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Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana

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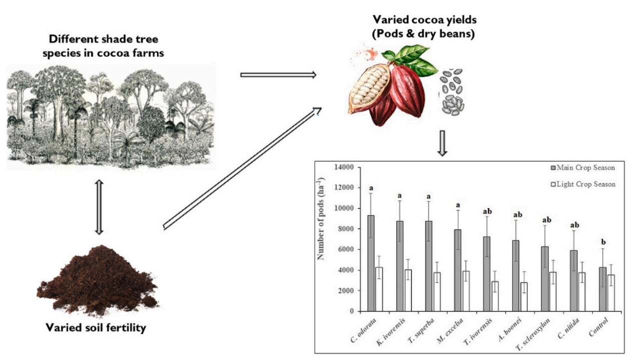
HIGHLIGHTS

- Though cocoa agroforestry systems (CAF) support cocoa yield, species-specific information is limited to advance CAF adoption.
- We assessed the impacts of eight common shade tree species on soil fertility and yield compared with unshaded control plots.
- The concentration of soil available P varied across the species, while soil acidity was affected by shade tree sizes.
- *Cedrela odorata, Khaya ivorensis, Terminalia superba,* and *Millicia excelsa* promoted cocoa production than the unshaded plots.
- There is the need for careful selection of shade tree species for adoption in CAF towards yield sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Cocoa agroforestry systems differ in the diversity of shade tree species composition. Though cocoa benefits from shade, there is a lack of species-specific information on shade trees that enhance soil fertility and yield.
OBJECTIVE: We examined how soil characteristics and cocoa yield were affected by eight commonly retained forest tree species, compared with unshaded control plots over a 3-year period.
METHODS: Using 74 circular plots from 10 cocoa farms in the Western region of Ghana, we sampled soils from two random points within each plot. Soil nutrients at the beginning and end of the study were analyzed, and yield was expressed as number of harvested pods and dry weight of beans per hectare.
RESULTS AND CONCLUSIONS: Levels of soil K and Ca were below recommended values. Although soil available phosphorus (P) was higher in control plots than under shade trees, yield around shade trees were higher than on

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unshaded plots. Cocoa yield differences between shade tree species and control plots were significant only in the major crop season, but not in the minor crop season. Cocoa yields under *Cedrela odorata, Khaya ivorensis, Terminalia superba* and *Milicia excelsa* were significantly higher than on control plots. Hence, the inclusion of specific shade tree species in cocoa agroforestry systems is important to maintain high yields in cocoa systems with low inputs.

SIGNIFICANCE: To our knowledge, this study presents one of the first attempt to assess the impacts of specific shade tree species on soil characteristics and cocoa yield.

1. Introduction

Yields and revenues from cocoa (*Theobroma cacao* L.) support some 6 million smallholder farmers who cultivate the crop on about 10.2 million ha in over 60 humid tropical countries (Asante et al., 2021; Somarriba and Lopez-Sampson, 2018). In West Africa, where more than two-thirds of the world's cocoa is produced (Abdulai et al., 2020), current cocoa yields are 80–95% below potential production levels (Asante et al., 2021) estimated at 1000 kg ha^{-1} and 1900 kg ha^{-1} for on-farm and production on experimental fields, respectively (Bymolt et al., 2018). Major causes for the shortfall include increased temperature and erratic rainfall (Läderach et al., 2013), poor agronomic practices (Asante et al., 2021), pests and diseases, ageing cocoa farms, poor soil conditions, high cost of inputs, and low quality genetic materials (Anim-Kwapong and Frimpong, 2004; Vaast and Somarriba, 2014; Wessel and Quist-Wessel, 2015).

The adoption of cocoa agroforestry systems (CAS), thus the deliberate integration of regenerated or planted forest or fruit tree species in cocoa farms for ecological and socio-economic benefits, has been recommended to improve cocoa health and yields (Asare et al., 2014; Asare and David, 2011; Tscharntke et al., 2011; Wessel and Quist-Wessel, 2015). In West Africa for example, cocoa yields were higher in CAS compared to cultivation in full sun under low inputs usage (Asare et al., 2016). CAS is known to enhance soil fertility and nutrient uptake, improve pest and disease control, and provide alternative income source for farmers (Isaac et al., 2007; Vaast and Somarriba, 2014; Vaast et al., 2015). The system further helps to conserve biodiversity, promote carbon sequestration, and increase food security in addition to serving as sources for collecting plant materials for traditional medications (Asare et al., 2014; Tscharntke et al., 2011; Wade et al., 2010).

Contrary to the afore-mentioned positive contributions of shade trees, some studies (Armengot et al., 2016; Ahenkorah et al., 1987; Cunningham and Arnold, 1962) have shown higher cocoa yields under low or no-shade conditions but with intense inputs (fertilizers and agrochemicals). Also, hybrid cocoa genotype cultivation on previously forested areas were reported to yield higher but for a shorter life span, and with high input demands under full sun conditions compared with CAS (Asare et al., 2019; Obiri et al., 2007). Babin et al. (2010) and Adjinah and Opoku (2010) identified some shade trees e.g. *Cola nitida* in CAS as alternative hosts for pest and disease. In addition, Ryan et al. (2009), Ruf (2011) and Smith Dumont et al. (2014) reported physical damages when shade trees or their heavy branches fall on cocoa trees.

These contrasting results have led some farmers to remove shade trees on their farms due to perceived competition for light, water, and nutrients. Some authors prescribe the introduction of superior hybrid cocoa genotypes as the measure to improve yields and enhance income generation despite the heavy dependence on external inputs and strong negative environmental footprint (Gockowski and Sonwa, 2011; Ruf, 2011; Vaast and Somarriba, 2014). The argument has been made that, though cocoa cultivation under full-sun systems ensures early yield increases, the practice compromises environmental integrity and yield sustainability. Even though some farmers subscribe to the practice due to the initial yield advantages compared to CAS (Anga, 2014; Carr and Lockwood, 2011; Tondoh et al., 2015), most cocoa farms in West Africa are still cultivated under conditions of relatively low inputs (Bymolt et al., 2018; Asante-Poku and Angelucci, 2013). There may be unexplored advantages associated with combining the right shade tree species with cocoa regarding soil fertility improvement and yield advancement.

