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Impact of common shade tree species on microclimate and cocoa growth in agroforestry systems in Ghana

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Abstract Climate change is a growing threat to agriculture globally, with most substantial impacts expected in tropical smallholder systems such as cocoa farms in West Africa. Cocoa agroforestry is widely believed to enhance resilience to climatic extremes due to protection and a favourable microclimate under the shade trees. Morphological traits of many locally used shade tree species and their specific contribution to microclimate for climate-resilient cocoa production remain unclear. Therefore, aboveground morphology and sub canopy microclimate of eight common shade tree species were investigated in cocoa agroforestry systems in the Ahafo region, Ghana. Additionally, the growth of cocoa trees in three different distance zones to the shade tree stem was measured. The eight different shade tree species exhibited considerable variation in their impact on microclimate and cocoa growth. *M. indica* and *M. excelsa* allowed lowest light transmission, with the highest microclimatic buffering effect, i.e., reducing vapour pressure deficit and daily fluctuations of temperature and relative humidity. Cocoa trees around *M. lucida* and *F. capensis* were the highest in growth, characterized by height and stem diameter. However, a universally superior shade tree species could not be identified implying the need for shade tree diversity allowing various microclimatic conditions within an agroforestry system to spread risk of climate extremes. Cocoa tree growth was more affected by distance to the shade tree than by shade tree species, resulting in enhanced growth with distance to the stem. These findings provide a better understanding of species-related differences on cocoa growing conditions and climate change adaptation strategies.

Keywords Morphology · Functional traits · *Theobroma cacao* L. · Climate change adaptation · Vapour pressure deficit

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Introduction

Climate change is a rapidly rising threat to agriculture globally, affecting growing conditions by rising temperature and altered precipitation patterns. The most substantial impacts are expected in tropical, rain-fed smallholder systems (Morton 2007), which currently produce about 95% of the world's cocoa (Anga 2016). Ghana, the world's second largest cocoa producer, accounts for roughly 20% of the global cocoa bean supply (Ghana Cocoa Board 2018). With an increasing global demand, cocoa cultivation in Ghana has been growing to an area of 1.7 million hectares over the last three decades (Wainaina et al. 2021). However, because of climate change, a stagnation or even decrease in the future is predicted (Ghana Cocoa Board 2018; Kozicka et al. 2018). Given that more than two million people are employed along the supply chain (Ghana Cocoa Board 2018), ensuring the future of cocoa farming in Ghana is also of high socio-economic importance, calling for swift adaptation strategies.

Cocoa (*Theobroma cacao* L.) is a tropical tree crop originating from the understory of the Amazon rainforest and thus has optimal growth and a longer productive lifetime under low shade levels since shade prevents early senescence reported for full sun exposure (Galyuon et al. 1996; Mensah et al. 2023; Obiri et al. 2007). Intercropping cocoa with shade trees in agroforestry systems (AFS) is widely practiced and perceived as a strategy to adapt to and mitigate the effects of climate change as shade trees buffer extreme weather conditions, providing a favourable microclimate while at the same time sequestering atmospheric carbon (Blaser-Hart et al. 2021; Niether et al. 2018b, 2020; Thomson et al. 2020). Moreover, shade trees often provide other ecosystem services, such as wind blockage, erosion control (Beer et al. 1987; Thomson et al. 2020), weed suppression (Graefe et al. 2017) and improved nutrient cycling by accessing nutrients in deeper soil layers (Buresh et al. 2004). By providing additional products, such as timber and fruits, shade trees can also increase the total system productivity (Niether et al. 2020). Cocoa agroforestry is therefore promoted by the Ghana Forest Plantation strategy and National Climate Change Policy (Thomson et al. 2020).

In contrast, dense spacing of shade trees can result in competition for water, nutrients and rooting space (Graefe et al. 2017; Niether et al. 2020), thereby causing slower vegetative growth of cocoa trees compared to monocultures (Schneider et al. 2017). This competition may also reduce cocoa tree resilience under extreme drought and heat (Abdulai et al. 2018b). Optimal shade tree density and shade levels depend on a variety of site- and system-specific factors. Under current conditions, the Cocoa Research Institute of Ghana (CRIG) recommends keeping 16 to 18 high shade trees per hectare, spaced 24 m x 24 m, providing a shade level of 30% to 40% (Acheampong et al. 2014). The impact of shade trees on cocoa yields varies among studies, with some reporting reductions (Niether et al. 2020) while others indicate increased yields (Asare et al. 2019; Asitoakor et al. 2022) in shaded systems. Beside spacing of shade trees, also the species selection may have an effect on understory cocoa growth and production due to morphological growth characteristics and leaf traits (Asigbaase et al. 2023; Beer 1987; Sauvadet et al. 2020).

