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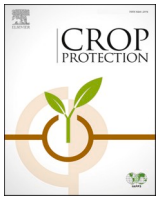
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The potential of selected shade tree species for managing mirids and black pod disease infection in cocoa agroforestry systems in Ghana

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ABSTRACT

Pests and diseases are major determinants of cocoa yield, but continuous synthetic chemical control of cocoa pests contributes to environmental pollution and high production costs. As an alternative, we assessed the influence of eight commonly retained forest tree species on mirid and black pod disease infestation, compared to unshaded portions in 10 cocoa fields in the Western region of Ghana. The influence of tree species, on-farm temperature, rainfall, and relative air humidity was assessed on mirid population densities on cocoa trees, and mirid and black pod disease infested pods from May 2018 to December 2020. Shade tree species had significant effects on mirid densities and resulting pod damages, with highest mirid occurrence in *Triplochiton scleroxylon* K. Schum (0.51 ± 0.12 mirids tree^{-1} yr^{-1}) and lowest occurrence in *Khaya ivorensis* A. Chem (0.21 ± 0.07 mirids tree^{-1} yr^{-1}), *Cedrela odorata* L. (0.22 ± 0.09 mirids tree^{-1} yr^{-1}) and *Milicia excelsa* (Welw.) C. Berg. (0.24 ± 0.09 mirids tree^{-1} yr^{-1}) plots, compared to the unshaded control plots (0.48 ± 0.12 mirids tree^{-1} yr^{-1}). Black pod disease (caused by *Phytophthora* spp.) infection was significantly different among species with highest pod damage observed around *Cola nitida* Schott and Endl. and least in unshaded areas. The occurrence of black pod disease varied with seasons and correlated with monthly rainfall and humidity, while mirid infestation correlated with monthly temperature. The diameter of shade trees and the density of cocoa trees influenced both mirid infestation and black pod disease infection. Hence, careful selection of shade tree species appears to be an important strategy to enhance integrated pest management (IPM) in cocoa systems.

1. Introduction

Pests and diseases are among the most limiting factors for yield in cocoa (*Theobroma cacao* L.) (Almeida and Valle, 2007). Cocoa is grown under tropical conditions, where high temperatures and erratic rainfall patterns are known to favour insect pest (e.g. mirids) infestations and black pod disease infection (Dormon et al., 2007; Abdulai et al., 2020). Mirids are widespread in the major cocoa production areas in Africa, and have a life cycle of approximately 41 days from egg to adult stages (Mariau, 1999; Entwistle, 2008; Anikwe et al., 2009). The insects feed by insertion of mouth parts into cocoa pods and soft tissues, with simultaneous sucking of juice and secretion of saliva (Anikwe et al., 2009) causing lesions (dark, depressed oily spots) on attacked parts (Mariau, 1999). The lesions function as entry points for pathogens such as black pod (*Phytophthora* spp.) and dieback caused by *Fusarium* spp. and *Lasiodiplodia* spp. (Adu-Acheampong and Archer 2011). Feeding activities of mirids lead to weakness, wilting and up to 75% yield losses in cocoa (Padi, 1997; Anikwe et al., 2009; Awudzi et al., 2017).

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Black pod disease (BPD) is caused mainly by *Phytophthora megakarya* and *P. palmivora*. In West Africa, *P. megakarya* predominates and leads to up to 80% yield losses in cocoa plantations if unmanaged (Despréaux et al., 1988; Berry and Cilas, 1994). All stages of pod development are affected by BPD (Akrofi et al., 2015), with initial brown to black spot symptoms that spread to cover the entire pod. The beans within affected pods are damaged approximately 15 days after infection (Dooh et al., 2015). Frequency of infection is influenced by farm management practices such as pruning, and varies with the seasons, as climatic factors such as high rainfall, high air humidity and low temperatures increase incidences of BPD infections (Akrofi et al., 2003; Nyassé et al., 2007). In addition, the presence of shade trees can influence the incidence of black pod disease and affect cocoa production (Idowu, 1989; Mariau, 1999; Anikwe et al., 2010; Asitoakor et al., 2022).

West Africa produces about 70% of the world's cocoa (Abdulai et al., 2020) and relies on extension services for advice on pesticide application and other crop management practices including pruning and weeding to manage mirid infestation and BPD infections (Baah and Anchirinah, 2011;Cocoa Health and Extension Division [CHED] & World Cocoa Foundation [WCF], 2016). Despite these measures, yields are relatively low with Ghana and Cote d'Ivoire producing on average 400 and 550 kg ha^{-1}, respectively (Oomes et al., 2016; Bymolt et al., 2018; Asante et al., 2021). These yields are below the estimated on-farm potentials of above 1000 kg ha^{-1} y^{-1} (Ofori-Frimpong et al., 2007; Aneani and Ofori-Frimpong, 2013; Abdulai et al., 2020).

From the 1950s, the development of resistant cocoa varieties and the use of pesticides (e.g., Nicotine sulphate and Dichlorodiphenyltrichloroethane, Endrin, Dieldrin, Heptachlor and Lindane, metalaxyl and copper-1-oxide and Mandipropamid and Mefenoxam (Metalaxyl-M)) were the major mirid and BPD control measures (Adu-Acheampong et al., 2015). However, the application of pesticides increases production costs and poses risks to the environment, farmers and consumers (Bhandari, 2014; Adu-Acheampong et al., 2015). With over 1.5 million ha of cocoa plantations in Ghana (Adu-Acheampong et al., 2015; FAO-STAT, 2021), mainly owned by smallholder farmers, adequate pesticide application for effective mirid and BPD management is untenable economically. The financial implications compel farmers to apply cheaper and unapproved pesticides that reduce yield and contaminate cocoa beans (Adu-Acheampong et al., 2015). The increasing global demand for safe cocoa beans without contaminants suggest the adoption of environmentally friendly means of managing cocoa pests through natural manipulation of the cultivation system in order to promote biological control of these pests and diseases (Adu-Acheampong et al., 2015) and the rational use of approved pesticides.