Shade tree species in cocoa systems vary in diversity due to farmers' preferences and perceived advantages (Graefe et al., 2017). Tree species have different morphology and physiology that affect their interactions with cocoa plants. Several studies including Asare (2005), Graefe et al. (2017) and Abdulai et al. (2018) have assessed farmers' knowledge on shade and the importance of shade tree species in cocoa agroforestry. Nevertheless, comparisons or combination of farmers' knowledge and scientific assessment of the impacts of specific shade tree species is limited. Asare et al. (2016) and Dawoe et al. (2010) identified this gap and recommended such studies to better tackle and explain interactions between shade trees and cocoa. While some species may positively influence yield, longevity of cocoa trees, availability of nutrients, and resilience to climate change (Graefe et al., 2017), others may compete with the crop for light, water and nutrients (Wartenberga et al., 2017; Isaac et al., 2007). To further our understanding of the role of shade trees in cocoa productivity, we hypothesize that shade trees species differ in their influence on soil fertility and yields of cocoa, some having positive impacts and some having negative impacts. Therefore, we examined how eight commonly retained forest tree species (*Alstonia boonei, Cedrela odorata, Cola nitida, Khaya ivorensis, Milicia excelsa, Terminalia ivorensis, Terminalia superba* and *Triplochiton scleroxylon*) impacted soil fertility and yield in CAS compared with full-sun cocoa systems in the Western region of Ghana.

2. Materials and methods

2.1. Study area

We conducted the study in three cocoa growing communities in two administrative districts in the Western region of Ghana. The communities were Asankragua (5° 49.885′ N; 2° 26.525′ W) and Nkrankrom (5° 42.392′ N; 2° 24.203′ W) both in the Wassa Amenfi West District, and Achichire (5° 41.633′ N; 2° 18.341′W) in the Wassa Amenfi Central District (Fig. 1). The districts are located in the Moist Evergreen forest vegetation zone (Hall and Swaine, 1976), characterized by a semi-equatorial climate with relatively high annual rainfall (1500 mm – 1750 mm), moderate daily temperatures (22–34 °C) and high relative humidity (70–90%). Two rainy periods, the major (April – July), and the minor (September–October) define "main crop" and "light crop" cocoa seasons experienced in the districts. Both districts contribute a significant proportion of the total regional cocoa beans for export.

Soils in the districts developed from the Birimian system (middle Pre-Cambrian) (Adu, 1992), and consist of argillaceous sediments metamorphosed into phyllites (GSS, 2014). They are classified as Forest Ochrosol-Oxysol Intergrades (Brammer, 1962), with high nitrogen, available Ca^{2+} and organic matter contents (Asare et al., 2016). Cocoa farming with patches of teak (*Tectona grandis*), rubber (*Hevea brasiliensis*) plantations, timber logging and recent illegal gold mining dominate the land uses in the two districts.

2.2. Farm selection and data collection

We collected data from 10 cocoa fields selected as experimental sites during the 2018/2019 to 2020/2021 crop seasons, starting April 2018 and ending February 2021. The seasons comprised three 'main crop' periods (September – January), and three 'light crop' periods (February – August). The fields were established on previous forest lands and purposively selected based on similarity in management practices, age (8–28 years), common source of planting material and willingness of farmers to participate. Cocoa trees on the fields were pruned two times annually with regular removal of mistletoe (*Tapinanthus bangwensis*), and the application of inorganic fertilizers (125–165 kg ha^{-1} yr^{-1} of NPK 0–22-18) and between 5.6 and 8.0 L ha^{-1} of pesticides (insecticides and fungicides).

We selected eight shade tree species (Table 1; Fig. 2) for assessment based on farmers' knowledge and preferences through informal interviews, and a previous study by Graefe et al. (2017). The species included both species considered as "desirable" and "undesirable" from the view point of enhancing cocoa production (Asare, 2005). Undesirable species from Malvaceae family are believed to be alternative hosts for the cocoa mirid (*Sahlbergella singularis* Hagl. and *Distantiella theobroma* Distant) (Babin et al., 2010) that may cause considerable yield losses. Apart from *Cedrela odorata* which was solely planted or introduced by the farmers, the other species were from either remnants of previous forests or deliberately planted by farmers. Expert knowledge together with farmers' assistance and reference from "Photo-guide for the forest trees of Ghana" (Hawthorne and Gyakari, 2006) were used to identify shade tree species. We ensured that each field had four to eight of the selected species which were tagged and used as reference point in the center to demarcate circular plots with radius 10 m from the trunk. Each plot was at least 30 m from other plots to avoid plot overlaps during the study.

Both shade trees and cocoa trees within plots were identified with unique codes, and their diameter at breast height (dbh, assessed at 1.3 m) measured in meters using a diameter tape (Table 1). Cocoa density was obtained by counts of cocoa trees per plot (Table 1), and cocoa tree distance to shade tree measured with surveyors' tape. The crown area (CA) of shade trees was determined by measurement of crown diameter (CD) across four different directions of the crown spread, i.e. distances between two drip points of the shade trees through the center (Blozan, 2006). Average CD was calculated and used to determine CA (Asare et al., 2016), which was then used to establish the proportion of plot shaded in relation to the total plot size.

For comparison, one to two unshaded circular control plots (radius = 10 m) in open locations within each field were demarcated. On the shaded plots, cocoa density and dbh were measured, and plot area determined using plot radius (Table 1). During the period of study, each field was exempted from fertilizer and pesticide applications. The selected tree species and unshaded plots are hereafter referred to as treatments.