Considering the use of multiple shade tree species with different specific characteristics in AFS with cocoa, this study aims to characterise the aboveground morphology of eight shade tree species commonly used in Ghanaian cocoa agroforestry systems (Abdulai et al. 2018a; Asante et al. 2021; Asigbaase et al. 2023) and to describe their effects on sub canopy microclimate and growth of surrounding cocoa trees. The central questions were (a) whether and how the investigated shade tree species differ in their morphological traits, microclimatic impact and cocoa tree growth parameters, and (b) whether specific traits or species can be considered most favourable for climate-resilient cocoa AFS. We hypothesized that shade trees commonly used in Ghanaian agroforestry systems with cocoa have distinct morphological traits, which provide specific microclimatic environments for the understory cocoa and influence the development of the cocoa trees.

Understanding these factors is crucial for developing effective cocoa AFS that can withstand climate change and support sustainable cocoa farming in West Africa.

Material and methods

Study site and farm characteristics

The study was conducted from April to June 2022 in the village of Boaso (7°06′36.4″N 2°03′53.6″W) in the south-eastern part of the Ahafo region in Ghana. The regional climate is semi-humid tropical, characterized by an average annual precipitation of 1206 mm and two dry seasons in August, and November to February (climate data estimated from Harris et al. (2020)). January records the lowest average rainfall at 9.3 mm, while precipitation peaks in October at 175.6 mm. Over the period from 2000 to 2020, the mean annual temperature was 27.1 °C, with February having the highest mean temperature (30.1 °C) and August the lowest (25.1 °C). The current climate meets the optimal growth conditions of cocoa, which refer to a temperature of 20–30 °C, 2000 h of sunshine per year and relative humidity ranging from 70 to 80% during daytime and 90 to 100% at night (Afoakwa 2016). However, rainfall is below the optimum range of 1500–2500 mm (Afoakwa 2016). Existing land use systems were characterized by mixed cropping and short fallow (mostly until 2003 when cocoa plantation establishment started in the region).

Data collection was conducted in ten cocoa agroforestry systems ranging from 1.5 to 10 hectares (mean 4.8 ha) that were selected according to farm characteristics such as similarity in plantation age, management, soil texture, and planting materials that were identified in a preliminary study (Abdulai et al. in preparation). Cocoa trees of the hybrid variety Akokora Bedi were planted ten to 15 years ago with a spacing of three meter (resulting in an estimated density of 1111 to 1500 cocoa trees per hectare). Fertilizers, pesticides and herbicides was applied upon availability; most of the fieldwork was done manually. Pruning of cocoa trees was conducted throughout the year, with heavy pruning before the beginning of the rainy season (March to May). Twelve to 20 shade trees per hectare AFS were randomly spread. The shade trees were naturally regenerated and typically older than cocoa trees (age > 20 years). They were retained during land preparations for the cocoa plantations and served as early shade for young cocoa trees.

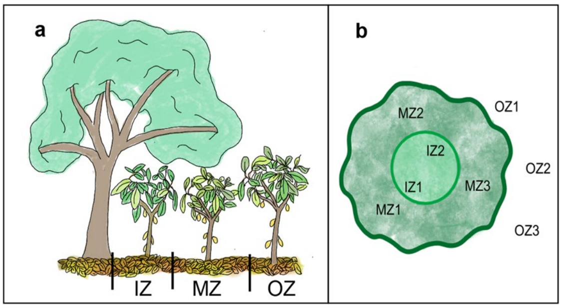

Fig. 2 **a** Representation of shade zones and **b** cocoa sampling design. IZ = inner zone (within a 3-m-distance to the stem), MZ = mid zone (within the edge of the canopy), OZ = outer zone (outside the canopy). Numbers represent repetitions of cocoa trees on the respective zone

Tree species selection and study design

Eight different shade tree species (Fig. 1, Additional file 1: Table A1) were identified in a preliminary study (Abdulai et al. in preparation) for further characterisation with five replications each, spread over ten farms (in total 40 shade tree individuals). Species were selected due to their high abundance in the cocoa growing regions of West Africa (Abdulai et al. 2018a; Sauvadet et al. 2020) implying importance for local producers. Although the species have different foliage phenology (deciduous or evergreen), foliage was fully abundant in all trees during the assessment period.

Around each shade tree individual, eight cocoa trees were selected for data collection (in total 320 cocoa trees): two in the inner shade zone (IZ, within a 3-m-distance to the stem), three in the mid zone (MZ, within the edge of the shade tree canopy), and three in the outer zone (OZ, outside the edge of the shade tree canopy) (Fig. 2).

