by shade regimes and soil conditions (Asitoakor et al., 2022; Blaser et al., 2018; Asare et al., 2016), shade tree crown architecture (Asante et al., 2021), farm management practices (Dumont et al., 2014), climate change (Dumont et al., 2014; Armengot et al., 2020) and pests and disease (Deberdt et al., 2008; Akrofi et al., 2015; Bisseleua et al., 2011; Mahob et al., 2015). Ameyaw et al. (2018), Graefe et al. (2017) and Ashley et al. (2015) documented the perceptions of farmer regarding adaptation and mitigation strategies in cocoa systems, and Black et al. (2021) and Schroth et al. (2016) modeled climate change impacts on cocoa productivity in West Africa using climate models. Mensah et al. (2022), using infrared heaters, showed that elevated temperatures may have a negative impact on cocoa physiology. However, empirical field-based data to explain the influences of climate variability on occurrence of cocoa pests and diseases and their effects on productivity from a spatio-temporal perspective are lacking in West Africa. The objective of this study was to assess how cocoa trees performed under different climatic conditions from south (cooler – humid) to North (hotter and drier) in the cocoa growing belts of Ghana. We hypothesized that cocoa tree vigour, canopy health, yield and black pod disease infections would be highest in the humid southern part, while pest occurrences and their damage to pods would be highest in the dry northern part.

2. Materials and methods

2.1. Study areas

The study was conducted for four years (February to December in 2016, and January to December in 2017, 2018 and 2019) in three cocoa growing communities: Yebrebreninyini (N 05′ 39.887, W 002′ 32.741), Anyinakrom (N 06′ 48.966, W 002′ 30.214), and Akumadan (N 07′ 24.049, W 001′ 48.432) along a climate gradient from the southern, middle, and northern sections of Ghana's cocoa belt, respectively (Fig. 1). Yebrebreninyini, Anyinakrom, and Akumadan are henceforth referred to as southern cocoa belt (SCB), middle cocoa belt (MCB), and northern cocoa belt (NCB), respectively. SCB is found in the Moist Evergreen (ME) vegetation zone in Wassa Amenfi West District of the Western region. It is characterized by mean annual temperature ranges of 24 °C–29 °C, annual rainfall of 1400–1850 mm, and relative humidity greater than 70%. The soils are mainly Acrisols, Alfisols and Oxisols (Abdulai et al., 2020; Anim-Kwapong & Frimpong, 2004). MCB is found in the Moist Semi-deciduous vegetation zone in the Asutifi South district of the Ahafo region. It is relatively moderate in temperature (25.5–30 °C), annual rainfall (1200–400 mm), average relative humidity (65–80%) and with Acrisol, Alfisol and Oxisol soil types (Abdulai et al., 2020). NCB is found within the Forest-savanna transition zone with dry semi-deciduous vegetation (Abdulai et al., 2017; Asare, 2016) with mean annual rainfall, temperature and relative humidity at 1200 mm, 27–30 °C, and less than 70%, respectively. It is located in the Offinso North district of Ashanti region with predominantly Acrisol and Alfisol soil types.

2.2. Selection and characteristics of cocoa farms

We followed recommendations from Ghana's Cocoa Purchasing Clerks (CPCs) (individuals who buy and record cocoa beans from farmers on behalf of licensed buying companies) to select 23 farmers and their respective farms (6 in NCB, 9 in MCB, and 8 in SCB) based on previous studies by Abdulai et al. (2017) and Graefe et al. (2017). We also considered similarities in farm characteristics such as percentage shade levels and density of cocoa trees, and the willingness of farmers to participate. The ages of farms (8–28 years), types and sources of planting materials (hybrid, from the Seed Production Division of the Ghana Cocoa Board (COCOBOD)), species of shade trees on farms, and agronomic/farm management practices were derived using informal interviews. Farm sizes ranging from 0.6 to 6.0 ha were determined by walking the boundaries of each farm with a GPS device (Garmin GPSMAP 64st, Garmin Ltd. USA). Cocoa tree density per farm was obtained by counts in cocoa stands along transects within farms and expressed per hectare. Total annual yields (weighed dried beans after fermentation and drying) were monitored and recorded as sum of yields during both light crop and main crop seasons.

To ensure representative sampling, imaginary diagonal lines across the farms were established from north to south and from east to west, along which 460 cocoa trees (20 from each farm at varied intervals) were randomly selected and tagged for monthly monitoring. Shade trees nearest to the selected cocoa trees were identified by a combination of local knowledge and a photo guide reference (Hawthorne & Gyakari, 2006) and their distance to cocoa trees measured. The crown areas of shade trees were determined by the drip-line horizontal ground-level crown projection method (Bellow & Nair, 2003). Total shade levels within farms were based on the number of shade trees, and the estimated proportion of transmitted light reaching cocoa canopies based on previous data (Abdulai et al., 2017).