2.3. Determination of soil characteristics

Soils were sampled at two random points in each plot with an auger at 0 - 30 cm depth at the beginning (April 2018) and end of the field data collection (February 2021). We bulked the samples, labelled them according to plots, and transported them to the Ecological Laboratory, University of Ghana for measurement of acidity (pH), percentage Carbon (%C), percentage total nitrogen (%N), available phosphorus (P), exchangeable potassium (K), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na). Soil acidity was determined through a 1:1 soil to distilled water ratio using a Metrohm 691 pH meter (Mclean, 1982), %C content by the wet combustion method of Walkley and Black (1934), %N content by Semi-Micro Kjeldahl Digestion method (Black, 1965), and available P according to Bray and Kurtz (1945). Exchangeable K^{2+}, Mg^{2+}, and Ca^{2+} were estimated through flame photometry (Black, 1965) and atomic absorption spectrometry (AAS) after extraction with 1.0 M ammonium

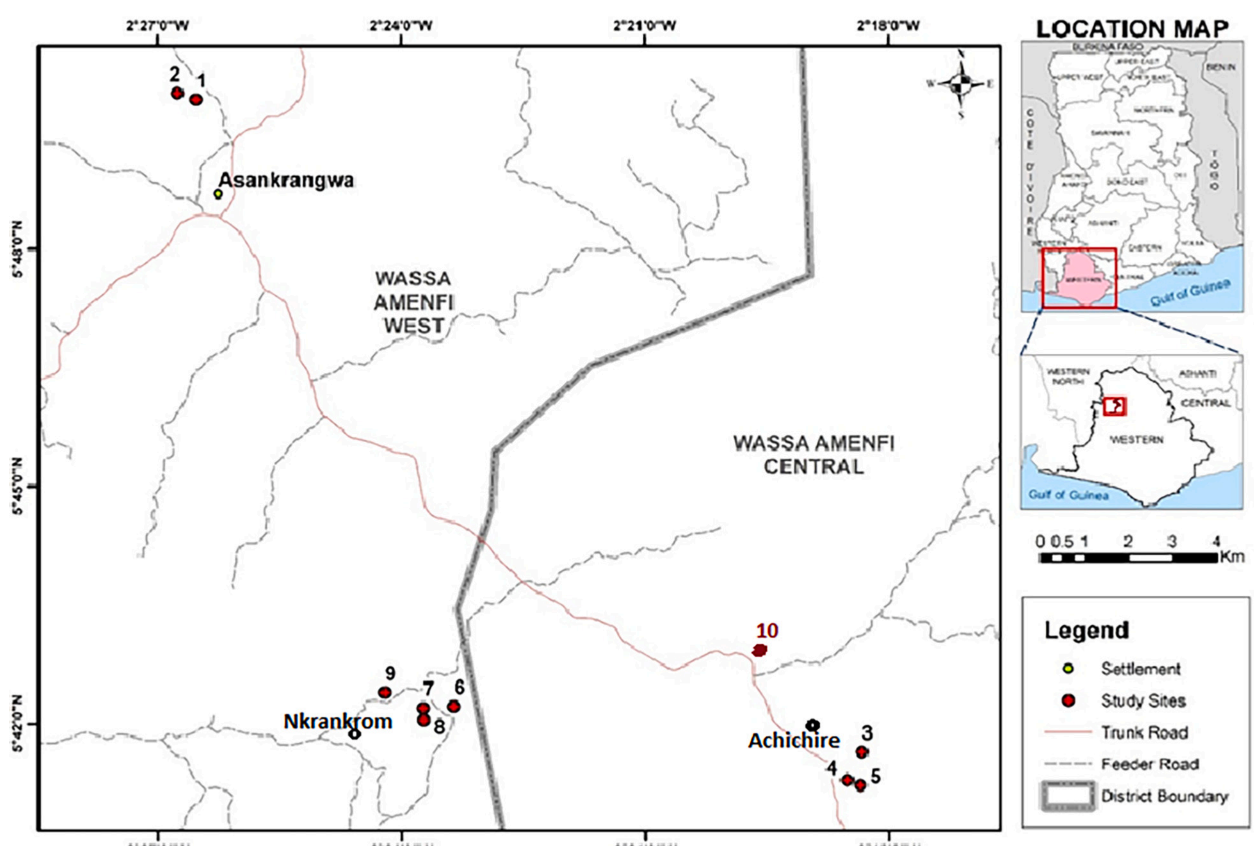

Fig. 1. Location of study communities in Ghana.

Table 1
Characteristics of treatments and study plots (Values represent mean ± s.e.). CRIG = Cocoa Research Institute of Ghana, D = deciduous, SD = Semi-deciduous, N = Number of sampled plots, P = Shade tree planted by farmers, R = Shade tree from remnants of previous forest, * = status by Graefe et al. (2017).

Treatment	Family	Source	N	Shade tree dbh (m)	Plot area (m^2)	% Shade	Cocoa density (trees/plot)	Cocoa tree dbh (m)	CRIG Recommendation status
Alstonia boonei (D)	Apocynaceae	P, R	7	0.29 ± 0.04	257 ± 28	68 ± 1	17 ± 1	0.11 ± 0.01	Desirable*
Cedrela odorata (D)	Meliaceae	P	3	0.51 ± 0.07	243 ± 40	32 ± 1	14 ± 2	0.11 ± 0.01	Desirable
Cola nitida (SD)	Malvaceae	P, R	6	0.47 ± 0.08	241 ± 27	62 ± 1	13 ± 1	0.10 ± 0.01	Undesirable
Khaya ivorensis (SD)	Meliaceae	P, R	8	0.53 ± 0.08	247 ± 25	41 ± 1	14 ± 1	0.11 ± 0.01	Desirable
Milicia excelsa (D)	Moraceae	P, R	10	0.54 ± 0.03	244 ± 24	60 ± 1	13 ± 1	0.10 ± 0.01	Desirable*
Terminalia ivorensis (D)	Combretaceae	P, R	9	0.43 ± 0.05	250 ± 26	73 ± 1	14 ± 1	0.10 ± 0.01	Desirable*
Terminalia superba (D)	Combretaceae	P, R	9	0.45 ± 0.09	248 ± 24	61 ± 1	16 ± 1	0.11 ± 0.01	Desirable*
Triplochiton scleroxylon (D)	Malvaceae	P, R	6	0.80 ± 0.09	227 ± 33	51 ± 1	16 ± 2	0.09 ± 0.01	Undesirable
Control (no-shade)	–		16	–	242 ± 27	–	18 ± 1	0.17 ± 0.04	–