There is growing consensus that cocoa agroforestry is one of the practices that can help promote natural processes to reduce the incidence of mirids and BPD, thereby reducing the irrational use of agrochemicals (FAO, 2018). Cocoa agroforestry may be used as a management strategy in disease and insect control (Babin et al., 2010; Tscharntke et al., 2011; Asare et al., 2016; Vaast et al., 2016) to improve farmers' income (Ofori-Frimpong et al., 2007; van Vliet et al., 2015) through increased yield (Asare et al., 2016). In spite of this, farmers have varied perceptions of the benefits of agroforestry, and their preferences for shade tree species vary (Graefe et al., 2017). Thus, exploring the use of shade trees as an integrated pest management (IPM) tool to improve yields in cocoa growing systems is important (Andres et al., 2018; Asare et al., 2019; Blaser et al., 2018). However, there is little information on how the choice of shade tree species can contribute to IPM in cocoa systems even though a few studies show how mirids disperse, aggregate, and distribute spatially (Babin et al., 2010; Bisseleua et al., 2011; Awudzi et al., 2017). To improve our understanding of the role of shade tree species in cocoa pest and disease management, we selected eight commonly planted or retained shade tree species in cocoa systems and assessed how they influenced the incidence of mirid infestation and BPD infections. Our hypothesis was that shade tree species differ in their impact on mirid infestation and BPD infection rates.

2. Materials and methods

2.1. Description of study area

The study was conducted from May 1, 2018, to December 31, 2020 in ten cocoa fields in three communities; Achichire (N 05′ 41.280, W 002′ 18.514) and Nkrankrom (N 05'.42.392, W 002′ 24.203) in the Wassa Amenfi Central District, and Asankragwa (N 05′ 49.885, W 002′ 26.525) in the Wassa Amenfi West District of the Western region of Ghana (Asitoakor et al., 2022). The fields are located in the Moist Evergreen ecological zone with mean annual rainfall at 1500 mm–1750 mm and mean monthly temperature and relative humidity of 24–29 °C and 10–100 %, respectively (GSS, 2014). Forest Ochrosol-Oxysol constitutes the soil type in the districts (Brammer, 1962) that supports the cultivation of cocoa (amidst forest trees), coffee, oil palm, cola, and rubber (GSS, 2014). The districts contribute significantly to the total annual cocoa production in Ghana (Asare et al., 2016; Graefe et al., 2017).

2.2. Experimental setup and treatments

The ten cocoa fields were selected based on the diversity of forest tree species, similar farm management practices, age and common source of planting materials. Prior to the study, cocoa trees on the fields were pruned twice annually with regular removal of mistletoe (*Tapinanthus bangwensis* Engl. & K. Krause), frequent weeding and the application of inorganic fertilizer (125–165 kg ha^{-1} yr^{-1} of NPK 0-22-18), insecticides (Etofenprox) and fungicides (Copper hydroxide/Dicopper chloride trihydroxide) at rates ranging from 5.6 to 8.0 L ha^{-1} $year^{-1}$. However, during the period of the study, all fields were exempted from fertilizer and pesticide applications.

Based on interviews with farmers and a previous study (Graefe et al., 2017), eight forest tree species were selected (Table 1) (Asitoakor et al., 2022) and used as treatments. The species were identified with help from farmers and confirmed by use of a botanical guide (Hawthorne and Gyakari, 2006). The species included both species considered as "desirable" and "undesirable" shade trees for cocoa production (Manu and Tetteh, 1987; Sauvadet et al., 2020) (Table 1). *Cedrela odorata* L. from South America was the only exotic species, while the other species were native and either remnants of previous forests or deliberately planted by farmers.

In each field, we delineated four to eight circular plots using the selected shade trees as the central reference points. The plots were 10 m in radius from the trunk of the shade trees, and at least 30 m from each other, to avoid the overlap of plots. Each field contained one or two unshaded control plots demarcated in open areas of the fields. Cocoa trees within each plot were assigned unique codes and monitored monthly for mirid infestation and BPD infection. The basal area of both shade trees and cocoa trees within plots were determined through measurement of diameter at breast height (1.30 m above ground, and 0.3 m above eventual tree buttresses) using diameter tapes. We estimated the proportion of crown cover of each shade tree by the ground-level crown projection method (Bellow and Nair, 2003), and calculated the cocoa density based on counts of the cocoa trees (Table 1).

2.3. Evaluation of mirid population, mirid infestation and black pod diseases (BPD) infection

Mirid counts, the total number of pods and the number of cocoa pods with symptoms of mirid infestation and BPD infection were observed monthly by the visual hand-height assessment method (Collingwood, 1971). The method involved visual inspection of pods and their peduncles, stems, and branches up to 2.5 m above the ground in the morning (6:00–9:00 a.m.) for mirid presence. The mirids were counted, and wounds (vivid circular or elliptical dark feeding lesions) (Awudzi et al., 2017) on cocoa pods were recorded as damage caused by mirids. Rottenness and black coloured patches on part or the whole pod surface

Table 1
Treatment and study plot characteristics (Values represent means ± s.e.) [D = deciduous, SD = Semi-deciduous, P = Shade tree planted by farmers, R = Shade tree from remnants of previous forest, N = Number of sampled plots/replications, CRIG = Cocoa Research Institute of Ghana].