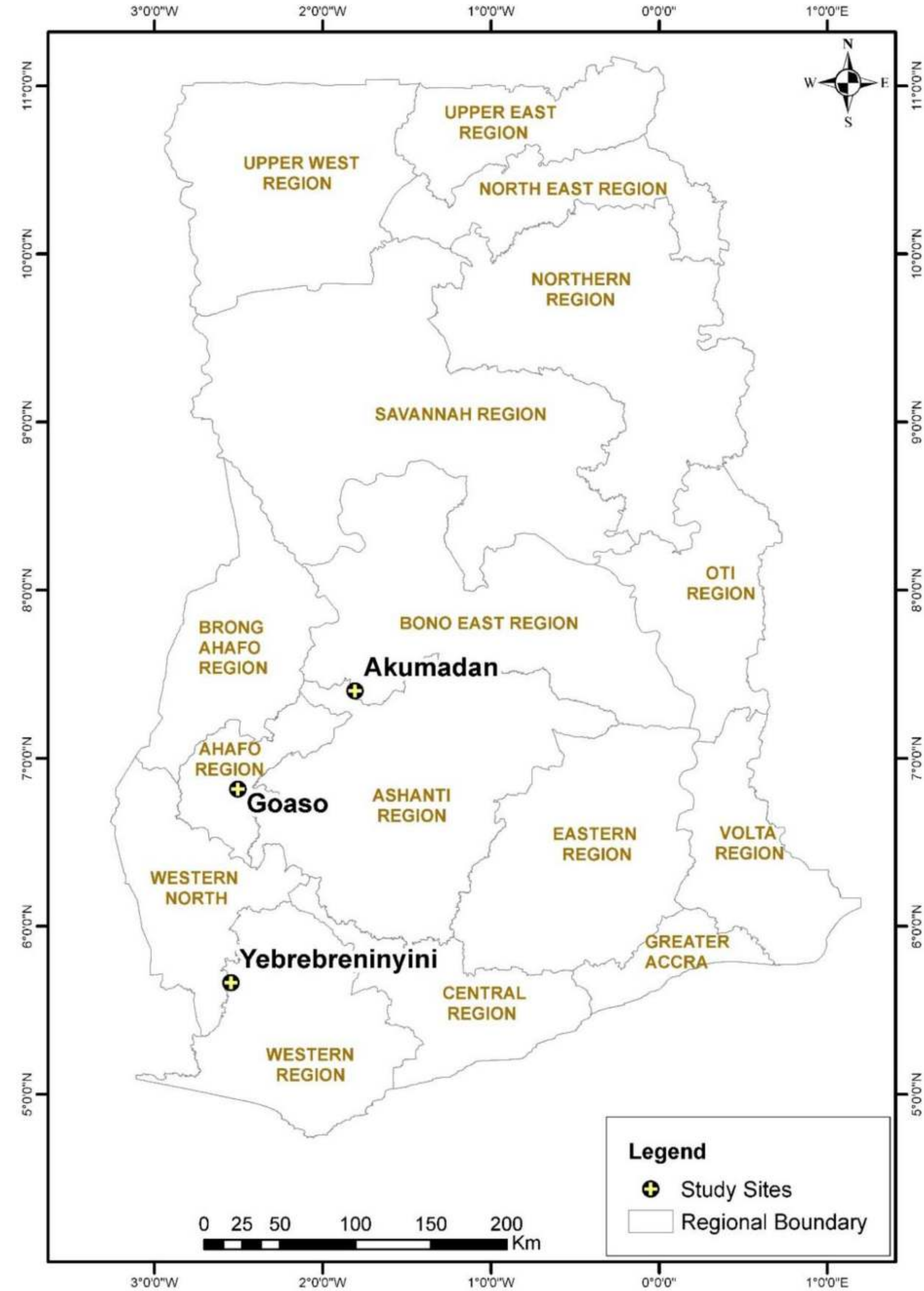

Fig. 1. Location of study communities in Ghana.

Soil chemical properties were assessed in composite soil samples, pooled from the four corners and the center of each farm using a soil auger to a depth of 0–30 cm. Measurements included acidity (pH), percentage organic matter (%OM), and concentrations of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). The tests were undertaken in the Ecological Laboratory of the University of Ghana, where soil pH was determined in a 1:1 soil to distilled water ratio using a Metrohm 691 pH meter (Mclean, 1982). Organic matter was determined by wet combustion method of Walkley and Black (1934), while the Semi-Micro Kjeldahl Digestion method was used to derive the total nitrogen content (Black, 1965). Available P was determined according to Bray and Kurtz (1945) while exchangeable K, Mg, Ca, and Na contents were estimated using flame photometry (Black, 1965) and atomic absorption spectrometry (AAS) after extraction with 1.0 M ammonium acetate.

2.3. Measurement of climatic conditions

On-farm temperatures and relative humidity were obtained from two randomly selected farms in each cocoa community during the study. Two data loggers (iButton DS1923-F5#, Hygrochron Temperature and Humidity data logger, Maxim Integrated Productions, CA, USA) were installed in radiation shielded houses at 2 m above the ground and set to read temperature and relative humidity at 30 min intervals. We downloaded data every 3 months and calculated mean monthly temperatures and relative humidity for the two farms separately. Rainfall was measured with rain-gauges (Rosenborg Exclusive Tradløs Regnmåler, Model 35980, Carrin Electronics limited, Hong Kong) installed in the open in each community, and monitored for monthly and annual rainfalls throughout the study.

2.4. Measurement of cocoa health and productivity

We used tree canopy health, flower intensity, and number of damaged young pods (cherelles) due to mirids, cocoa shield bugs, and black pod disease as cocoa health indicators. A combination of visual hand-height (2.5 m) assessment methods (Collingwood, 1971), and ranking on a 0–4 scale were adopted for canopy health, and flower intensity (Table 1). Canopy assessment was based on the presence and coloration of leaves and vegetative flushes, while flower intensity was based on how sparsely or clustered flowers occurred. Number of wilted cherelles, damaged cherelles/matured pods due to mirids, cocoa shield bugs, and black pod diseases were counted and ranked for damage severity (Table 1).

Table 1
Descriptions of cocoa health indicator categorization.

Rank	Description of criteria Flowering intensity	Canopy health	Severity of damage pods/ cherelles
0	No flowers	Dead branches with virtually no leaves or very few leaves, with almost no canopy.	No damage (no cherelle /matured pod)
1	Low flowering	Poorly healthy canopy. Very few leaves (pale and yellowish coloration) and with numerous dead branches.	Few damages (between 1 and 3 cherelles /pods)
2	Medium flowering	Medium healthy canopy. Few branches with leaves and few new leaf flushes. Many pale and yellowish leaves.	Mild damages (between 4 and 6 cherelles /pods)
3	High flowering	Healthy canopy. Less dense canopy with many branches and many leaves and flushes.	Severely damaged (between 7 and 9 cherelles /pods)
4	Very high flowering	Very healthy. Very dense canopy with lots of branches, dense foliage and with leave flushes.	Highly severe damages (10 and above, cherelles /pods)

Mirids and cocoa shield bugs damages were distinguished by pod wounds (vivid circular or elliptical dark feeding lesions) symptoms after mirid feeding (Awudzi et al., 2017), and by yellowing at the points of attack and distortion of cherelles /pods for cocoa shield bugs. Black pod disease was identified by portions of rottenness, and black coloration patches on part or whole pod surfaces.

As productivity indicators, we used three parameters: (i) total number of cherelles and matured pods, (ii) total number of harvested pods, and (iii) dry weight of cocoa beans from harvested pods. Monthly visual inspections and counts of cherelles, matured and harvested pods were undertaken on the selected cocoa tree trunks and main branches up to 2.5 m. Extracted cocoa beans from harvested pods were pooled per farm to obtained larger volumes for heap fermentation. The fermentation was undertaken for 5–7 days. Beans were open air dried to constant weight, and then weighed using an electronic scale.

3. Analysis of data

Following entry, data were ordered in Microsoft Excel, and exported to R version 3.6.3 (R Core Team, 2020) for analysis. Differences in farm characteristics and management were analyzed using one-way analysis of variance (ANOVA) with cocoa community (CC) as the single factor. Data relating to cocoa health and yield were analyzed according to a repeated measurements mixed model, using cocoa communities (CC), distances between cocoa tree and nearest shade tree (Distance in m), and crown area of nearest shade tree (CA in m^2) as fixed effects. We included individual farms, sampling month and year as random effects, and interaction terms of communities and the distance between shade trees and cocoa trees, shade tree crown area, and year as expressed in the full model below. Y represents both continuous and ranked dependent variables.

$$Y = \alpha(CC) + \beta(Distance) + \gamma(CA) + \lambda(CC : Distance) + \mu(CC : CA) + \delta(CC : Year) + A(Farm) + B(Month) + C(Year)$$

Continuous data (relating to yield and damaged pods due to mirids, shield bugs and black pod diseases) were analyzed using linear mixed effect models through the “lme4” package in R (Bates et al., 2015). Data on cherelles, matured and harvested pods were square root transformed when visual inspection showed deviation from normal distributions based on normality and homogeneity tests by plots of residuals against fitted values in normal Q-Q plots. Because dry beans of cocoa were obtained by bulking at farm levels, and within very few months of the year, we analyzed dry beans with community and year as factors. Ranked variables including canopy health and flower intensity, were analyzed by ordinal regression models from the “Ordinal-package” in R (Christensen, 2019).