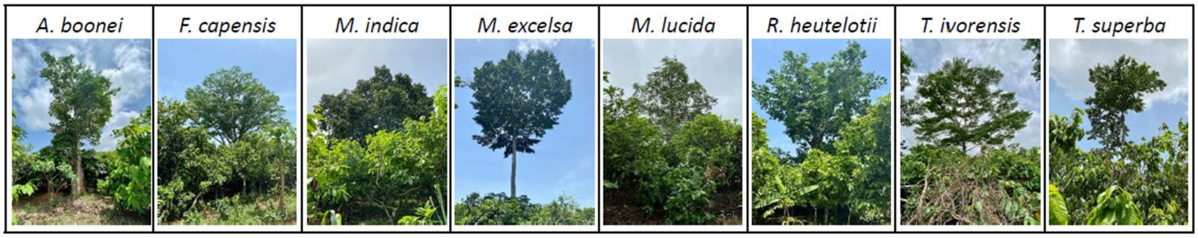

Fig. 1 Photographs of eight selected shade tree species

Growth parameters

Growth parameters were collected for shade trees (five individuals each of eight species) and respective cocoa trees (320 individuals) at the different shade tree impact zones. Shade tree height (at crown tip) and stem height (at the lowest branch of the crown) were measured using a vertex laser rangefinder (Vertex III, Häglöf Sweden AB, Långsele, Sweden). The diameter at breast height (DBH) was measured with a diameter tape at 1.3 m. The crown shape was visually classified into round, oval, weeping, umbrella and irregular, as suggested by Othman et al. (2015). Crown diameter (CD) and crown area (CA) were estimated from drone photos using ArcMap 10.8 (ESRI, Redlands, CA): CD was obtained by averaging the longest and shortest crown extent, and CA was measured as the area of a polygon corresponding to the tree crown.

Cocoa tree height and stem diameter at 1 m above the ground (DBH1) were measured with a marked bamboo stick and measuring tape, respectively. Additionally, the foliage of the cocoa trees was classified on a scale from 1 (no leaves) to 5 (lush and healthy canopy).

Microclimate

Photosynthetically active radiation (PAR, in µmol m^{-2} s^{-1}) was measured at five spots below the shade tree canopy but above the cocoa canopy at 7 m above the ground using a PAR/LAI Ceptometer AccuPAR LP-80 (Decagon Devices, Inc., Pullman, Washington, USA) in the morning (9:00 to 10:00 h), at midday (11:30 to 12:30 h) and in the afternoon (15:00 to 16:00 h) under clear sky conditions (Acheampong et al. 2014; Niether et al. 2018a, b). The mean of the five values for each individual shade tree was calculate to account for heterogeneous light conditions and compared to the PAR in full sun measured outside the canopy at the same time. The light that was not absorbed by the shade tree crown is the transmitted light presented here as percentage of total PAR.

Relative air humidity (RH) [%] and temperature [°C] were recorded with data loggers (Tinytag, Gemini Data Loggers Ltd., Chichester, UK) placed above the cocoa canopy at 7 m above the soil, but below the shade tree canopy and above unshaded cocoa (control). To prevent measurement inaccuracies caused by direct sunlight, the loggers were covered with pots wrapped in aluminium foil following the approach of Asare and Raebild (2016). Data was recorded at hourly intervals for ten days under one tree per species before the loggers were transferred to the next individual to finally obtain three species related replicates. The average daily course over all repetitions and measurement days was calculated for each species and the respective control. The buffering effects describes the difference between control and sub canopy values. The vapour pressure deficit of the air (VPD) was calculated on a daily basis according to Allen et al. (1998) (Additional file 1: Table A2).

Statistical analysis

Linear mixed-effects models were applied using R (R Core Team 2023) to analyse (1) the species effect of the shade tree species (fixed factor species: 8 levels) on the morphological traits (tree height, stem height, DBH, CD and CA) with shade tree nested to farm included as a random factor; and (2) the effect of shade tree species and unshaded control (fixed factor species: 9 levels) on microclimatic parameters (daily mean temperature, temperature fluctuation, RH, minimum RH and VPD). To describe the effect of shade tree species (8 levels) on the share of transmitted radiation (PAR), the time of the day was added as a second fixed factor (time: 3 levels) with no interaction. Additionally, we tested the effect of shade tree species (8 levels) and distance to the stem (3 levels) on cocoa growth parameters (height, DBH1, foliage). The significance of the effects was tested (lmerTest R package, Kuznetsova et al. 2017) and when significant differences were observed, post-hoc tests of pairwise comparison with least significant means were applied (lsmeans R package, Lenth 2016). When necessary, data were log- or Box-Cox-transformed to meet the requirement of normality and homoscedasticity of the residuals. Results are shown as mean ± standard error (se). Pearsons' r was calculated to show correlation between parameters. Data frames were calculated with the plyr R package (Wickham 2011) and graphs were designed with the ggplot2 R package (Wickham 2016).