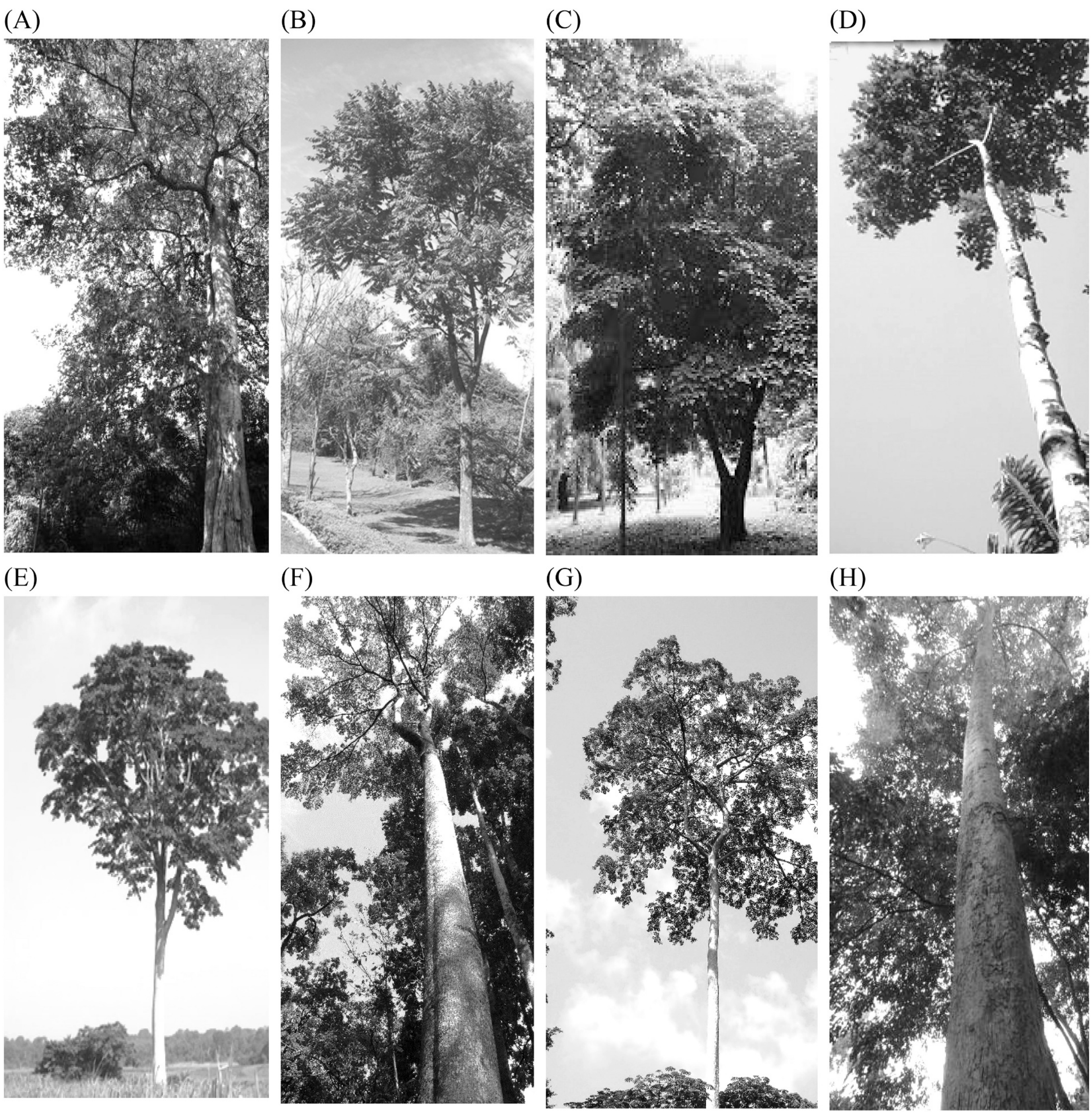

Fig. 2. Sample illustrations of the eight selected shade tree species used as treatment in this study; (A) *Alstonia broonei,* (B) *Cedrela odorata,* (C) *Cola nitida,* (D) *Khaya ivorensis,* (E) *Milicia excelsa,* (F) *Terminalia ivorensis,* (G) *Terminalia superba,* and (H) *Triplochiton scleroxylon.*

acetate.

2.4. Determination of climatic conditions

Field measurement of air temperature and relative humidity was undertaken by installing two data loggers (iButton DS1923-F5#, Hygrochron Temperature and Humidity data logger, Maxim Integrated Productions, CA, USA) in two randomly selected fields. The loggers were mounted 2 m above ground within cocoa canopy, shielded from direct radiation from the sun and configured to read parameters at 30 min intervals. We downloaded data every three months and determined mean monthly temperature range (24.4–27.0 °C), and relative humidity range (69.7–96.2%). We further measured rainfall with a wireless rain-gauge device (Rosenborg Exclusive Tradlos Regnmaler, Model 35,980, Carrin Electronics limited, HongKong) installed at 1.5 m above the ground and free from splash from adjacent objects. Daily rainfall (in millimeters) was monitored, recorded, and summed to derived monthly (4.3–279.6 mm) and annual (1258–1345 mm) rainfall.

2.5. Yield determination

We assessed yield by counting all healthy harvested pods per cocoa trees and pooling at plot levels every two weeks, and by measuring the dry weight of beans after breaking the pooled pods, extracting and fermenting wet beans for 5–7 days, and open air drying for 5–7 days (Asare et al., 2016). Consequently, yields were extrapolated to total number of pods ha^{-1} and total dry weight of cocoa beans in kg ha^{-1}.