The best fitted models were selected after series of backward model reduction procedures using the Akaike Information Criterium (AIC). For tests of significance, we used likelihood ratio tests to obtain p-values, followed by post hoc Tukey tests via the “emmeans” package in R (Lenth, 2020) to ascertain sources of variation where tests showed significant differences. We partitioned the variance explained by the fixed factors (Marginal ($R^2_{(m)}$)) and the variance explained by both the fixed and random factors (Conditional ($R^2_{(c)}$)) in the models from the “vegan” package (Oksanen et al., 2019) and “MuMIn” package (Barton 2022) in R. We further calculated the proportional changes in variance (PCV) of the random effects of each of the models, and then explored the relationship between climatic conditions (rainfall and temperature) and cocoa productivity (dry weight of cocoa beans) by regression analysis for the three communities.

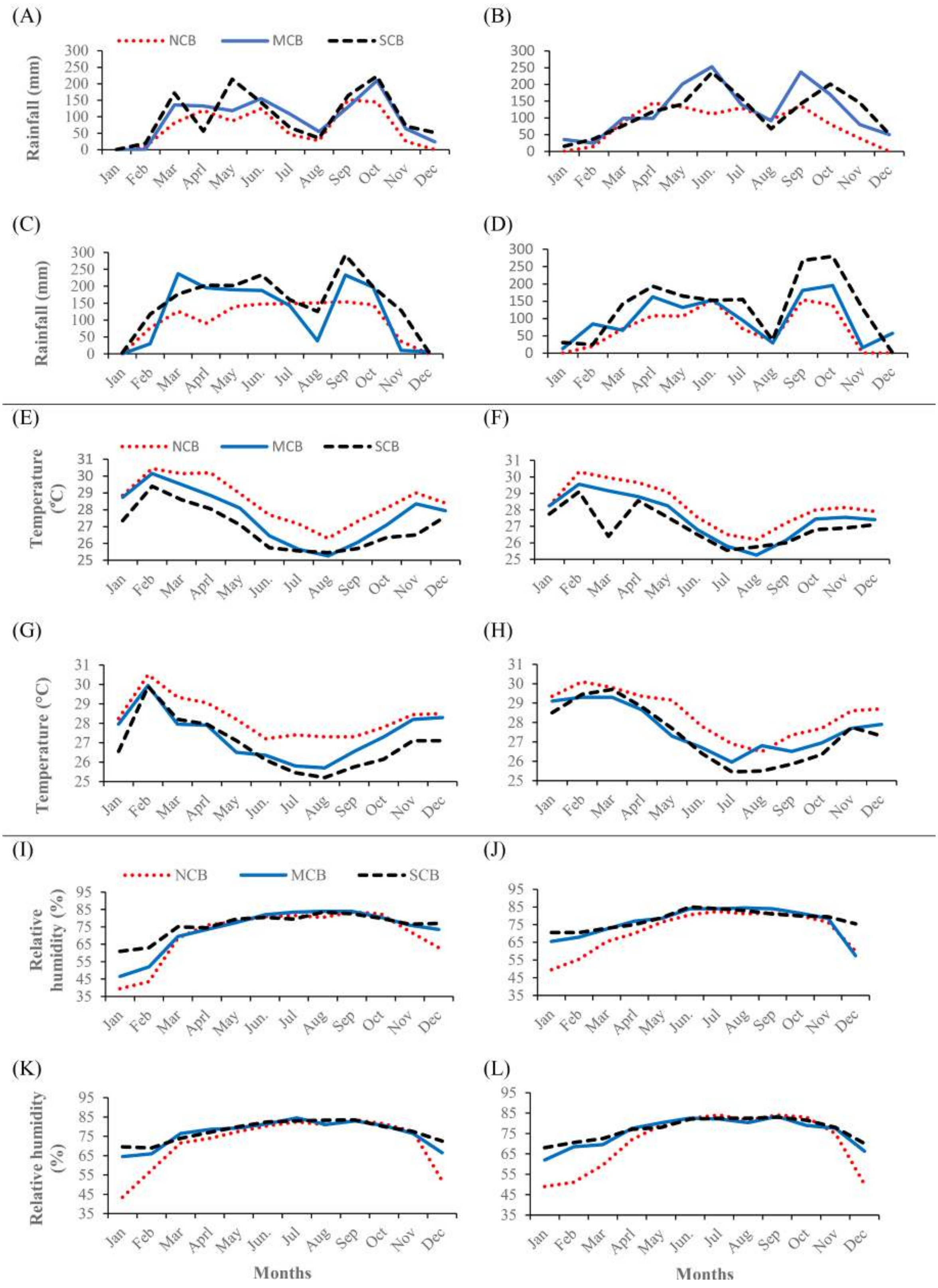

Fig. 2. Mean monthly and annual rainfall, temperature, and relative humidity distributions in 2016 (A, E, I); 2017 (B, F, J); 2018 (C, G, K); and 2019 (D, H, L) across the three study communities; NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt.

4. Results

4.1. Farm characteristics and climatic conditions across communities

Mean monthly and annual rainfall, temperature, and relative humidity (Fig. 2) varied across the three communities and years. Annual rainfall was higher at 1507 ± 134 mm (±se) and 1231 ± 153 mm (±se) in SCB and MCB, respectively, compared with 966 ± 90 mm (±se) in NCB. Relative humidity was also higher in SCB and MCB compared to NCB, while higher monthly temperatures were recorded in NCB compared to SCB and MCB (Fig. 2). Unlike rainfall in which the highest volumes were recorded in 2018 and least in 2016, variations in temperature and relative humidity were not consistent across the cocoa areas in the four years (Fig. 2).

Cocoa tree density, percentage shade levels, and the average distance of cocoa trees from the nearest shade tree were almost similar across the three cocoa communities (Table 2). Crown areas of the shade trees were significantly different with highest and lowest measurements in MCB and NCB, respectively (Table 2).

Persea americana was the most common shade tree species, found in all three communities. In NCB, frequently encountered species included *Morinda lucida* and *Holarrhena floribunda*, whereas at MCB, a range of species including *Terminalia superba, Milicia excelsa* and *Bombax buonopozense* were found. Three species, *Terminalia superba, Terminalia ivorensis*, and *Alstonia boonei* were the most encountered shade trees in SCB (Table 3).

Pesticide application in terms of dosage and frequency, and foliar fertilizer applications were not significantly different across the study communities (Table 2). The application of fungicides for black pod disease management was highest in SCB with more than twice the usage in MCB and NCB. The quantity and frequency of soil fertilizer application was highest in MCB and about three times the application in NCB and SCB (Table 2).

Table 2
Comparison of farm characteristics and management (Mean ± SE) in the north, middle and south cocoa communities (na = non-available data; * = significant difference; different letters indicate significant difference at $p < 0.05$ across communities; NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt).