Results

Shade tree aboveground morphology

The eight shade tree species exhibited morphological characteristics (Table 1). The DBH ranged from 46.3 cm for *T. ivorensis* to 100.6 cm for *F. capensis*. *F. capensis* was also the tallest tree species with a height of 20.6 m, and *T. superba* the shortest (15.4 m). Stem height varied from 6.3 m (*M. indica*) to 12.0 m (*R. heutelotii*). *A. boonei* were the smallest in CD and CA with 9.7 m and 85.1 m^2, respectively, in contrast to *M. indica* with the largest CD (15.9 m) and CA (213.0 m^2). Although there was intraspecific variation, generally, the crowns of *T. superba*, *T. ivorensis* and *M. excelsa* were round, *M. lucida*, *R. heudelotii* and *A. boonei* exhibited irregular crown shapes, *M. indica* was with branching downwards, and *F. capensis* with an umbrella crown shape. DBH was positively correlated to tree height ($r=0.39$, $p=0.013$) and stem height ($r=0.44$, $p=0.005$), but crown expansion (CA or CD) was not explained by height ($p=0.410$ and $p=0.485$, respectively).

Microclimate affected by the shade tree canopy

Average PAR under open sky was 1350 µmol m^{-2} s^{-1} in the morning, increased to 1857 µmol m^{-2} s^{-1} at midday and decreased again to 1075 µmol m^{-2} s^{-1} in the afternoon. The shade tree canopies reduced the light transmission to the cocoa trees in the understory on average to 21.9% (PAR: 272 µmol m^{-2} s^{-1}) but with variation over the day: light transmission was 25.8% in the morning, decreased to 13.0% at midday and increased again to 26.8% in the afternoon.

Within shade tree species, the transmitted light was statistically not different (species: $p=0.148$; time: $p=0.180$). *M. indica* exhibited the highest shading, with a transmission of 4% of the light resulting in the lowest mean PAR (62 µmol m^{-2} s^{-1}). In contrast, *F. capensis* recorded the highest PAR transmission through the canopy, i.e. 45% in the morning and 21% around midday, resulting in the highest sub canopy PAR (487.4 µmol m^{-2} s^{-1}) (Fig. 3, Additional file 1: Table A3).

On average over the whole day, temperature was 0.8 °C lower and RH 2.5% higher, resulting in a 0.5 kPa lower VPD, 3.4 °C lower temperature fluctuation (difference between highest and lowest temperature) and 8.0% points higher minimum RH under the shade tree canopies compared to the unshaded control (Additional file 1: Table A4). Coming along with the lowest light transmission, the highest buffering (temperature, RH, VPD) was obtained under the canopy of *M. indica*, while *T. superba*, *T. ivorensis* and *R. heudelotii* remained the highest VPD.

During the night, the lowest temperature was reached at 6:00 h and RH was at 100% from 4:00 h

Table 1 Shade tree traits as mean values and standard error (se)

Species	Height (m)		Stem height (m)		DBH (cm)		Crown diameter (m)		Crown area (m²)	
	mean	se	mean	Se	mean	se	mean	se	mean	se
A. boonei	18.3	± 2.6	7.4	± 1.5 a	95.8	± 13.1b	9.7	± 1.6	85.1	± 24.0 ab
F. capensis	20.6	± 3.0	11.7	± 1.8abc	100.6	± 13.2ab	15.4	± 3.2	199.9	± 58.6 ab
M. excelsa	19.2	± 2.7	10.8	± 2.1ab	99.4	± 12.6b	15.7	± 1.6	170.0	± 32.9ab
M. indica	15.4	± 2.1	6.3	± 1.0abc	79.1	± 7.4ab	15.9	± 1.0	213.0	± 23.3 b
M. lucida	16.2	± 2.7	7.1	± 1.1abc	49.8	± 8.9a	11.3	± 0.8	91.1	± 13.1 ab
R. heudelotii	18.4	± 2.3	11.9	± 1.7c	97.5	± 13.8b	9.4	± 1.1	73.0	± 15.5a
T. ivorensis	17.2	± 2.2	7.2	± 0.8abc	46.3	± 6.5a	14.3	± 2.8	198.8	± 76.8 ab
T. superba	15.4	± 1.3	8.3	± 1.0bc	50.1	± 9.7ab	12.1	± 1.9	111.0	± 26.9ab
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Species	0.9	0.536	4.6	0.003	7.4	<0.001	2.4	0.046	3.2	0.014

DBH: diameter at breast height (1.3 m). F- and p-value show results of linear-mixed effects models. Significant differences at $P<0.05$ from the post-hoc HSD tests are indicated with lower- case letters, species with common letters are not significantly different and vice versa