2.6. Data analysis

Data analysis was conducted in R version 3.6.3 (R Core Team, 2020). For analysis of treatment effects on both soil properties and yield, we used linear mixed-effect models built from the “lme4” package (Bates et al., 2015). The models were validated through tests of assumptions of normality and variance homogeneity, including plots of residuals against fitted values in normal Q-Q plots. In the model (1), pH, %C, %N, P, Mg^{+2}, Ca^{+2}, K^{+} and Na^{+2} were analyzed with treatment (Tt) as a fixed effect, shade tree basal area (Ba), cocoa density (Cd) and sampling time (St) as co-variates, and farm (Fm) as a random effect.

$$Y_{(soil)} = \alpha(Tt)) + \beta(Ba) + \gamma(Cd) + \mu(St) + \mathrm{A}(Fm) \tag{1}$$

For the analysis of yields [harvested pods ha^{-1} and dry weight of beans ha^{-1}] we further included cocoa tree dbh (Cdbh) as an additional co-variate, and the crop season (Cs), thus 3 main crop and 3 light crop, and year (Yr), thus 2018/2019, 2019/2020, 2020/2021, as additional random effects in the model (2). Inclusion of the ages of cocoa farms as co-variate did not significantly influence cocoa yield, hence age was omitted in the final model.

$$Y_{(yield)} = \alpha(Tt) + \beta(Ba) + \gamma(Cd) + \mu\ (Cdbh) + \mathrm{A}(Fm) + \mathrm{B}(Cs) + \mathrm{C}(Yr) \tag{2}$$

Visual inspection of the residual plots showed deviations from normality for the yield data, hence we performed series of data transformations and selected cubic root transformation as the best fit for the data. We then performed backward reduction procedures on the models, using the Akaike Information Criterium (AIC) to select the best-fitted models (Burnham and Anderson, 2013). Asymptotic chi-square tests (indicated as “Pr (Chi)” in Table 3) on the likelihood ratio test (LRT) statistics established on maximum likelihood fits and parameter estimates were used in testing for significance. Where significant differences between treatments were identified, Tukey's post hoc tests for multiple comparisons were used to verify the sources of variabilities. Because we had unbalanced data, we calculated and used the least square means (LSM) of yields for each treatment through the ‘emmeans’ package in R (Lenth, 2020) and illustrated the outputs in graphs.

3. Results

3.1. Soil characteristics

We observed significantly different concentrations of available soil P among treatments, while the other soil properties showed less variation among treatments (Table 2). Tukey's post hoc tests on available P showed that soils under *Alstonia boonei, Cedrela odorata, Milicia excelsa*, and *Terminalia superba* had significantly lower concentrations than the control plots, and below what is usually considered the estimated minimum recommended threshold (20 μg g^{-1}) for cocoa production (Ahenkorah, 1981). Available P concentrations in the soils under *Cola nitida, Khaya ivorensis*, *Terminalia ivorensis* and *Triplochiton scleroxylon* plots were above the minimum recommended thresholds for cocoa production but lower than the control plots (Table 2). The soils were generally acidic and with exchangeable K^{+} and Ca^{2+} concentrations lower than minimum recommended thresholds for cocoa production. The concentrations of total nitrogen (%N), organic carbon (%C), and exchangeable Mg^{2+} were higher than their respective minimum thresholds (Table 2).

We found significant differences in most soil properties between the beginning and after the third year (thus *p*-value $_{(time)}$ in Table 2) of the study. Soil acidity, %N, %C, and exchangeable K^{+}, Mg^{2+} and Ca^{2+} increased while the concentrations of available P and exchangeable Na^{+} decreased (Table 2). We observed an overall significant negative effect of the basal area or size of the shade tree species on soil pH (thus, pH = 0.59 x (shade tree basal area) + 4.28; LRT = 4.45, $p = 0.035$), meaning that larger trees tended to induce lower soil pH.

3.2. Yield as influenced by shade tree species

We observed an overall average of 10,891 ± 3007 pods ha^{-1} year^{-1} in this study. The lowest and highest pod quantities across the treatments were 7749 ± 2889 pods ha^{-1} year $^{-1}$ and 13,578 ± 3251 pods ha^{-1} year^{-1} in unshaded (control plots) and *Cedrela odorata* plots, respectively. The number of harvested pods depended strongly on crop seasons (LRT = 17.99, p – value = 0.035) (Fig. 3) with average production in main crop seasons (7249 ± 1976 pods ha^{-1}) approximately two times that in the light crop seasons (3642 ± 1030 pods ha^{-1}). A significant effect of the treatments on the total number of harvested pods and in the main crop seasons was observed, while treatments had no effect in the light crop seasons (Table 3, Fig. 3). The density of cocoa had a significant and positive impact on pod production during the light crop seasons (Table 3).

All the shade tree plots had a higher total number of pods than the controls. The Tukey post hoc tests showed significantly higher total quantities of pods (for both major and light crop seasons) in the *C. odorata, K. ivorensis, T. superba,* and *M. excelsa* plots compared to the control plots. Cocoa trees under *Cedrela odorata* produced approximately 43% more pods than the control plots, *K. ivorensis* (39%). *T. superba* (38%), *M. excelsa* (34%), *T. ivorensis* (24%), *A. boonei* (20%), *T. scleroxylon* (23%) and *C. nitida* (20%).

The overall average production of dry cocoa beans at plot level was 608 ± 164 kg ha^{-1} year^{-1}. The lowest mean production of dry beans was observed in the control plots (438 ± 157 kg ha^{-1} year^{-1}), while the highest productions were found under *C. odorata* (701 ± 178 kg ha^{-1} year^{-1}) and *K. ivorensis* (702 ± 161 kg ha^{-1} year^{-1}). The seasonal patterns were similar to those observed for number of pods (Fig. 3) but with significant influence of the density of cocoa and marginal effects of the dbh of shade trees (Table 3). The mean dry weight of beans in the main crop periods (391 ± 102 kg ha^{-1}) was almost two times the weight in the light crop periods (217 ± 62 kg ha^{-1}).