Parameters	Cocoa community			*P* - value
	NCB (*N* = 6)	MCB (*N* = 9)	SCB (*N* = 8)	
Cocoa and shade characteristics				
Cocoa trees per ha	2117 ± 195	1756 ± 158	1812 ± 168	0.291
% Shade level/cover	18.2 ± 4.8	18.8 ± 4.1	17.6 ± 3.8	0.185
Shade tree distance to sampled cocoa (m)	9.5 ± 1.6	11.7 ± 1.1	11.2 ± 1.7	0.475
Shade tree crown area (x 10^2 m^2)	8.0 ± 1.0[a]	16.3 ± 1.9[b]	10.3 ± 1.9[a]	0.005*
Management practices				
Weeding frequency ($year^{-1}$)	3 ± 1[b]	6 ± 1[a]	7 ± 1[a]	<0.001*
Pesticides usage (Litre ha^{-1})	5.6 ± 2.7	9.5 ± 2.0	6.6 ± 0.9	0.272
Pesticide application frequency ($year^{-1}$)	2 ± 1[a]	6 ± 1[b]	3 ± 1[a]	<0.001*
Fungicide (sachets ha^{-1})	3.1 ± 1.2[a]	3.4 ± 1.3[a]	7.4 ± 2.5[b]	0.004*
Fungicide application frequency ($year^{-1}$)	1.5 ± 0.6	0.6 ± 0.2	1.0 ± 0.2	0.117
Herbicide application frequency ($year^{-1}$)	na	2.2 ± 0.4	0.2 ± 0.2	-
Foliar fertilizer application (Litres ha^{-1})	2.1 ± 1.3	0.8 ± 0.4	1.6 ± 0.3	0.379
Foliar fertilizer application frequency ($year^{-1}$)	0.3 ± 0.2	0.7 ± 0.3	1.3 ± 0.2	0.056
Soil fertilizer application (kg ha^{-1})	113.5 ± 64.1[a]	337.3 ± 60.9[b]	134.1 ± 33.1[a]	0.007*
Soil fertilizer application frequency ($year^{-1}$)	0.3 ± 0.2[a]	0.9 ± 0.1[b]	0.8 ± 0.2[b]	0.046*

Aside percentage N that was marginally different, all soil properties tested varied significantly across the three communities with MCB recording the highest percentages and/or concentration in almost all categories (Table 4).

4.2. Cocoa health along climate gradient

Cocoa tree canopy health was significantly different for the various years in the three cocoa communities as indicated by the interaction between cocoa community and years (Fig. 3; Table 5). The healthiest canopy trees were observed in SCB followed by MCB and NCB (Fig. 3). Cocoa trees in SCB were healthier in 2016 and 2017 than in 2018 and 2019 (mean scores ranging from 3.2 to 3.9). MCB had moderately healthy cocoa trees with a mean score of 2.8 while about 51% of cocoa trees in NCB were less healthy (defined as scores below 3) throughout the study (Fig. 3). Flower intensity also varied significantly between years and across communities with highest flowering in SCB, followed by MCB and NCB (Fig. 3; Table 5).

There were significant negative effects of the cocoa tree distance from the shade tree on cocoa canopy health, and positive effects of the crown area of shade trees on the cocoa tree canopy health (Table 5). The intensity of flowering was positively influenced by cocoa tree distance from shade trees and the crown area of the shade trees (Table 5). This indicated that cocoa canopy health decreased with increasing distance from shade trees but increased with increasing shade tree crown area, while the intensity of flowering of the cocoa trees increased with increasing distance from the shade tree, and with the size of the shade tree canopy. Cocoa trees further away from shade trees and in the vicinity of shade trees with larger crown areas had higher flowering intensity.

Further, a significant interaction existed between communities and years with respect to cocoa tree canopy health and flower intensity (Table 5). This shows that the performance of cocoa trees in term of the health of canopies and the intensity of flowering varied between the years in the three sites. The cocoa canopies were healthiest in 2017 in SCB and less healthy in 2018 in NCB, while the flower intensity was highest in SCB and least in MCB in 2016. More than 80% of the proportion of the variability observed with regards to canopy health and flower intensity was due to the differences between farms not accounted for by the communities as indicated by the PCV in Table 6.

Occurrence of wilted cherelles, and damaged cherelles due to mirids, shield bugs and black pod disease varied significantly with years and across the communities (Table 5). The mean number of wilted cherelles ranged from 5.8 ± 1.2 cherelles $tree^{-1}$ in MCB, over 8.4 ± 1.2 in NCB, to 19.9 ± 1.2 in SCB. Number of mirid infested cherelles were highest in NCB (2.8 ± 0.1), followed by MCB (1.9 ± 0.1) and least in SCB (2.0 ± 0.1), while number of shield bug damages were highest in MCB (0.3 ± 0.9) and SCB (0.3 ± 0.7) and least in NCB (0.2 ± 0.6). Mean black pod disease infestation on cherelles was at 0.6 ± 1.1 cherelles, 0.2 ± 0.8 cherelles and 0.1 ± 0.6 cherelles in SCB, MCB and NCB respectively. The number of matured pods infested by black pod diseases were similar at 0.52 ± 0.02 pods $tree^{-1}$ in SCB, 0.53 ± 0.04 pods $tree^{-1}$ in MCB, and 0.31 ± 0.02 pods in NCB. Similar black pod infestation rates were observed across the communities, but with significant interactions between community and the distance between shade trees and cocoa trees (Table 5). The infestation was however found to decrease with increasing distance of cocoa trees to shade trees but increased with increasing shade tree crown area (Table 5). The slopes of the interactions indicated a decreasing effect of distance in NCB (Estimate = -0.0094 ± 0.0351, t – value = -0.268) and SCB (Estimate = -0.0574 ± 0.0298, t-value = 1.928), while there was almost no effect at MCB (Estimate = 0.1416 ± 0.0476, t-value = 2.974). Most of the variations observed in cherelle wilt and damaged cherelles/pods due to mirids, shield bugs and black pod diseases may be attributable to differences between farms, months, and years of assessment rather than the influences of the fixed effects (the distance between shade trees and cocoa

Table 3
Number of shade tree species recorded near sampled cocoa trees (NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt; D = deciduous, SD = Semi-deciduous, E=Evergreen).

Rank	Species name	Leaf habit	Family	NCB	MCB	SCB	Total
1	*Persea americana*	E	Lauraceae	21	10	10	41
2	*Terminalia superba*	D	Combretaceae	2	16	22	40
3	*Morinda lucida*	E	Rubiaceae	12	23	0	35
4	*Milicia excelsa*	D	Moraceae	3	16	9	28
5	*Bombax buonopozense*	D	Bombacaceae	4	16	0	20
6	*Terminalia ivorensis*	D	Combretaceae	2	1	16	19
7	*Citrus sinensis*	E	Rutaceae	9	7	1	17
8	*Alstonia boonei*	D	Apocynaceae	0	3	12	15
9	*Musanga cecropioides*	E	Cecropiaceae	0	9	6	15
10	*Holarrhena floribunda*	D	Apocynaceae	14	0	0	14
11	*Amphimas pterocarpoides*	D	Leguminosae	0	13	0	13
12	*Trilepisium madagascariense*	E	Moraceae	1	11	0	12
13	*Antiaris toxicaria*	D	Moraceae	7	3	1	11
14	*Khaya ivorensis*	SD	Meliaceae	1	2	8	11
15	*Pentaclethra macrophylla*	E	Fabaceae	0	0	9	9

Table 4
Variability of soil properties (Mean ± SE) in the north, middle and south cocoa communities.(Different letters indicate significant difference at $p < 0.05$ across communities, NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt).