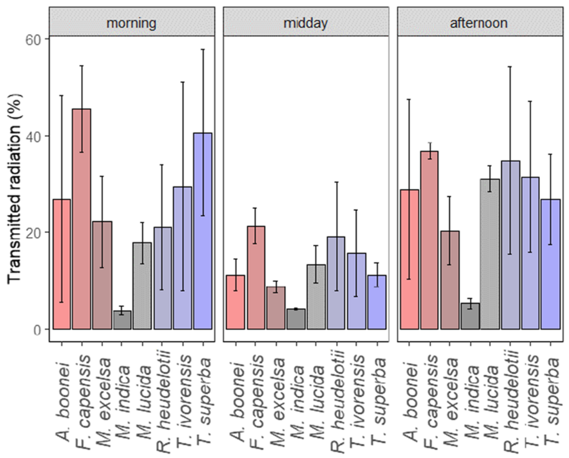

Fig. 3 Photoosynthetically active radiation transmitted through the canopy of the eight shade tree species at three times of the day as precentage of total radiation (%). Bars indicate the mean, error bars the standard error

to 7:00 h (Fig. 4). Sub canopy temperature and RH were similar to the unshaded control (indicated by zero temperature and RH difference).

Throughout the day, the microclimate under the shade tree canopy was buffered, i.e., the temperature remained lower and RH higher compared to unshaded conditions. Strongest temperature and RH buffering was observed already at midday for all species, while sub canopy temperature was highest and RH lowest between 14:00 h and 15:00 h with a delay of about two hours.

In the morning between 6:00 h and 9:00 h, sub canopy temperature of *F. capensis, M. lucida* and *T. ivorensis* was slightly above than the unshaded temperature (positive difference), before the effect changed to maintaining a lower temperature (negative difference) under the canopy throughout the day such as the other species. All species except *M. indica* showed a lower sub canopy RH between 7:00 h and 9: h in the morning before remaining a higher RH than the control throughout the day.

Cocoa growth

Cocoa trees had an overall mean height of 5.0 m, but their height was influenced by shade tree species ($p=0.013$) and distance to the shade tree stem ($p<0.001$) (Fig. 5). Cocoa trees in the inner zone (4.6 m) were shorter than cocoa trees in the middle zone (5.0 m) and outer zone (5.2 m). The tallest cocoa trees were growing next to *F. capensis* (5.4 m); they were significantly taller than cocoa trees around *M. indica* (4.9 m).

Cocoa DBH1 was 11.3 cm on average, but decreased by distance from the shade tree stem ($p>0.001$) from the outer zone (12.2 cm) to the middle zone (11.3 cm) and the inner zone (10.1 cm). The shade tree species were not significantly affecting the cocoa DBH1, though cocoa trees under the canopy of *T. superba* had the smallest DBH1 (10.6 cm) and under *F. capensis* the largest (12.3 cm).

The average foliage of the cocoa trees scored 3.6 and increase with distance from the stem ($p=0.002$) from 3.4 in the inner zone to 3.6 in the middle zone and 3.7 in the outer zone. In addition, shade tree species influenced the cocoa foliage ($p=0.044$): best foliage was developed under the canopy of *M. lucida* (4.0), the least under *F. capensis* (3.5).

Discussion

Shade tree morphology and microclimate

Aboveground morphological traits of selected shade trees demonstrate limited species specific differences, particularly in DBH, stem height, crown area and shape, although individuals of the same species showed variation, presumably depending on tree and farm age as well as local growing conditions such as soil and biophysical factors (Asigbaase et al. 2023). Under similar conditions, variations in morphological traits of shade trees species in cocoa agroforestry systems has been shown to be limited and therefore allow categorization of species into functional groups as demonstrated by Blaser-Hart et al. (2021) with tree canopy height. The lack of strong differences among most of the studied shade tree species therefore confirms existence of morphological trait groups which can be targeted in shade tree impact studies in cocoa agroforestry system in future studies.

Nonetheless, the clustering of the shade species could vary depending on specific morphological traits as observed between tree height and crown expansion. The tallest shade tree species (*F. capensis*, *M. excelsa*, *R. heudelotii* and *A. boonei*) also had the largest DBH, but tree height was not necessarily related to the crown expansion, e.g. the tall