Treatment/Source	CRIG Recommendation status	Family	N	Plot area (m^2)	Cocoa trees per plot	Shade tree dbh (m)	Crown Cover (%)
Control (no-shade)	–	–	16	242 ± 27	18 ± 1	–	–
Alstonia boonei De Wild (D′ P, R)	Desirable	Apocynaceae	7	257 ± 28	17 ± 1	0.29 ± 0.04	68 ± 1
Cedrela odorata L. (D; P)	Desirable	Meliaceae	3	243 ± 40	14 ± 2	0.51 ± 0.07	32 ± 1
Khaya ivorensis A. Chem (SD; P, R)	Desirable	Meliaceae	8	247 ± 25	14 ± 1	0.53 ± 0.08	41 ± 1
Milicia excelsa (Welw.) C. Berg. (D; P, R)	Desirable	Moraceae	10	244 ± 24	13 ± 1	0.54 ± 0.03	60 ± 1
Terminalia ivorensis A. Chev. (D; P, R)	Desirable	Combretaceae	9	250 ± 26	14 ± 1	0.43 ± 0.05	73 ± 1
Terminalia superba Engl. & Diels (D; P, R)	Desirable	Combretaceae	9	248 ± 24	16 ± 1	0.45 ± 0.09	61 ± 1
Cola nitida Schott & Endl. (SD; P, R)	Undesirable	Malvaceae	6	241 ± 27	13 ± 1	0.47 ± 0.08	62 ± 1
Triplochiton scleroxylon K. Schum (D; P, R)	Undesirable	Malvaceae	6	227 ± 33	16 ± 2	0.80 ± 0.09	51 ± 1

(Source: Manu and Tetteh 1987; Asitoakor et al., 2022).

by the fungi (*P. megakarya* and/or *P. palmivora*) were taken as signs of BPD and pods showing symptoms were counted. Proportions of pods infested with mirids and BPD infection to the total number of pods were calculated.

2.4. Determination of on-farm temperature, relative humidity, and rainfall

Two data loggers (iButton DS1923-F5#, Hygrochron Temperature and Humidity data logger, Maxim Integrated Productions, CA, USA) were installed to monitor temperature and relative humidity in 2 randomly selected fields. The devices were shielded from direct irradiance and positioned 2 m above ground within the cocoa canopy and set to record data every 30 min. Data were downloaded every 3 months and mean monthly temperatures and relative humidity were calculated. A wireless rain-gauge device (Rosenborg Exclusive Tradløs Regnmåler, Model 35980, Carrin Electronics limited, Hong Kong) mounted 1.5 m above ground in open areas in each community was used to monitor daily, monthly, and annual rainfall.

2.5. Data analysis

For data analysis, we used R version 4.3.0 (R Core Team, 2023). Two linear mixed effect models were fitted using the "lme4" package (Bates et al., 2015) to determine treatment effects on mirid populations and damaged pods. In the first model (1), we used the treatments (Tt) made up of the shade trees and control treatments, and the farm locality (FL) as fixed effects and cocoa tree density (CD) as co-variates. In the second model (2), we excluded the control treatment and used only the shade trees treatment (TT) as fixed effects in addition to CD, FL and the basal area (BA) of shade trees as co-variates. This was to assess the effects of tree sizes on the dependent variables (*Y*; thus the numbers of mirids, and the numbers and proportions of mirids and BPD infested pods). The fields (FD), crop season (CS); thus May–October = main crop season and November–April = minor crop season, and year (YR) were included as random effects in both models as expressed below.

$$Y = \alpha(\mathrm{Tt}) + \beta(\mathrm{CD}) + \delta(\mathrm{FL}) + A(\mathrm{FD}) + B(\mathrm{CS}) + C(\mathrm{YR}) \quad (1)$$

$$Y = \alpha(\mathrm{TT}) + \beta(\mathrm{CD}) + \gamma(\mathrm{BA}) + \delta(\mathrm{FL}) + A(\mathrm{FD}) + B(\mathrm{CS}) + C(\mathrm{YR}) \quad (2)$$

Interaction terms between the treatments and crop season (Tt:CS) and the treatments and year (Tt:YR and TT:YR) were further included in the models to estimate the seasonal responses of the shade tree species. Residual plots showed deviations from normality for mirid population and damaged pods due to mirids and BPD, hence the data were log transformed prior to modelling. For tests of significance of the remaining effects, we used asymptotic chi-square tests on the maximum likelihood ratio test statistics. Where significant differences were observed, a post hoc Tukey test through the "emmeans" package in R (Lenth, 2020) was used for mean separation.

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 "MuMIn" (Barton, 2022) packages in R. We conducted Pearson correlation analysis to determine the associations between the climatic variables (rainfall, humidity, and temperature) and pod production, mirid population, and pod damages due to BPD and mirids. Because damages from mirids and BPD infections in cocoa develop over a period (especially considering the 41 days life cycle of mirids), our correlation analysis was conducted in two ways; (i) climatic parameters against mirid infestation and BPD infection in the same month, and (ii) climatic parameters against the mirid infestation and BPD infection of the next month. The proportion of damaged pods due to mirids and BPD were calculated by dividing the number of infested pods by the total number of produced pods. Mirids and BPD challenges are often continuous and across seasons, hence we conducted a Pearson correlation analysis between the production of pods and the proportion of mirids and BPD damaged pods across the main and minor crop seasons.

3. Results

3.1. Relationship between shade tree species, mirid infestation and black pod disease infection

Overall, 100,005 cocoa pods were counted in the study, with an annual average pod production of 33.2 ± 4.7 pods $tree^{-1}$ which varied with season at 22.8 ± 5.2 pods $tree^{-1}$ and 10.4 ± 4.1 pods $tree^{-1}$ in the main crop and minor crop seasons, respectively (Fig. 1A). The highest and lowest number of pods were observed in *K. ivorensis* and control plots, respectively (Fig. 1A). The average number of cocoa pods per tree and the number of pods infested by mirids and BPD infection were significantly different between the treatments and seasons (Fig. 1; Table 2). To distinguish the genera *Cola* and *Terminalia* from *Cedrela* and *Triplochiton*, we hereafter refer to *Cedrela* and *Triplochiton* as Ce and Tr, respectively.