We observed a significant and positive influence of the co-variate dbh of cocoa trees on the amount of dry beans produced in the light crop season (Table 3). This means that within treatments, cocoa trees with larger dbh tended to have higher dry weight of beans, even in full-

Table 2
Comparisons of least square means (LSM) (±s.e.) of soil properties as influenced by treatments at both the beginning and the end of the study. Different letters following values of available P indicate significant differences according to Tukey's tests ($P < 0.05$). Threshold values adopted from Ahenkorah (1981).

Treatments	pH	Total N (%)	C (%)	Available P (μg g^{-1})	K^+ (cmol kg^{-1})	Mg^{2+} (cmol kg^{-1})	Ca^{2+} (cmol kg^{-1})	Na^+ (cmol kg^{-1})
Threshold	5.6–7.2	0.09	2.03	20.0	0.25	1.33	7.5	–
A. boonei	4.6 ± 0.2	0.10 ± 0.01	2.36 ± 0.56	18.7 ± 1.3 a	0.08 ± 0.02	5.34 ± 0.61	4.22 ± 1.23	0.10 ± 0.01
C. odorata	4.6 ± 0.3	0.10 ± 0.01	3.36 ± 0.75	18.5 ± 1.5 a	0.20 ± 0.16	5.77 ± 0.88	6.19 ± 1.96	0.10 ± 0.01
C. nitida	4.2 ± 0.2	0.11 ± 0.01	3.66 ± 0.57	20.7 ± 1.4 ab	0.09 ± 0.02	6.52 ± 0.63	3.82 ± 1.24	0.10 ± 0.01
K. ivorensis	4.1 ± 0.2	0.10 ± 0.01	2.76 ± 0.51	22.4 ± 1.3 ab	0.09 ± 0.04	5.05 ± 0.57	2.31 ± 1.10	0.10 ± 0.00
M. excelsa	4.3 ± 0.2	0.11 ± 0.01	3.80 ± 0.50	18.7 ± 1.3 a	0.07 ± 0.02	5.80 ± 0.51	5.48 ± 1.18	0.13 ± 0.01
T. ivorensis	4.5 ± 0.2	0.10 ± 0.01	2.82 ± 0.51	20.7 ± 1.3 ab	0.04 ± 0.01	6.22 ± 0.57	3.79 ± 1.13	0.16 ± 0.01
T. superba	4.6 ± 0.2	0.10 ± 0.01	2.83 ± 0.47	19.4 ± 1.3 a	0.05 ± 0.01	6.38 ± 0.53	4.29 ± 1.11	0.11 ± 0.01
T. scleroxylon	4.5 ± 0.2	0.10 ± 0.01	3.04 ± 0.60	20.7 ± 1.4 ab	0.05 ± 0.02	6.19 ± 0.66	5.14 ± 1.40	0.17 ± 0.01
Control	4.4 ± 0.1	0.10 ± 0.01	3.61 ± 0.44	32.1 ± 1.2 b	0.07 ± 0.01	5.08 ± 0.43	2.82 ± 0.88	0.12 ± 0.01
$LRT_{(treatment)}$	10.74	6.79	8.68	24.34	12.85	11.08	7.75	7.71
P - value $_{(treatment)}$	0.217	0.559	0.370	0.002	0.117	0.198	0.458	0.462
Mean $_{(before)}$	4.6 ± 0.1	0.09 ± 0.00	2.49 ± 0.05	24.86 ± 1.64	0.06 ± 0.01	4.43 ± 0.29	1.72 ± 0.12	0.20 ± 0.01
Mean $_{(After)}$	4.2 ± 0.1	0.11 ± 0.00	2.89 ± 0.06	20.71 ± 1.32	0.09 ± 0.02	6.86 ± 0.18	2.35 ± 0.17	0.13 ± 0.01
$LRT_{(time)}$	7.98	36.82	37.88	3.15	3.16	48.70	15.26	35.09
P - value $_{(time)}$	0.005	1.30 e^{-9}	7.53 e^{-10}	0.076	0.076	2.99 e^{-12}	9.39 e^{-5}	3.15 e^{-9}

sun plots where cocoa trees were large but had low yields compared to shaded plots. Cocoa trees around *C. odorata* and *K. ivorensis* produced more dry beans than the control at 38%, *T. superba* (34%), *T. ivorensis* (31%), *M. excelsa* (29%), *A. broonei* (25%), *T. scleroxylon* (23%), and *C. nitida* (20%).

4. Discussion

4.1. Shade tree species impacts on soil fertility

The observed similarities in soil characteristics across treatments in this study except for available P were expected and consistent with observations of the limited influence of shade trees on soil fertility in cocoa systems (Andres et al., 2018; Blaser et al., 2017). Some authors (Carr and Lockwood, 2011; Isaac et al., 2007) found nutrient competition between shade trees and cocoa. Although shade trees in cocoa farms can potentially increase total soil C and N concentrations due to higher decomposition rates under shade trees (Blaser et al., 2017; Ofori-Frimpong et al., 2007a, 2007b), the overall effect may be too small to affect the total fertility of cocoa soils. Other factors such as fertilizer (both organic and inorganic) applications, rainfall and nitrogen fixation are major sources of nutrient variations in cocoa systems (van Vliet et al., 2015). It would be interesting to also study the effects of N-fixing species on cocoa productivity in West Africa, given that values of available N are in the low range (Table 2). Under high rainfall conditions, there is rapid vegetative growth of cocoa that is controlled by frequent pruning, providing a source of organic materials that decomposes to advance soil nutrition (Van Noordwijk et al., 1997). The addition from the pruning source may cause rapid nutrient recycling that may nullify added litter from shade trees in cocoa systems.