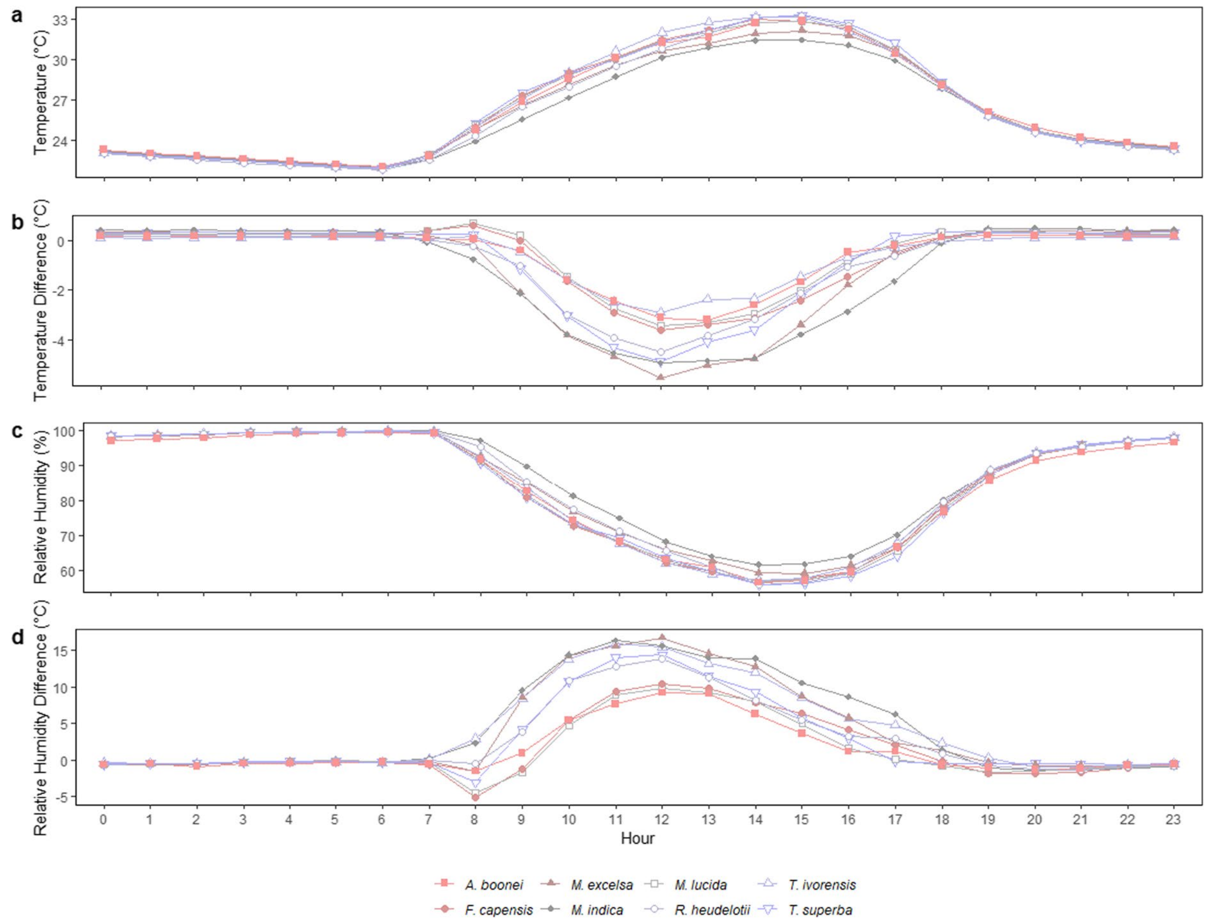

Fig. 4 Microclimate under the shade tree canopy in the course of the day; **a** mean temperature and **b** temperature difference to unshaded conditions (in °C); **c** relative humidity and **d** relative humidity difference to unshaded conditions (in %). The shade tree species are differentiated by colours and shapes

A. boonei had the smallest crown expansion and, conversely, the low crown of *M. indica* had the largest expansion. These relationships of tree traits were also shown by Asigbaase et al. (2023) for a variety of shade trees used in Ghanaian cocoa agroforestry system. Although the tree height has been shown to key for shade tree sub canopy microclimate conditions (Blaser-Hart et al. 2021), the crown size can also be important in influencing shade tree density and subsequent overall effect on AFS productivity.

The influence of leaf phenology, crown shape and height of the shade tree species as well as of each individual tree must be considered when interpreting PAR interception and microclimate under the shade tree canopy (Isaac et al. 2007; Blaser-Hart et al. 2021). As also observed by Niether et al. (2020) and Mensah et al. (2023), temperature and VPD were generally lower, the temperature amplitude was smaller and RH was higher under a shade tree canopy compared to the unshaded control, creating a more stable microclimate with less extremes.

The effective microclimatic buffering of *M. indica* might be explained by the shielding effect of a low and wide-reaching crown in combination with a dense foliage indicated by a strong light interception throughout the day. Despite the studied *T. superba* recording similar mean tree and stem height to *M. indica*, the high diurnal PAR variation is attributed to the lower crown expansion and presumably, a lower foliage density allowing higher light transmission. The high crown of *F. capensis* allowed the highest light transmission as expected of elevated canopy