Comparison between the shade tree species and the unshaded control plots from model (1) showed that the presence of mirids on cocoa trees increased in the following order: *Ce. odorata, M. excelsa, K. ivorensis, T. superba, T. ivorensis, C. nitida, A. boonei* and *Tr. scleroxylon.* However, cocoa trees in unshaded plots had about twice the number of damaged pods due to mirids compared with those under *Ce. odorata, M. excelsa*, and *K. ivorensis* plots, which recorded the least mirid pod damage in both seasons. Black pod disease infection was highest in *C. nitida* and *Tr. scleroxylon* plots while cocoa trees in the control unshaded areas had the least. The proportions of damaged cocoa pods due to mirids and BPD infection also varied across the treatments (Fig. 1C and D). The highest proportion of mirid infestation was observed in the unshaded plots while the least was recorded in *K. ivorensis, Ce. odorata* and *M. excelsa* plots (Fig. 1D). The highest proportion of BPD infection was recorded in *C. nitida* and *Tr. scleroxylon* while the least was observed in *Ce. odorata*,

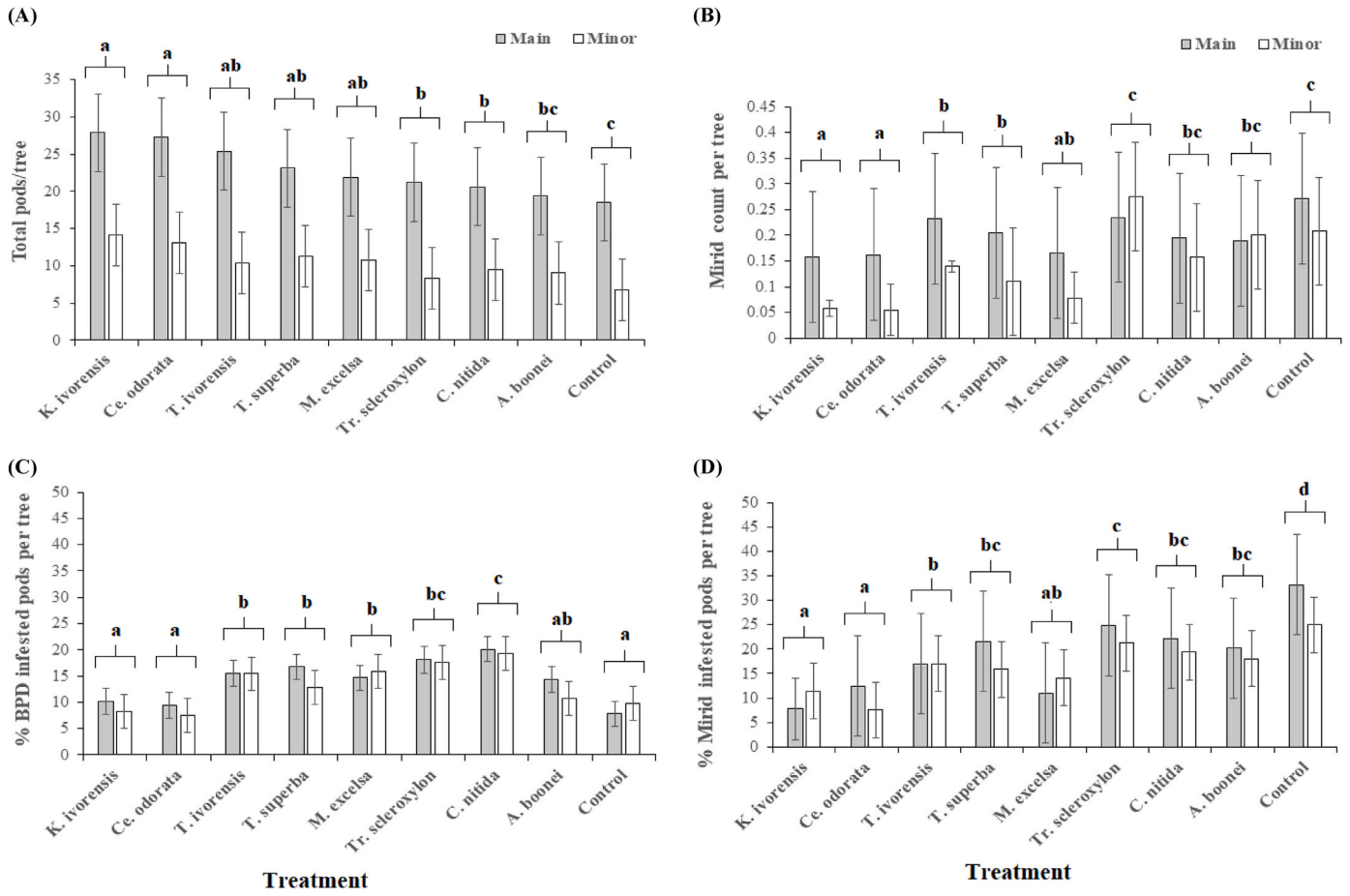


Fig. 1. Least square mean values (±s.e.) of seasonal (A) cocoa productions, (B) mirid counts, and the percentage damaged cocoa pods due to (C) black pod disease (BPD) and (D) mirids across treatments during the study (from May 2018 to December 2020). [Different letters indicate differences in overall (thus sum of the two seasons) number of pods produced, mirid counts and percentage damaged pods due to BPD and mirids between treatments].

K. ivorensis and the control plots (Fig. 1C).

From model (1), the density of cocoa trees negatively impacted the production of cocoa pods (Estimate = −4.04 ± 0.14 trees m^{-2}), mirid population (Estimate = −0.93 ± 0.06 trees m^{-2}) and pod damages from mirid infestations (Estimate = −1.94 ± 0.12 trees m^{-2}). This implies that increasing cocoa tree density decreased productivity while reducing infestation of mirids and their corresponding damage effect on pods. On the contrary, the more crowded cocoa trees were, the higher the infection of BPD (Estimate = 1.10 ± 0.27 trees m^{-2}). A significant interaction was observed between treatment and seasons as well as the treatment and years (Table 2) showing that the shade tree species had different impact on the production of pods, mirid population, damaged pods due to mirids, and BPD across the seasons and years of assessment.

Results from model (2) indicated that cocoa trees under larger shade trees (as assessed by basal area) had higher populations of mirids as well as increased pod damages due to mirid infestations and BPD infection (Table 3). Between 12 and 18% of the variation was caused by the fixed elements in the models, which included treatments (shade tree species), shade tree basal area and cocoa density. Including random factors, this level increased up to 42% of the variability observed (Table 3), leaving a considerable amount of variation to the residuals.