Parameters	Cocoa community			*p* - value
	NCB ($N = 6$)	MCB ($N = 9$)	SCB ($N = 8$)	
pH	7.0 ± 0.2^{a}	6.9 ± 0.2^{a}	5.4 ± 0.1^{b}	< 0.001
% N	0.13 ± 0.01^{a}	0.13 ± 0.02^{a}	0.15 ± 0.01^{b}	0.053
% OM	2.14 ± 0.30	2.59 ± 0.33	2.98 ± 0.18	0.028
Ca (cmol kg^{-1})	7.08 ± 0.92^{a}	14.86 ± 4.27^{b}	3.32 ± 0.63^{a}	0.007
Mg (cmol kg^{-1})	1.91 ± 0.27^{a}	4.30 ± 1.02^{b}	1.11 ± 0.19^{ab}	0.006
K (cmol kg^{-1})	0.18 ± 0.02^{a}	0.29 ± 0.04^{b}	0.23 ± 0.02^{ab}	0.032
Na (cmol kg^{-1})	0.08 ± 0.01^{a}	0.17 ± 0.02^{b}	0.13 ± 0.01^{ab}	0.002
P (cmol kg^{-1})	9.25 ± 1.02^{a}	19.63 ± 5.24^{b}	7.77 ± 0.94^{a}	0.020

trees and the crown area of the shade trees) (Table 6).

4.3. Cocoa productivity along climatic gradient

The highest cocoa productivity was observed in SCB followed by MCB and NCB. Across all years, the dry weight of cocoa beans extracted from harvested pods ranged from 0.60 ± 0.01 kg tree^{-1} in NCB to over 0.84 ± 0.02 kg tree^{-1} in MCB and 0.99 ± 0.02 kg tree^{-1} in SCB with different years of high and low production (Fig. 4). Average annual weight of dry cocoa beans at farm level ranged from 315 ± 80 kg ha^{-1} in NCB, 748 ± 113 kg ha^{-1} in MCB and 833 ± 98 kg ha^{-1} in SCB. For all variables relating to yield, we observed significant positive interactions between cocoa community and years (Table 7) with different years recording the highest and lowest production of cherelles, matured pods, and harvested cocoa pods across the communities (Fig. 4). At NCB, the highest productivity was seen in 2019, and the lowest in 2016, while MCB had the largest production in 2018 and the least in 2016. In SCB, the highest productivity was seen in 2016 and 2018 and the lowest in 2017.

The production of cherelles were significantly affected by interactions between cocoa tree distance from shade trees and the community, indicating that distance from the shade tree had different effects in the three communities (Table 7). The slopes of the interactions showed an increasing effect of distance on cherelle production in MCB (Estimate = 7.8 ± 1.3 m^{-1}) and SCB (Estimate = 7.2 ± 1.0 m^{-1}) but a neutral effect in NCB (Estimate = -0.5 ± 1.1 m^{-1}). Likewise, the production of matured pods was significantly affected by interactions between cocoa community and the size of shade tree crowns. The crown area of shade trees showed an increasing effect on matured pods in MCB (Estimate = 0.0014 ± 0.0003 m^{-2}) and NCB (Estimate = 0.0007 ± 0.0011 m^{-2}) but decreasing effects in SCB (Estimate = -0.0013 ± 0.0006 m^{-2}). A similar interaction was seen for the number of harvested pods, with the crown area of shade trees having increasing effects on harvested pods in MCB (Estimate = 0.0006 ± 0.0002 m^{-2}) and NCB (Estimate = 0.0010 ± 0.0007 m^{-2}) but decreasing effects in SCB (Estimate = -0.0009 ± 0.0003 m^{-2}).

The major part of the variation in the cherelles and matured/harvested pod were linked with differences between farms and years (Table 6). Plots of yields as a function of rainfall and temperatures showed that, SCB with higher annual rainfall and lower temperature also had higher production of dry beans of cocoa compared with MCB and NCB which had relatively lower rainfall and higher temperatures (Fig. 5). Within the sites however, productivity appeared to be unrelated to the analyzed weather parameters.

5. Discussions

5.1. Climatic difference and influences on farm characteristics

Climatic conditions in terms of rainfall, temperature and relative humidity are generally different across geographical areas. The Western region of Ghana where part of this study was undertaken is associated with the highest rainfall while the northern regions are associated with low rainfall and high temperatures. The variabilities observed in rainfall, temperature, and relative humidity from the south to north of Ghana's cocoa belt was expected and consistent with observations of Abdulai et al. (2017) and Graefe et al. (2017). It also confirms the climatic differences in agroecological zones from the south to the north of Ghana (Asare-Nuamah & Botchway, 2019). SCB found in the south-west with rainforest vegetation appears to be closer to optimal conditions for cocoa cultivation compared to NCB in the forest transition zone where the combination of limited rainfall and high temperatures limits options for cocoa cultivation. This is consistent with the climate suitability map generated for Ghana by Bunn et al. (2019).

The significant differences observed in cocoa tree canopy health across the communities may be attributed to the combined effects of climate factors (rainfall and temperature) (Abdulai et al., 2020; Graefe et al., 2017), soil fertility, and agronomic practices (Asante et al., 2021) including pruning, pests, and disease management (Table 2).

Crop reproductive growth starting with inflorescence or flowering are important processes toward fruit formation. In cocoa for instance, the magnitude of flowering is essential for pollination and pod production. Flowering is often triggered by warm conditions with optimal thresholds at about 27 °C in cocoa (Lahive et al., 2019; Sale, 1969). NCB being the warmest belt was expected to bear the most flowers. None the less, flowering was higher in SCB and MCB compared to NCB. This is possibly connected to moisture constraints on flowering rather than temperature in this study as recorded temperatures were within