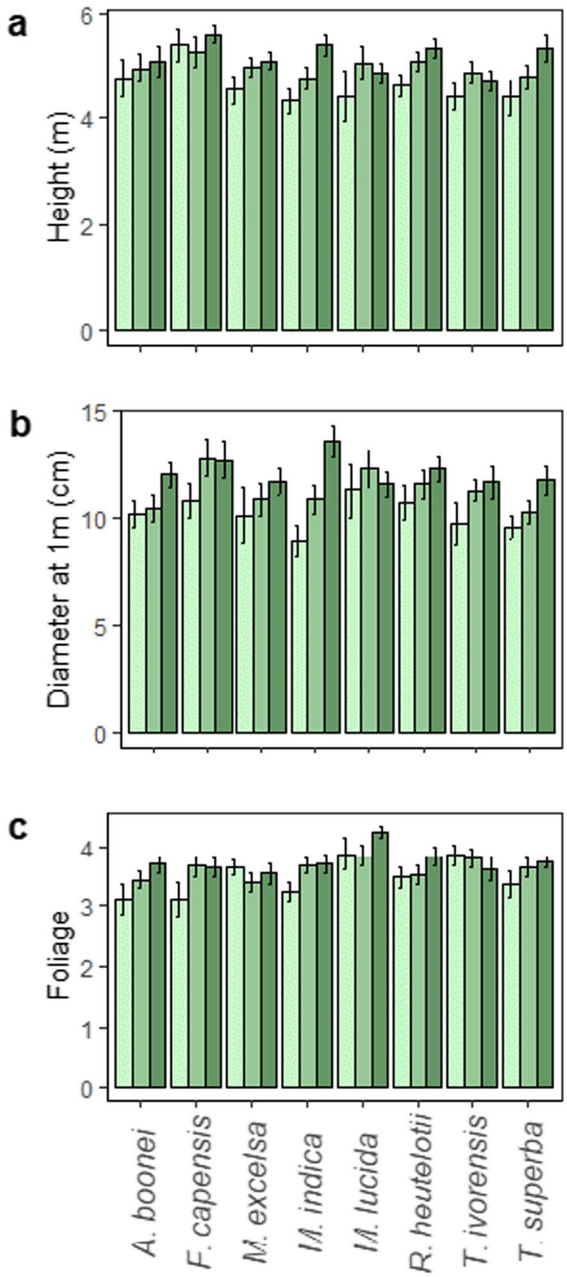

Fig. 5 Cocoa tree growth indicated as a) cocoa height, b) cocoa diameter at 1 m, and c) cocoa foliage (as category) in three zones (inner = light green, middle = green, outer = dark green) within the canopy influence of the shade tree species. Bars indicate the mean, error bars the standard error

trees (Blaser-Hart et al. 2021), while the microclimatic buffering is not as strong as under a lower canopy trees of *M. indica* although the crown had a similar expansion.

The diurnal variation in PAR transmission through the canopy may be attributed to the changing angle of sunlight as it progresses throughout the day ((Blaser-Hart et al. 2021; Niether et al. 2018b, 2020; Thomson et al. 2020) but can further be explained by tree morphological traits. As an underlying effect of the different diurnal light transmissions, also the temperature and RH curves across species vary.

According to an assumption raised by Niether et al. (2020) and confirmed by (Blaser-Hart et al. (2021), shade tree species with a low stem height (and therefore a lower distance between their canopy and the cocoa trees) provide different microclimatic growing conditions for the cocoa trees than species with a higher canopy. Our finding comparing low stem species (e.g., *M. indica*, *M. lucida, T. ivorensis* and *A. boonei*) and higher stem species (e.g., *M. excelsa*, *F. capensis*, *R. heudelotii*) did not provide consistent evidence for this hypothesis, although they show some indications. Other shade tree characteristics, e.g. foliage and other leave traits, should be considered for further predictions of microclimatic conditions under the shade tree canopy.

However, with expected increase in temperature extremes and other extreme weather events due to climate change, any microclimatic buffering will be important to maintain understory cocoa photosynthesis and therefore production, while reducing water loss through evaporation and cocoa transpiration with high temperature, low RH and VPD increase (Läderach 2013; Lahive et al. 2019).

Shade tree impact on cocoa in agroforestry system

Cocoa growth was affected more by the distance to the shade tree stem than by the shade tree species itself. The observed increase in cocoa growth from the inner to the outer zone was also reported by Blaser et al. (2017), indicating unfavourable growing conditions close to the shade tree stem caused by competition for light, but also water, nutrients and rooting space between the shade tree and the cocoa tree (Schneider et al. 2017). However, belowground interactions, particularly their impact on water status, remain less studied and are sometimes contradictory (Abdulai et al. 2018b; Lahive et al. 2019) and have to be evaluated and discussed elsewhere.