The number of cocoa pods produced in the main and minor seasons were highly correlated across tree species ($R^2 = 0.91$, $p < 0.001$) (Fig. 2) indicating that the number of pods produced in one season is linked with the productivity in the subsequent season. Mirid counts were positively correlated with the proportion of pods damaged by mirids, however the number of pods and percentage damaged pods due to mirids were negatively correlated (Fig. 2), suggesting that plots with high cocoa productivity also had low damage caused by mirids. The percentage of damaged pods due to BPD was not associated with the number of pods produced (Fig. 2), indicating that the production of cocoa pods was relatively unaffected by BPD infection across tree species.

3.2. Relationship between climatic conditions, mirid infestation and black pod disease infection

Our results showed a bimodal rainfall regime with dry and rainy seasons in the study area (Fig. 3A). Rainfall and relative humidity were highest in September and October, and the least rainfall was observed between December and February (Fig. 3A). The highest mean monthly temperatures were recorded between November and April, while lowest mean monthly temperatures were recorded between June and August (Fig. 3A). We observed a significant positive relationship between rainfall and relative humidity ($r = 0.63$, $t = 4.41$, $p < 0.001$) and a significant negative relationship between rainfall and temperature ($r = -0.53$, $t = -3.42$, $p = 0.002$), and relative humidity and temperature ($r = -0.67$, $t = -5$, $p < 0.001$).

The mean monthly density of mirids fluctuated (0.03 ± 0.01 to 0.85 ± 0.03 mirids per cocoa tree) (Fig. 3B). A total of 3792 mirids were counted at an overall average of 0.19 ± 0.01 (se) mirids per cocoa tree per season. The density of mirids generally increased from the beginning to the end of the study with highest mirid counts occurring between June to December 2020 (Fig. 3B). Cocoa pod production followed seasonal trends with highest production in the main crop season (May–October) and the lowest production in the minor crop season (November–April) (Fig. 3B). The number of pods infested by mirids, and

Table 2
Results from the linear mixed-effects model (1) for treatments and cocoa density effects on cocoa pod production and pods damaged by mirid infestations and black pod disease infection in the study.

Test Parameters	Df	LRT	Pr (Chi)
Total pod production			
Treatment	8	140.29	<0.0001
Cocoa density	1	794.55	<0.0001
Farm locality	2	2.59	0.2746
Treatment: Year	18	110.86	<0.0001
Treatment: Season	9	111.32	<0.0001
Mirid population			
Treatment	8	230.06	<0.0001
Cocoa density	1	181.90	<0.0001
Farm locality	2	8.80	0.0123
Treatment: Year	18	217.53	<0.0001
Treatment: Season	9	99.47	<0.0001
Mirid pod infestation			
Treatment	8	275.38	<0.0001
Cocoa density	1	217.22	<0.0001
Farm locality	2	17.61	0.0002
Treatment: Year	18	137.69	<0.0001
Treatment: Season	9	172.73	<0.0001
Prop. Mirid infestation			
Treatment	8	139.78	<0.0001
Cocoa density	1	121.58	<0.0001
Farm locality	2	22.83	<0.0001
Treatment: Year	18	262.90	<0.0001
Treatment: Season	9	194.34	<0.0001
BPD pod infestation			
Treatment	8	284.18	<0.0001
Cocoa density	1	13.60	0.0002
Farm locality	2	6.26	0.0437
Treatment: Year	18	168.88	<0.0001
Treatment: Season	9	2.85	0.8989
Prop. BPD infestation			
Treatment	8	218.83	<0.0001
Cocoa density	1	536.98	<0.0001
Farm locality	2	13.38	<0.0001
Treatment: Year	18	189.35	<0.0001
Treatment: Season	9	126.42	<0.0001

[Df = degrees of freedom, LRT = Likelihood Ratio Test-statistics, Pr (Chi) = Asymptotic chi-square tests, BPD = Black pod disease].

Table 3
Variance explained by the fixed factors (shade tree only; $R^2_{(m)}$), fixed and random factors ($R^2_{(c)}$) and estimates and p-values of basal area and cocoa density components from model (2). [BPD = Black pod disease, Prop. = proportions].

Parameters	$R^2_{(m)}$	$R^2_{(c)}$	Basal area		Cocoa density	
			Estimate (m^2)	p-values	Estimate (trees m^{-2})	p-values
Total pod production	0.12	0.35	0.08	0.018	−4.55	<0.001
Mirid population	0.14	0.20	0.05	0.001	−0.97	<0.001
Mirid pod infestation	0.12	0.36	0.14	<0.001	−2.26	<0.001
Prop. Mirid infestation	0.13	0.42	0.04	0.451	−4.47	<0.001
BPD pod infection	0.15	0.23	0.28	<0.001	0.79	<0.001
Prop. BPD infection	0.18	0.31	0.05	0.329	5.83	<0.001

BPD also varied with overall mean monthly infestation at 4 ± 1 pods per tree for mirids and 3 ± 1 pods per tree for BPD (Fig. 3C). We observed a positive relationship between pod production, mirid infestation and BPD infection, as when the number of produced pods increased, the damaged pods due to mirid infestation and BPD infection also increased (Fig. 3C). Furthermore, the proportion of cocoa pods infested by mirids, and those infected with BPD varied with months across the study period (Fig. 3D).

Rainfall and relative humidity showed a positive correlation with the production of cocoa pods and BPD infections while temperatures had a negative association with pod production and BPD infection (Table 4). Temperature had a positive association with pod damage caused by mirid infestation (Table 4). More than 40% of the variation in pod production in the study was explained by variations in rainfall and relative humidity while variation in temperature explained 65% of the variation in pod production.