The significant difference in available P between shaded and unshaded areas during the study was contrary to findings of Blaser et al. (2017), Isaac et al. (2007) and Ofori-Frimpong et al. (2007a, 2007b) who found no effects of shade trees on available P. The contrast may be due to variations in agronomic practices (e.g. prior fertilizer application, and shade tree pruning regimes), geographical locations, and climatic conditions in the Western region where this study was conducted against the Ashanti and Eastern region for the other studies. According to Asare et al. (2016) and Ofori-Frimpong et al. (2007a, 2007b), available P is lower than the minimum recommended thresholds across Ghana's cocoa landscape. This was confirmed by half the treatments in this study recording available P concentrations lower than the 20μgg^{-1} threshold indicated by Ahenkorah (1981). The Tukey post hoc test showing significantly lower available P for plots with *A. boonei, C. odorata, M. excelsa* and *T. superba* compared to unshaded plots indicates relatively higher nutrient competition or immobilization by these species. This confirms that plant species have varied nutrient requirements and nutrient uptake potentials (Cruz et al., 2019; van Vliet et al., 2015). Phosphorus availability in soils depends on complex interactions between plant species, soil organic matter, soil type and pH (Schroth et al., 2003), and more investigations will be needed to clarify why these species have especially low values for soil P.

The high soil acidity with pH values below the optimal range of 6–7.5 (Wood and Lass, 1985) in the study confirmed observations by Asare et al. (2016), Blaser et al. (2017) and Ofori-Frimpong et al. (2007a, 2007b) that Ghana's cocoa landscapes contain acidic soils due to geological origin, as well as prolonged cultivation and fertilizer applications. The soils are naturally acidic due to the type and nature of parental materials (Brammer, 1962). According to Snoeck et al. (2010), high rainfall (a characteristic of the study area) induces leaching of exchangeable cations with resultant high acidity and hence lower availability for plant uptake (Baligar et al., 2001). Apart from Mg^{2+} which was above the recommended threshold, the other cations (K^+ and Ca^{2+}) were low, suggesting possible negative implications for pod formation and development of the cocoa trees (van Vliet et al., 2015).

4.2. Shade tree species effects on cocoa yield

Mean yields recorded in this study were considerably below the potential on-farm yield (1000 kg ha^{-1}) indicated by Bymolt et al. (2018), and the experimental yield (2125 kg ha^{-1}) by Abdulai et al. (2020). Cocoa yield has over the past decades been low in most cocoa areas of Ghana with levels around 400 kg ha^{-1} (Aneani and Ofori-Frimpong, 2013). Lower yields were expected because of the low levels of input applications in the study area (Abdulai et al., 2020; Asare et al., 2016). Still, the yields are similar to yields recorded in studies conducted in different parts of Ghana (Abdulai et al., 2020; Asare et al., 2019) and Côte d'Ivoire (Koko et al., 2013).

The impacts of season on the yield of cocoa as observed in this study affirms the importance of climatic conditions such as total rainfall and distribution for cocoa productivity. The main crop season in Ghana is characterized by high rainfall, high relative humidity and low temperatures, which favors cocoa production as it provides the necessary climatic conditions for cocoa growth and development (Abdulai et al., 2020). On the contrary, the light crop season is characterized by semi-drought conditions which affect physiological processes that impact the growth and productivity of the crop (Abdulai et al., 2018). The semi-drought nature of the season perhaps causes the selected shade trees (being semi-deciduous and deciduous) (Hawthorne and Gyakari, 2006) to lose their foliage and hence unable to influence yield during the light crop season as observed in this study.