Cocoa leaves are light sensitive and photosynthetic light saturation was described at 400 μmol m^{-2} s^{-1}, when reduced photosynthesis can impact growth and yield negatively (Balasimha et al. 1991; Baligar et al. 2008; Raja Harun and Hardwick 1988; Suárez Salazar et al. 2018). Due to the strong shading effect of the canopies, this threshold value was only reached under the high crown of *F. capensis* and *T. superba*. Cocoa trees under *F. capensis* exhibited the greatest height and DBH1, despite having less dense foliage compared to trees under other canopy influence. The strong shading likely influenced the photosynthesis and subsequent yield of the cocoa trees directly under the canopy of the dense foliage shade trees, although the differences among shade tree species with respect to cocoa trees morphological traits were not substantial. No shading effect on cocoa growth parameters (cocoa tree DBH1) as observed in this study, even when PAR transmission was at its lowest (*M. indica*, *M. excelsa* and *A. boonei*) could be attribute to the promotion of vegetative growth due to efficient water use and nutrient availability (Isaac et al. 2007; Köhler et al. 2014). These cocoa trees might have adapted to the high shade level by enhancing their light harvesting ability, for example through increased photosynthetic pigments and enhanced foliage, along with other adaptation mechanisms like reduced dark respiration and decreased specific leaf area (Suárez Salazar et al. 2018).

A reduced PAR through shading can also have positive effects, such as the prevention of excessive vegetative growth like flushing (Beer et al. 1987) and enhance yield production (Mensah et al. 2023) but the bottleneck is always the increase risk of fungal disease (black pod) infection as emphasized by farmers (Graefe et al. 2017).

Even though the daily mean VPD did not exceed the threshold of 2 kPa, at which the photosynthetic rate of cocoa decreases (Balasimha et al. 1991), this critical value could be easily reached during the day when temperature exceeded 35 °C. The microclimatic buffering of the shade trees, especially the lower VPD, might have positively affected the growth of the cocoa trees as shown in other microclimatic studies (Niether et al. 2018b). In the long-term, the reduced exposure to stressful climatic conditions and a probably lower short-term yield might be compensated by the extended cocoa life cycle in shaded systems due to reduced stress (Obiri et al. 2007).

To realize these microclimatic, productivity and ecosystems benefits of shade trees, recent study by Blaser et al. (2018) identified shade levels threshold of 30%. The Cocoa Research Institute of Ghana (CRIG) actually advises a shade level of AFS between 30 and 40% (Acheampong et al. 2014). Due to the heterogeneity of cocoa AFS, resulting from unregularly spacing, distribution and shade characteristics of shade trees and tree species, maintaining a constant shade level across the system is challenging. To minimize excessive light absorption, careful species selection is essential. For instance, choosing species like *F. capensis* with a favourable balance between light transmission and microclimatic conditions, can be effective. Furthermore, implementing shade tree management practices, such as pruning, helps in reducing canopy density and facilitates light penetration during critical cocoa physiology stages, such as flowering (Esche et al. 2023; Niether et al. 2018a).

Strong microclimatic buffering could become more important for future climatic conditions when maximum dry season temperatures are predicted to restrict cocoa productivity severely with the progression of climate change. As rising average temperatures result in higher evapotranspiration rates, water availability for cocoa trees indirectly decreases (Läderach 2013). Although most participating farmers reported drought as their biggest challenge in cocoa production already today (personal communication and Abdulai et al. 2018a), annual precipitation in Ghana's semi-deciduous forest regions is expected to decline by 10.9% in 2050 and 18.6% in 2080 compared to 2004, further intensifying drought stress (Anim-Kwapong and Frimpong 2004). Consequently, the Ghana Cocoa Board (2018) forecasts a 28% yield decline by 2050 and even questions profitable cocoa production in Ghana by 2080, given insufficient soil moisture. Therefore, including shade tree species with strong temperature buffering could be an adaptation measure to reduce evapotranspiration of cocoa trees, provided that this effect is not offset by competition for soil moisture (Abdulai et al. 2018b; Niether et al. 2018b).

Conclusions

The shade tree species differed in their aboveground morphology and therefore affected the microclimate and growth of surrounding cocoa trees, but no ideal trait or specifically suitable species for cocoa AFS could be identified. The shade trees species could therefore be considered under simplified groups based on similar morphological traits, e.g. to their ability to create a more stable microclimate under the canopy, and by increasing growth of surrounding cocoa trees. A shade tree species combination in cocoa AFS is still recommended to maintain heterogeneity in the production systems for adaptation to various climatic conditions.

Cocoa growth was more affected by the distance from the shade tree stem than by the species itself, implying that growing conditions were less suitable close to the stem. When establishing modern cocoa AFS, careful consideration of shade tree species selection must be complemented by thoughtful planting design, e.g., establishing rows of shade trees with diverse species mixtures at respective distance to the cocoa rows. Despite the microclimatic effects of the species, additional factors, including cultural and product characteristics of the species, as well as local field conditions like climate, soil fertility, and management practices should be considered.

For better understanding and maintaining productive and climate-resilient cocoa AFS, further research on shade tree traits, including leave and foliage characteristics, but also AFS and shade tree management (e.g., species selection, planting density, selective thinning and pruning) over long-term is required.

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Declarations

Competing interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be considered as a potential conflict of interest.

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