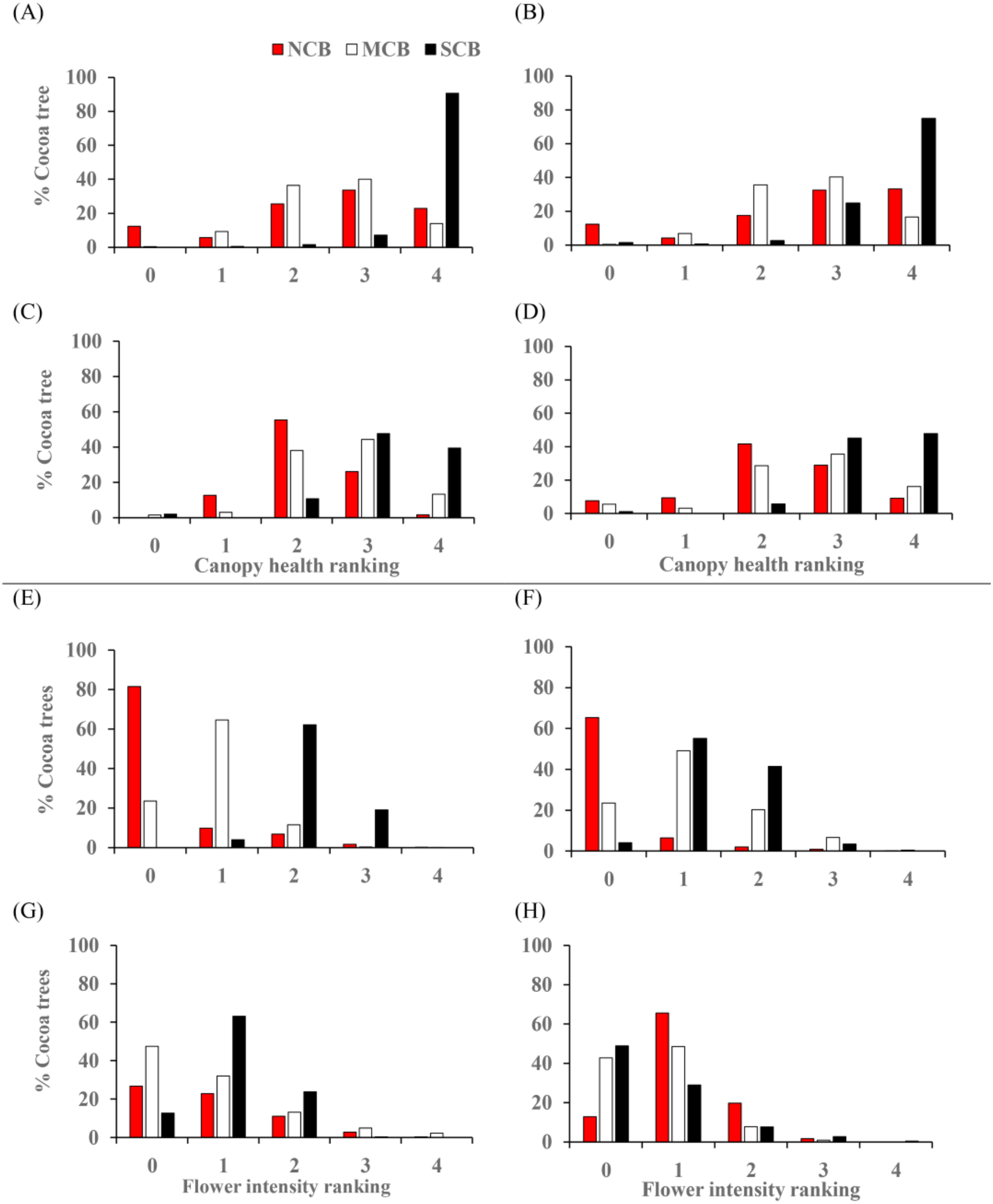

Fig. 3. Percentage annual distribution of cocoa canopy health and flower intensity scores in 2016 (A, E), 2017 (B, F); 2018 (C, G) and 2019 (D, H) across the three cocoa communities (0 = almost no canopy/no flower; 1 = poor canopy/low flowering; 2 = medium health canopy/medium flowering; 3 = healthy canopy/high flowering; 4 = very healthy canopy/very high flowering); NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt.

Table 5
Statistical tests of significance of cocoa health indicators with selected systematic effects and parameter estimates, and significant interaction terms from Linear mixed-effects models.
(* = significant difference at $p < 0.05$, ':' = interaction term between effects, CC = Cocoa communities; CA = Crown area of nearest shade tree; DF = Degree of freedom; NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt).

Cocoa health Indicator	Effects	DF	Estimate	LR-statistics	p - value
Canopy Health	CC	2		42.66	<0.001*
	Distance	1	-0.00775	11.84	0.001*
	CA	1	0.00031	4.76	0.029*
	CC : Year	9		877.03	<0.001*
Flower Intensity	CC	2		54.68	<0.001*
	Distance	1	0.00420	4.11	0.043*
	CA	1	0.00031	5.09	0.024*
	CC : Distance	2		5	0.082
	CC : Year	9		1876.45	<0.001*
Wilted Cherelles	CC	2		75.93	<0.001*
	Distance	1	-0.00058	0.16	0.689
	CA	1	0.00005	0.32	0.571
	CC:Year	9		1081.51	<0.001*
Capsid Cherelle	CC	2		15.18	0.001*
	Distance	1	-0.00045	0.16	0.691
	CA	1	0.00002	0.05	0.824
	CC:Year	9		387.41	<0.001*
Shield bugs cherelle	CC	2		2.42	0.299
	Distance	1	-0.00177	3.31	0.069
	CA	1	0.00008	1.68	0.195
	CC:Year	9		710.56	<0.001*
Black pod cherelle	CC	2		43.07	<0.001*
	Distance	1	-0.00320	8.94	0.003*
	CA	1	0.00017	5.69	0.017*
	CC:Year	9		228.87	<0.001*
	CC:CA	2		16.45	<0.001*
Black pod pods	CC	2		4.07	0.131
	Distance	1	-0.00083	1.25	0.264
	CA	1	0.00003	0.47	0.492
	CC : Distance	2		19.1	<0.001*
	CC : Year	9		204.17	<0.001*

Table 6
Results of the Linear mixed-effect models showing the proportional change in variance (PCV) and the variances explained by fixed factors ($R^2_{(m)}$) and both fixed and random factors ($R^2_{(c)}$) for the cocoa health and productivity indicators.

	PCV of Random Effects (%)			$R^2_{(m)}$(%)	$R^2_{(c)}$(%)
Cocoa Health Indicators	Farm	Month	Year		
Canopy health	85.67	-2.54	8.69	-	-
Flower intensity	91.77	10.28	-3.40	-	-
Cherelle Wilt	96.81	-2.31	-4.71	24.23	29.16
Capsid cherelle	50.77	2.72	-0.17	0.50	8.48
Shield Bugs	-2.70	3.94	-6.32	0.21	6.02
Black pod cherelle	86.57	-2.36	-2.90	3.82	13.65
Black pod pods	10.92	-3.86	0.51	0.24	4.77
Cocoa Productivity Indicators					
Total cherelles	83.74	6.21	-3.22	23.06	32.94
Matured pods	65.53	-4.11	-0.56	4.79	17.59
Harvested pods	32.58	-1.62	4.90	0.89	11.97
Dried beans	91.53	-	0.00	74.62	86.75

optimum ranges for cocoa cultivation at 26–31 °C in NCB, and 25–30 °C in both MCB and SCB.

The observed differences in cocoa health with communities and years where relatively wetter years and communities (Fig. 2) corresponded with high canopy health scores and high numbers of inflorescences (Fig. 3) emphasize the significance of climate variability in cocoa development. As with other tree crop species e.g *Mangifera indica* L. (mango) (Makhmale et al., 2016), cocoa requires moisture for nutrient uptake and other physiological processes (e.g photosynthesis) that impact canopy health and flowering. Moisture conditions are essential in the initiation and formation of flowers that further develop into fruits (Carr & Lockwood, 2011). In Ghana where agricultural production is mainly rain-fed, the importance of moisture through rainfall cannot be overemphasized. This was revealed through the significant positive relationship between rainfall and the health indicators, where SCB had higher rainfall than MCB and NCB, and also had cocoa trees with healthier canopies as well as higher numbers of inflorescences (Figs. 2 and 3). The observation further confirmed our hypothesis that, cocoa tree vigour and canopy health would be highest in the humid southern part of Ghana's cocoa belt compared to other regions of cocoa production.

The northern cocoa belt with current reduced rainfall may become more suitable for cocoa production with increased rainfall while the southern belt with already high rainfall may be impacted negatively from excessive rainfall leading to flooding. In this study, the within sites variations in rainfall appeared to have no simple relationship with yields, suggesting that other factors such as management practices may also be involved. In the case of temperature, the significantly positive relationship with insect pest infestations confirms the observations of Awudzi et al. (2020), Babin et al. (2010) and Mahob et al. (2015) that insect pests aggregate in open and warmer areas of cocoa farms. The two phenomena reiterate the foreseen negative impacts of climate change on cocoa production especially in West Africa (Läderach, 2011).