The increased yields under *C. odorata, T. superba*, *M. excelsa* and

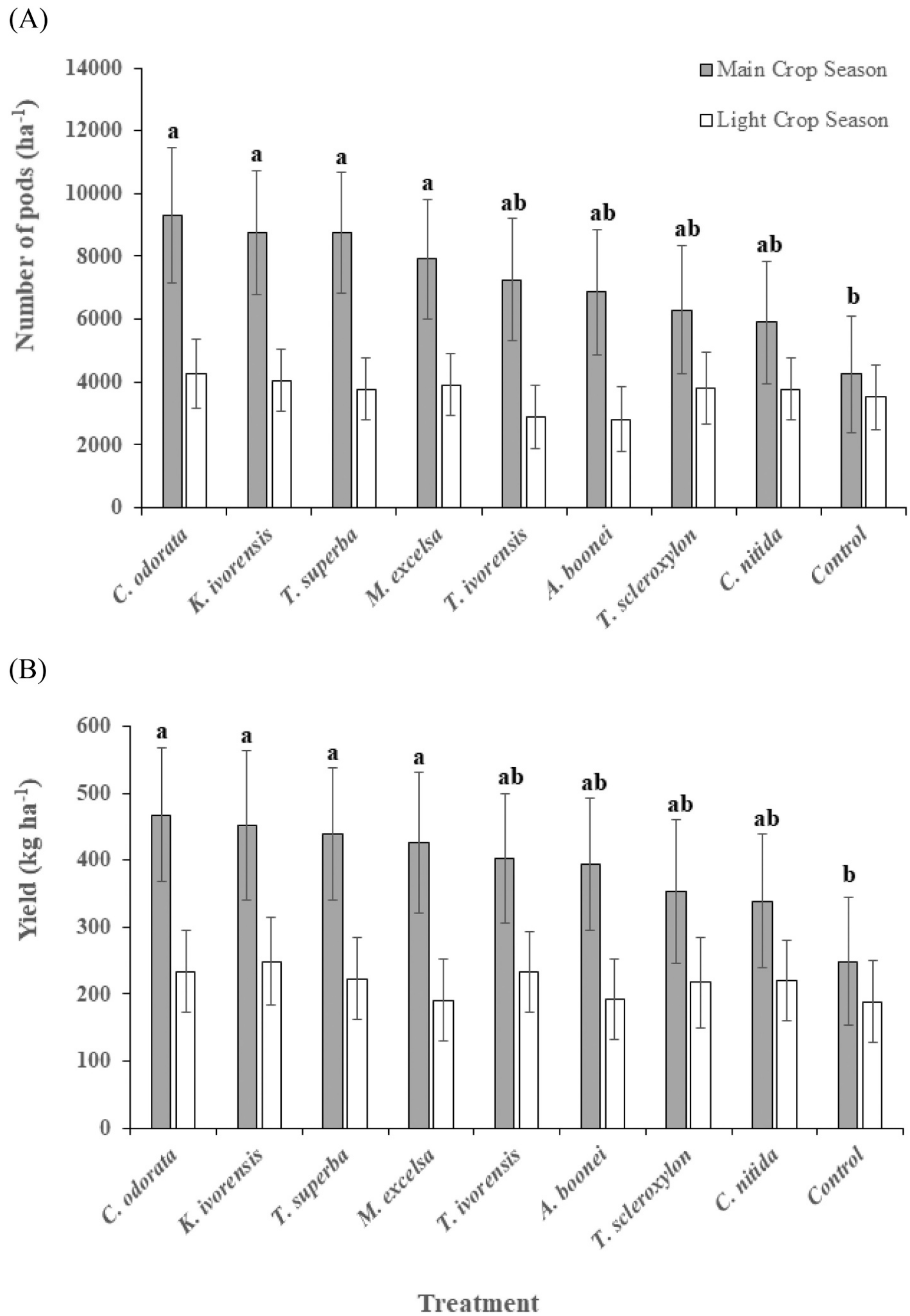

Fig. 3. Seasonal distribution of yields; (A) the number of harvested pods, and (B) the dry weight of cocoa beans, as influenced by the treatment (shade tree species and unshaded control plots) for the 3 years (values indicate LSM ± s.e.). Different letters over bars for main crops indicate significant differences according to Tukey's tests ($P < 0.05$).

K. ivorensis compared to the control unshaded areas may be attributed to the morphological structures of these species. The four species usually develop tall cylindrical boles with relatively small crowns with open canopies (Hawthorne and Gyakari, 2006). This enhances aeration and light penetration and may promote photosynthesis, flowering, fruiting, and yield (Almeida and Valle, 2007; van Vliet and Giller, 2017). The relatively higher aeration potentials of these species may also minimize the likelihood of pest and disease infestations especially black pod disease (caused by *Phytophthora megakarya* and *P. palmivora*) that is associated with dense canopies and yield losses (Akrofi et al., 2015). In addition, *C. odorata* and *K. ivorensis* belong to the Meliaceae family with characteristic unpleasant smell (Hawthorne and Gyakari, 2006) that repel certain insects (Heads, 2019) and hence may limit infestation by insects such as mirids (*Sahlbergella singularis* Hagl., Heteroptera: Miridae) that negatively impact yield. The deep root systems of the Meliaceae and Combretaceae species may further account for reduced soil water competition between shade trees and the cocoa plants (Hawthorne and Gyakari, 2006; van Vliet and Giller, 2017). *C. nitida,* and *T. scleroxylon* belong to the Malvaceae family as cocoa and are classified as undesirable according to Cocoa Research Institute of Ghana's (CRIG) recommendations (CRIG, 2010; UTZ, 2017). According to Babin et al. (2010) and Mahob et al. (2015), trees in the Malvaceae family serve as alternative hosts for the mirid pest that decrease cocoa yields. Therefore, it was unexpected to see the two species (*C. nitida,* and *T. scleroxylon*) having yields slightly above those of the unshaded plots. This finding will warrant further investigation to ascertain the extent of their impact

Table 3
Results of the linear mixed-effects models in the assessment of treatments and seasonal effects on the numbers of cocoa pods and production of dry beans in cocoa agroforestry systems in the study. '*' = Significant at $p < 0.05$; ns = non-significant, hence omitted in best fitted model. LRT = Likelihood Ratio Test-statistics, Pr (Chi) = Asymptotic chi-square tests, df = degrees of freedom.

Test parameters	df	Main Crop Season		Light Crop Season		Overall	
		LRT	Pr (Chi)	LRT	Pr (Chi)	LRT	Pr (Chi)
Number of pods							
Treatment	8	31.57	0.0001*	7.36	0.4987	43.46	< 0.0001*
Cocoa density	1	ns	ns	8.09	0.0044*	ns	ns
Treatment: crop season	9	–	–	–	–	20.66	0.0142*
Dry weight of beans							
Treatment	8	24.70	0.0017*	5.82	0.6673	33.12	< 0.0001*
Shade tree basal area	1	3.47	0.0624	3.37	0.0664	ns	ns
Cocoa tree dbh	1	3.30	0.0692	6.01	0.0143*	ns	ns
Treatment: crop season	9	–	–	–	–	14.69	0.0999

on cocoa.

The observation of higher yields in shaded cocoa plots in this study confirms previous observations of higher yields under shade in low-input cocoa systems (Asare et al., 2016), but contradicts those of Mortimer et al. (2017) finding higher yields in open-sun cocoa systems than in shaded farms. Although cocoa cultivation under full-sun open systems was credited with high yields at early stages through the pioneering works by Ahenkorah et al. (1974, 1987) and Cunningham and Arnold (1962), the full sun system has high requirements for inputs in terms of fertilizers and pesticides. This may certainly limit production as most cocoa cultivation in Ghana and Côte d'Ivoire is carried out by small holders who cannot afford such investments. In Ghana, the insufficient supply of nutrients required to meet high yield levels, has been the main reason for the low yield over the past decades. In that regard, cocoa agroforestry presents an alternative for cocoa yield enhancement (Abdulai et al., 2018, 2020; Asare et al., 2016, 2019).

5. Conclusion

Shade trees in our study positively affected yield under low input systems as compared to full-sun, even though shade trees seemed to have little (or in some cases negative effects with regards to available P) impact on nutrient availability in the soil. Though competition for water, nutrient, space, and light are mentioned as negative attributes of shade trees on cocoa farms, some species (e.g *Cedrela odorata, Terminalia superba, Khaya ivorensis* and *Milicia excelsa*) enhanced yield when used in CAS compared to a full-sun cocoa cultivation system. There is a need to selectively plant or/and retain these shade tree species on cocoa farms as these can increase yields. It is however recommended that, further research should be conducted on other commonly used shade tree species in CAS to comprehensively determine additional shade tree species that promote cocoa productivity.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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