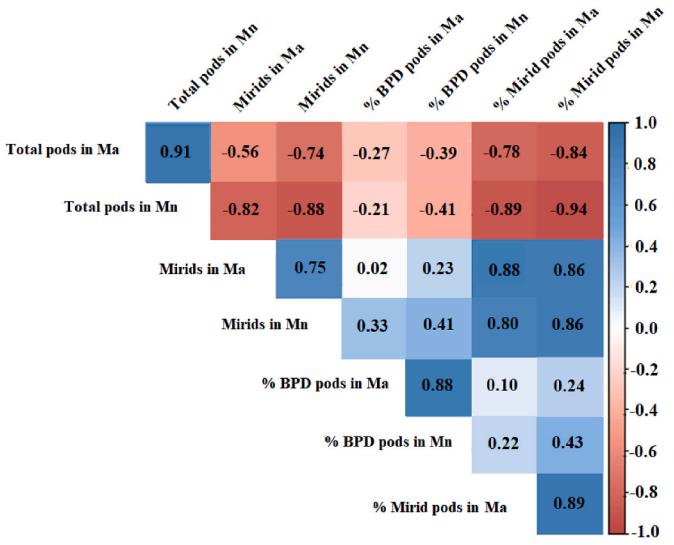


Fig. 2. Pearson correlation coefficients matrix for the relationship between the number of produced pods, mirid population, and percentage damaged pods due to mirid infestations and BPD infection across the species during the study. Correlation coefficients above 0.66 and below −0.66 are significant. [BPD = Black pod disease, Ma = main crop season, Mn = Minor crop season].

4. Discussion

4.1. Shade tree species interactions with mirid infestation and black pod disease infection

This study confirmed that the choice of shade tree species matters for both yield and the management of mirid infestations and BPD infection. Shade tree species assessed in this study varied in stem size, structure of the crown, and phenology, and hence influenced mirid infestation and BPD infection differently. Species with dense canopies provide more shade and more humid conditions, e.g. *C. nitida,* which appears to be more favourable for BPD infection. In contrast, less dense canopy trees, e.g. *Ce. Odorata, K. ivorensis* and *M. excelsa*, seem more suitable for the management of BPD (Fig. 1). The significant variation in mirid population density between the treatments where more mirids were found in the unshaded control plots confirmed the association of mirids with open and warm areas in cocoa systems (Babin et al., 2010). The lowest incidence of mirid infestation recorded on cocoa trees in *Ce. odorata* and *K. ivorensis* plots may be attributed to release of garlic or onion-like scent in the case of *Ce. odorata* and to the unpleasant, bitter taste that repels insects in the case of *K. ivorensis* (Hawthorne and Gyakari 2006). This perhaps accounted for the higher pod production and reduced mirid infestation in the *K. ivorensis* and *Ce. odorata* plots in this study. The high incidences of mirid infestation in species like *C. nitida* and *Tr. scleroxylon* may be explained by the fact that, like cocoa, they belong to the same Malvaceae family. Species of Malvaceae have been reported to produce mucilaginous juice or sap (Reznicek et al., 2011) upon which mirids feed, especially in low pod production periods or/and in the absence of pods. These observations support the report that species of Malvaceae can be alternative hosts for mirids in cocoa agroforestry systems (Babin et al., 2010). Furthermore, Sauvadet et al. (2020) demonstrated low compatibility between cocoa, *C. nitida* and *Tr. scleroxylon* since they