The observed decreases in canopy health with increasing distance from shade trees show the important role shade or shade trees play in enhancing cocoa health (Asare et al., 2019). The forest understory plant (cocoa) usually derives shielding from the direct sun radiation, thereby reducing temperatures and transpiration rates. The increases in flower intensity with increasing distance from shade trees (Table 5) revealed the likelihood of competition between the cocoa and shade trees for light which is essential for the inflorescence in plants. Shade trees on cocoa farms may compete for light, nutrients and water that impact cocoa health (van Vliet et al., 2015). On the contrary, the positive relationship observed between shade tree crown area and cocoa canopy health, and flower intensity in the study (Table 5) suggest that shade tree species and architecture may impact on cocoa-agroforestry systems (Asare, 2005; Asare & David, 2011; Sauvadet et al., 2020; Asitoakor et al., 2022).

The wilting of cherelles after fruiting has been associated with water stress, higher temperatures, and nutrient deficiencies (Daymond & Hadley, 2008), which may explain the high occurrences of cherelle wilt in NCB compared to SCB and MCB. The observation confirms previous findings that low precipitation in the northern part of the cocoa belt of Ghana leads to high levels of wilting of pods in cocoa (Abdulai et al. 2017). Usually, insect pest infestations in cocoa are predominant under dry environmental conditions (Awudzi et al., 2020; Babin et al., 2010; Mahob et al., 2015) while black pod fungal disease is prevalent under wet conditions in cocoa (Akrofi et al., 2015). The two phenomena where mirid and shield bugs effects were higher in drier communities compared to wet areas, and black pod disease occurrence corresponding with wetter areas in the south confirmed our hypothesis and show the significant effects climate variability have on cocoa pest and disease situations. The observation calls for concern in areas prone to drought, now and in the future (Läderach, 2011).

The impact of shade tree distance and shade tree crown area on black pod disease especially with cherelle infestation highlights the significance of shade management in cocoa-agroforestry systems (Akrofi et al., 2015; Asare et al., 2016). For example, the density of shade trees and their proximity to cocoa trees are critical in regulating on-farm relative humidity linked with black pod disease infestation. Management practices such as the pruning of both shade trees and cocoa trees promotes aeration that reduces humidity within cocoa farms and enhance the control of insect pests and diseases in cocoa. Contrary to our expectations, a negative relationship was observed between mirid infestation and the distance from shade trees, and the crown area of shade trees. The

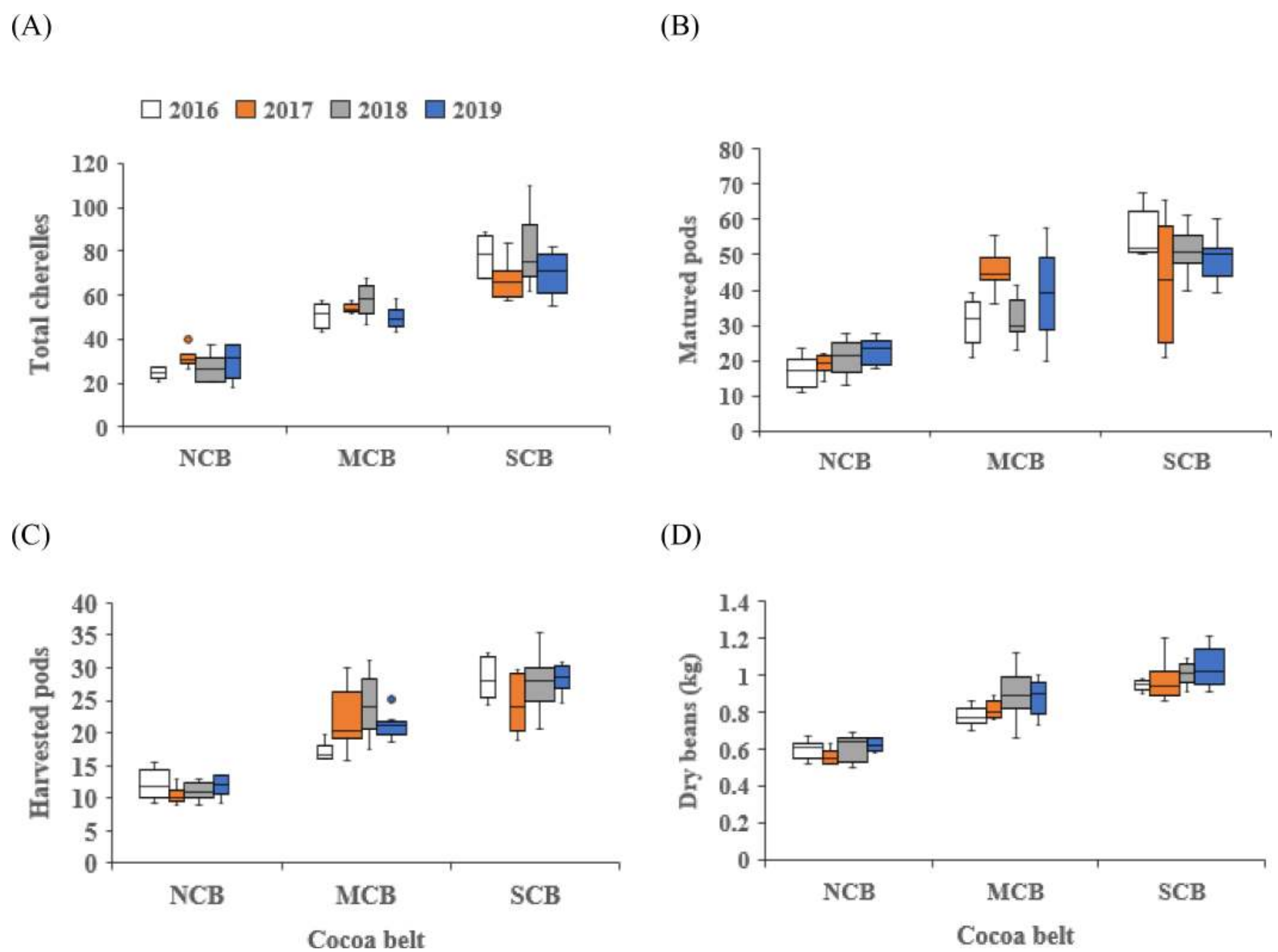

Fig. 4. Box plots illustrating the mean annual production of (A) cherelles, (B) mature pods, (C) harvested pods, and (D) dry beans per cocoa tree across the three cocoa communities (NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt).

Table 7
Statistical tests of significance of cocoa productivity indicators with selected systematic effects and parameter estimates, and significant interaction terms from the Linear mixed-effects models. (* = significant difference at $p < 0.05$, ':' = interaction term between effects; CC = Cocoa communities; CA = Crown area of nearest shade tree; DF = Degree of freedom).

Productivity indicators	Effects	DF	Estimate	LR-statistics	*p* - value
Total Cherelle	CC	2		42.27	<0.001*
	Distance	1	0.01653	3.95	0.047*
	CA	1	0.00064	1.36	0.243
	CC : Distance	2		19.99	<0.001*
	CC : Year	9		323.96	<0.001*
Matured pods	CC	2		24.64	<0.001*
	Distance	1	0.00100	0.06	0.799
	CA	1	0.00102	14.70	<0.001*
	CC : CA	2		7.33	0.026*
	CC : Year	9		799.41	<0.001*
Harvested pods	CC	2		10.38	0.006*
	Distance	1	0.00167	0.55	0.459
	CA	1	0.00018	1.23	0.267
	CC : CA	2		8.10	0.017*
	CC : Year	3		441.74	<0.001*
Dry beans	CC	2		49.97	<0.001*
	CC : Year	3		19.57	0.021*

observations however suggest the complexity of insect population dynamics and their damage characteristics in agricultural productivity. An interplay of multiple factors may influence mirid distributions and their impact in cocoa systems. The distribution of insect pests may not only be due to shade and climatic conditions as considered in this study, but also to other factors including the availability of food, predation, mortality and agronomic practices.

5.2. Climatic conditions and cocoa productivity

The significant differences observed in total cherelles, matured pods, harvested pods, and the dry beans of cocoa across the communities were expected and consistent with studies by Abdulai (2017) and Abdulai et al. (2020). Total mean yield (harvested pods) in SCB and MCB (27 pods per cocoa tree) was similar to the 30.3 and 28.7 pods per cocoa tree per year reported respectively in "cocoa – orange" and "cocoa – avocado" agroforestry by Koko et al. (2013) in Côte d'Ivoire. It further compares with the 30 pods per tree and 27 pods per tree obtained by Osei-Bonsu et al. (2002) in other cocoa – agroforestry systems in Ghana. The observed differences in the productivity parameters may be due to various factors including the variabilities in climatic and agronomic practices (Asante et al., 2021). For instance, fertilizer and pesticide applications were almost double in MCB compared to SCB, resulting in phosphorus concentrations (a major determinant in pod formation) being more than two times higher in MCB compared to SCB and NCB.

Relatively lower weight of dry beans were observed in this study at 0.99 ± 0.02kg (SCB), 0.84 ± 0.02kg (MCB) and 0.60 ± 0.01kg (NCB)

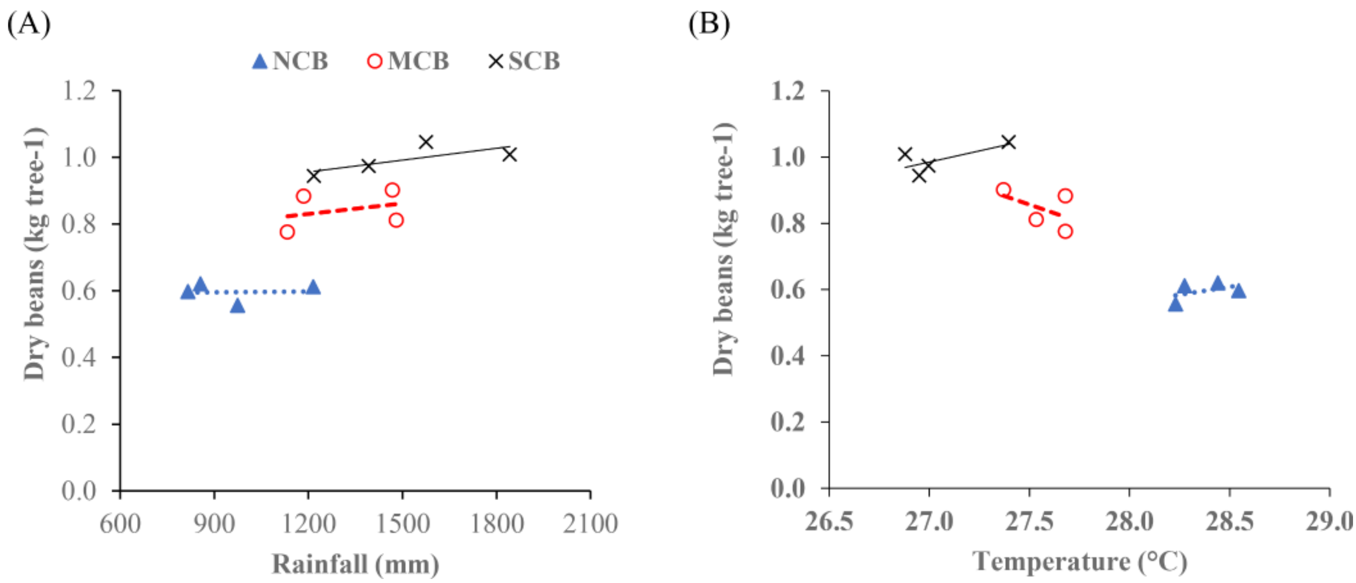

Fig. 5. Relationship between the dry weight of cocoa beans and (A) annual total rainfall, and (B) mean annual temperatures (NCB = Northern cocoa belt; MCB = Middle cocoa belt; SCB = Southern cocoa belt).

per cocoa tree compared with 1.21kg^{-1} per cocoa tree in "cocoa – orange" and 1.13 kg^{-1} per cocoa tree in "cocoa – avocado" systems in Cote d'Ivoire (Koko et al., 2013). The difference in weight between the two studies may be attributed to differences in age and management of cocoa trees, as 5-year-old cocoa farms with juvenal shade trees were used by Koko et al. (2013) against more established cocoa trees and somewhat depleted soils. This is highlighted by van Vliet et al. (2015) who indicated diminishing yield with decreased soil nutrition and age of farm.

Previous studies have attributed yield variability in cocoa to variation in genotype, soil nutrition, farm age and management effects (Abdul-Karimu et al., 2006; Abdulai et al., 2020; Wibaux et al., 2017). This study adds an important dimension by demonstrating that shade trees affect cocoa yields differently at different sites (Table 6). For instance, the significant positive effects of shade tree crown area on the production of matured and harvested pods (Table 7) in the less rainy communities (MCB and NCB) compared with SCB suggest that shade is linked with cocoa yield enhancements especially under reduced rainfall conditions. In addition, the decreasing effect of shade tree distance to cocoa tree on cherelle production in the site with least rainfall (NCB) is an interesting finding, indicating that shade trees in cocoa systems could help promote cherelle production under reduced rainfall scenarios. Unfortunately, the positive correlation observed between rainfall and cocoa productivity across sites (Fig. 5) strongly suggest that rainfall will be an important limitation for cocoa productivity (Abdulai 2017; Wood 1985).

This study has potential limitations including the lack of data on the soil moisture conditions of the sample fields across the three study communities. Soil moisture is directly influenced by rainfall and hence affects both soil nutrient availability and uptake in plants e.g., cocoa. The development and health of cocoa canopy, pod formation and yields are affected by the amount of soil nutrients and their uptake. In that regard, data on soil moisture could have been an important explanatory variable especially in comparing the influence of climate variability on cocoa health and productivity across the study fields and cocoa communities. Therefore, as a next step, we recommend the inclusion of soil moisture determination in future studies of this nature.

6. Conclusions

Climatic factors including especially rainfall and temperature are major causes of differences in the vegetative/reproductive growth, and productivity (yield) in cocoa. Relatively high rainfall occurrences are likely to offset temperature effects towards sustained cocoa health with regards to canopy health, and the development of flowers towards increased productivity (yields). Cocoa-agroforestry systems with shade tree components, can help minimize the negative effects of higher temperatures linked to incidences of insect pests, but also appear to interact in complex ways with occurrence of black pod disease, in some cases resulting in increased prevalence of the disease. Similar studies are therefore needed to provide information of the type of shade trees that better suit cocoa-agroforestry to avoid alternative host for pests, as well as nutrient and water competition. We recommend regular pruning of cocoa and shade trees to increase aeration towards the management of BPD in high rainfall areas, and an increase in shade tree components in dry regions for insect pest management in cocoa systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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