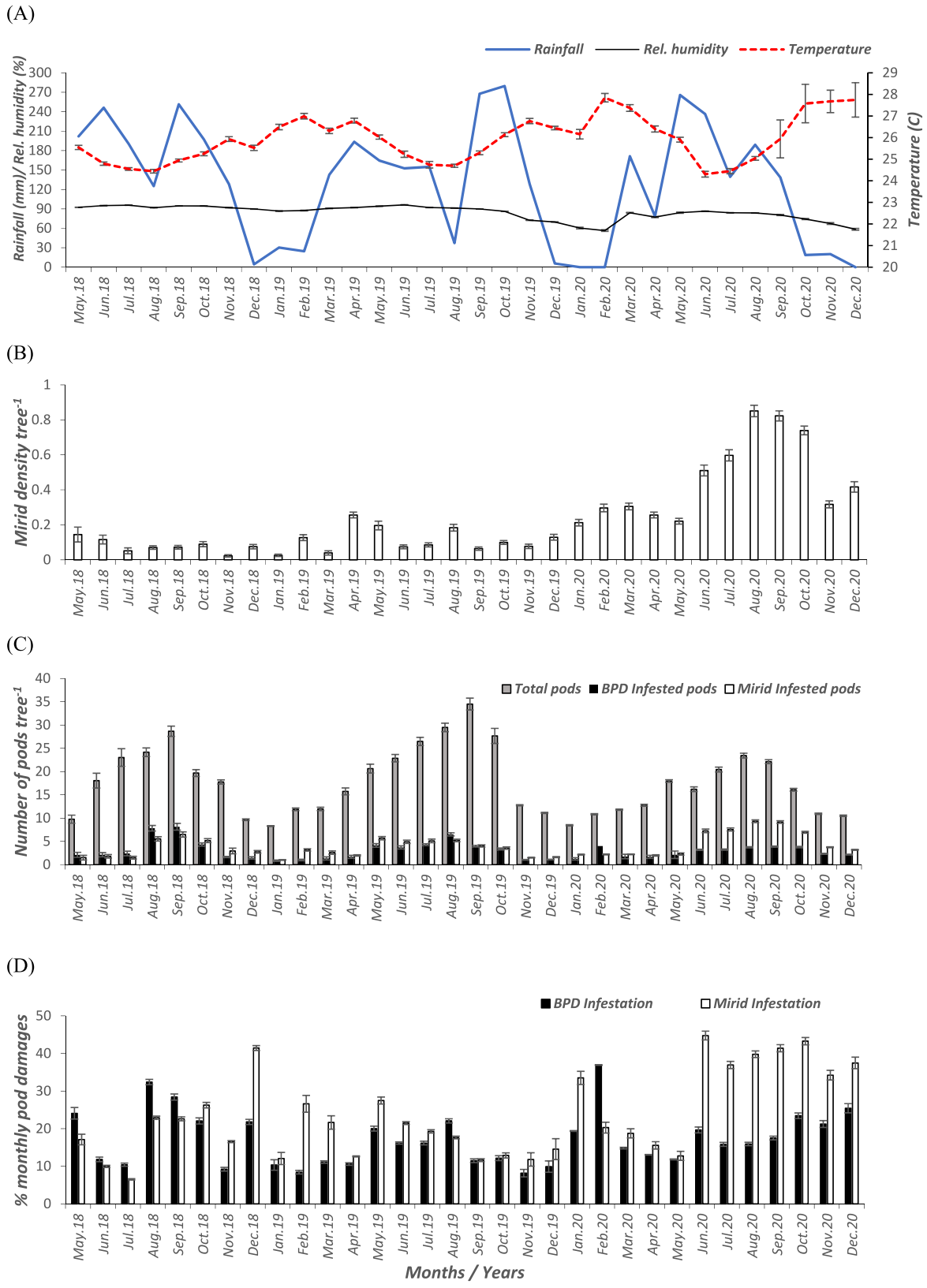


Fig. 3. Monthly distribution of (A) Rainfall, Relative humidity, and Temperature, (B) mirid counts per cocoa tree, (C) Pod production and infestation by mirids and BPD infection, and (D) the proportions of damaged pods from mirid infestation and BPD infection during the study [BPD = Black pod disease]. Values represent the least square means (±s.e.).

Table 4
Results of Pearson correlation analysis between mean monthly climatic factors and the number of pods produced, mirid population, and pod damage due to mirids and black pod disease (BPD). [Period A = previous months' measurement; Period B = current month; Prop. = proportions, r = coefficient of correlation, t = *t*-test statistics, '*' indicate significant values].

Parameters	Rainfall			Rel. humidity			Temperature		
	r	t	p-value	r	t	p-value	r	t	p-value
Period A									
Total pods	0.42	2.56	0.016*	0.56	3.65	0.001*	−0.71	−5.45	<0.001*
Mirid Counts	0.04	0.23	0.823	−0.36	−2.06	0.048*	0.04	0.20	0.841
Mirid infested pods	0.33	1.87	0.072	0.21	1.15	0.261	0.5	3.09	0.004*
Prop. of mirid pods	−0.50	−3.12	0.004*	−0.61	−4.17	<0.001*	0.55	3.54	0.001*
BPD infected pods	0.24	1.35	0.188	0.31	1.76	0.088	−0.59	−3.89	0.001*
Prop. of BPD	0.42	2.50	0.018*	0.55	3.51	0.001*	−0.25	−1.37	0.180
Period B									
Total pods	0.60	4.11	<0.001*	0.53	3.41	0.002*	−0.60	−4.12	<0.001*
Mirid Counts	−0.09	−0.52	0.607	−0.36	−2.09	0.045*	0.12	0.69	0.498
Mirid infested pods	0.21	1.03	0.310	0.15	0.83	0.411	0.38	2.26	0.031*
Prop. of mirid pods	0.69	5.15	<0.001*	0.62	4.27	<0.001*	0.56	3.66	0.001*
BPD infected pods	0.26	1.46	0.155	0.28	1.63	0.115	−0.47	−2.89	0.007*
Prop. of BPD pods	0.40	2.40	0.023*	0.47	2.92	0.007*	−0.39	−2.30	0.029*

belong to same family and therefore have a close evolutionary distance. Hence, shade trees grown/or retained in cocoa agroforestry systems must be selected from different families other than cocoa to enhance compatibility and positive interaction for growth and development of the crop (Sauvadet et al., 2020).

An important characteristic of shade trees that influence their potential contribution to pest and disease management is deciduousness during certain months of the year (especially in minor crop periods characterized by low or no rainfall). *Cola nitida* is evergreen and provides shade throughout the year with corresponding high relative humidity that favour BPD infection (Fig. 1C). Species such as *K. ivorensis, M. excelsa* and *Ce. odorata* are semi-deciduous and retain partial shade under water stress conditions. Complete or partial defoliation of shade trees in dry seasons increase penetration of sunlight, leading to elevated on-farm temperatures associated with pod wilt (Asitoakor et al., 2022), high rates of mirid infestation and pod damage (Babin et al., 2010; Mahob et al., 2015). However, the adoption of compatible shade trees with cocoa is based on farmers' perception of the interaction. Through informal interviews during this study, farmers mentioned negative interaction between cocoa and *C. nitida,* stating that they are a major cause of mirid infestations, BPD infections, lower yield, and death of nearby cocoa trees. Negative associations between cocoa and *C. nitida* were also reported by Dumont et al. (2014) and Graefe et al. (2017) in studies on shade tree services in Cote d'Ivoire and Ghana, respectively. Despite this disadvantage, some cocoa farmers prefer *C. nitida* because of the complementary income generated by the sale of Cola nuts and own consumption.

The strong correlation between the main and minor crop season with regards to the production of pods and the corresponding proportions of mirid and BPD damages under the shaded conditions (Fig. 2) provide some insight on the potential of shade trees for yield sustainability and IPM in cocoa. The significant role of the species in this study on yield or pod production has been established (Asitoakor et al., 2022) while their advantages with regard to the management of mirid and BPD from one season to another are shown in Fig. 2. Under smallholder cocoa systems, mirid and BPD transfer from one season to another is common especially in poorly managed farms where the non-removal and/or retention of BPD infected pods on cocoa trees are common. The lack of pruning of both cocoa trees and shade trees, especially shade trees with dense canopies, e.g. *C. nitida*, support the retention and transfer of BPD across seasons. With mirids, the alternative host function of certain shade tree species, together with the high mobility of the insect, favour the prevalence of the pest across seasons. Therefore, good farm management practices and rightful selection of shade trees on cocoa are recommended as IPM practices for cocoa.

4.2. The relationship between climatic factors, mirid infestation and black pod disease infection in cocoa

Mirid infestations and BPD infection in cocoa systems are strongly influenced by climatic factors (rainfall, temperature and relative humidity) and the intensity of agronomic/management practices including the retention of shade trees on farms. Here, the importance of climatic conditions on mirid incidence was confirmed by the seasonal variation and positive relationship between temperature and mirid infestation. High mirid populations have been reported under warmer conditions occurring especially in open areas in cocoa canopies (Babin et al., 2010; Abdulai et al., 2017; Asitoakor et al., 2022). In Ghana, Abdulai et al. (2018) observed increasing insect pest populations (including mirids) with increasing temperatures and reduced rainfall. Thus the expected reduction of rainfall and increase in temperature in sub-Saharan Africa due to climate change (Läderach et al., 2013; Olwig et al., 2024) could increase mirid activities in cocoa producing countries such as Ghana, Cote d'Ivoire, Nigeria, and Togo (Cilas and Bastide, 2020).

The observed positive association between rainfall/humidity and BPD infection confirmed the prevalence of the fungal disease under moist conditions (Talley et al., 2002; Abdulai et al., 2017). The correlations between the climatic conditions and mirid infestation and BPD infection with highest incidence in August and September suggest that management practices (e.g. regular pruning) that reduce atmospheric moisture in cocoa farms during this period may be beneficial. The seemingly negative effects of some shade trees (e.g. *C. nitida*) suggested by higher BPD infection, and the ameliorating effects of other shade trees (e.g. *Ce. odorata, K. ivorensis* and *M. excelsa*) resulting in fewer attacks by mirids, present a challenge for IPM in cocoa agroforestry given that shaded systems benefit mirid management while promoting BPD.

Although studies of mirids in cocoa usually show low and fluctuating population densities (Babin et al., 2010; Mahob et al., 2015; Awudzi et al., 2017; Mahot et al., 2020), a single mirid per cocoa tree may lead to high economic losses in poorly managed farms (Babin et al., 2010). The average densities of mirids observed in this study were lower than the suggested phytosanitary thresholds of 0.6 mirid per cocoa tree in Ghana (Padi and Owusu, 1998) and 0.7 mirid per cocoa tree in Cameroon (Decazy and Essono, 1979). Although the densities of mirids observed increased towards the end of the study (Fig. 3B), the overall low densities throughout the study may be credited to good agronomic practices including pruning (twice annually) adopted by the farmers, which have been noted to improve the health condition of cocoa trees (Armengot et al., 2020). Adopting shade trees such as *Ce. odorata* and *K. ivorensis* may provide a basis for their use for IPM in cocoa.

Peak periods of mirid infestations are followed by population

declines (Bisseleua et al., 2011; Adu-Acheampong et al., 2014; Mahob et al., 2015; Awudzi et al., 2017) as observed in Fig. 3C. This is attributed to the short life cycle of the insect and the dynamics of food sources to support their populations. The main crop season characterized by high rainfall is associated with high production of pods (Adu-Acheampong et al., 2014, 2015), new flushes and young twigs that increase the availability of food for mirid population growth. Positive relationships between food supply and sizes of insect populations were reported by Birch (1948), Hidalgo et al. (2013), Khaliq et al. (2014) and Mahob et al. (2015). Furthermore, mirids derive safe and secure sites for oviposition underneath the bark of young shoots and cocoa pods (Sarfo, 2013). The management of mirids is likely to become more difficult under climate change scenarios. This is because of the short life cycle of the insect (Adu-Acheampong et al., 2014; Awudzi et al., 2017), and the significant role temperature and humidity play in mirid desiccation (Entwistle, 2008; Mahob et al., 2015). The biological cycle of mirids is likely to be shortened under prolonged drought period and erratic rainfall. However, the effects may be minimized by the incorporation of shade tree species such as *Ce. odorata* and *K. ivorensis* that regulate on-farm temperature and relative humidity.

The high BPD infection during the peak rainy periods was expected as BPD in most tropical regions is mainly caused by *P. megakarya* and *P. palmivora* transmitted through primary and secondary inoculum spread from rainfall splashes (Ndoumbe-Nkeng et al., 2004). Hence, farmers ability to anticipate months with high rainfall is important for effective management of BPD (Akrofi et al., 2003). However, the combination of cultural practices (e.g. cocoa and shade tree pruning, weeding, pesticide application, removal of diseased pods) and the adoption of technologies (e.g. disease resistant varieties) are key approaches to control BPD (Akrofi et al., 2003; Asitoakor et al., 2022). Most of these approaches are costly and require technical skills which may not be available to smallholder farmers who predominate cocoa production. Some authors (Deberdt et al., 2008; Larbi-Koranteng et al., 2020) recommend biological control measures, for example, the use of *Trichoderma* spp. or other biological agents as alternative to agro-chemicals in order to address the persistent accumulation of chemical residues in the environment. Divergent views exist on the role of certain shade tree species and their influences in the management of BPD and mirids towards sustainable yield (Dumont et al., 2014; Graefe et al., 2017). Based on findings of this study, there appears to be a high potential associated with carefully selected shade tree species to tackle and minimize environmental pollution from excessive agro-chemical application while advancing and sustaining cocoa productivity although this might not necessarily stand for all agroecological systems.

Our study is limited by the short duration (two years) of the research, the lack of data on the light intensity within the treatment plots and the lack of replication of the experiment across other cocoa producing regions in West Africa. A longer duration of research may provide more grounds for drawing conclusions on the selected tree species and their relationships and interactions with cocoa trees with regard to mirid infestation and black pod disease infection. Measurement of the light reaching the cocoa canopies through the shade trees would help to decipher the quality of shade provided by the individual shade tree species. This may be an important explanatory variable for mirid occurrences, distribution and activity across the treatments. Therefore, we recommend longer periods of research and inclusion of light intensity determination in future studies of this nature.

5. Conclusion

Shade tree species influence mirid infestation and black pod disease infection differently in cocoa-agroforestry systems (CAS). Species such as *Ce. odorata, K. ivorensis* and *M. excelsa* appear to reduce mirid infestation compared to other species while *C. nitida* and *Tr. scleroxylon* favour increased mirid infestation and BPD infections. The density of cocoa trees and the sizes of shade trees in CAS are important factors for the management of mirid and BPD as they influence the micro-climate within cocoa fields. This calls for a careful selection process that considers shade species compatibility as a strategic tool in the management of mirid and BPD in the promotion of CAS.

CRediT authorship contribution statement

Bismark Kwesi Asitoakor: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anders Ræbild:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Richard Asare:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Philippe Vaast:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andy G. Howe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vincent Yao Eziah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kwadwo Owusu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eric Opoku Mensah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Ashie Kotey:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hans Peter Ravn:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Data availability

Data will be made available on request.

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