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The effectiveness of cocoa agroforests depends on shade-tree canopy height

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ABSTRACT

Agroforestry is often proposed as a ‘climate smart’ strategy for allowing agriculture to both adapt to and mitigate climate change and sustainably increase agricultural production. This is because shade trees in agroforests may buffer growing conditions by creating favorable microclimates (climate-change adaptation), and because shade trees can sequester additional carbon from the atmosphere (climate-change mitigation). However, a major challenge for agroforestry is to maximize these potential benefits while minimizing costs to production as a consequence of resource competition between shade trees and the primary crop. While the effects of shade-tree density and canopy cover on the costs and benefits of agroforests are increasingly well understood, the effects of the traits of shade trees on the effectiveness of agroforests have received less attention. Here, we assess how shade trees with different crown architecture influence production, adaptation, and mitigation goals in a major cocoa growing region in Ghana, West Africa. We quantified the effects of shade trees from nine different species across two classes of height-to-crown-base (low vs. elevated canopies) on yield, microclimate, and carbon storage. We show that shade trees with elevated crowns had large positive effects on carbon storage and neutral effects on yield, while shade trees with low crowns had smaller effects on carbon storage and simultaneously caused larger reductions in incoming light, which was associated with lower yield. Trees of both crown classes were equally effective at buffering sub-canopy temperatures and vapor pressure deficit, although trees with low crowns maintained higher relative humidity. Taken together, our results suggest that shade-tree species with elevated crowns improve the effectiveness of cocoa agroforests by providing maximum benefits for climate-change adaptation and mitigation, while minimizing short-term costs to cocoa production.

1. Introduction

Climate change poses many difficulties for the future of agriculture. Higher and more variable temperatures and changes in precipitation and humidity threaten production in many regions of the world (Rosenzweig et al., 2007; Porter et al., 2014). The impacts of climate change on agriculture are expected to be felt most severely in tropical, rain-fed, smallholder systems (Morton, 2007). Importantly, these systems produce food for a substantial proportion of the world’s population and produce the most significant share (~70–80%) of many globally important commodities such as cocoa, coffee, and cotton (Slingo et al., 2005; Fridell, 2014). Climate change will, therefore, have large impacts on the global supply of agricultural commodities and also directly threaten the livelihoods of smallholder households in these regions (Haile, 2005). Meanwhile, agriculture also remains a major contributor to climate change, compounding these problems (Garnett et al., 2013; Smith et al., 2014). There is, therefore, an urgent need for practical strategies that allow agriculture to (1) sustainably increase production while helping farmers to (2) adapt to and (3) mitigate the worst effects of climate change. Agricultural strategies that meet all three objectives are commonly known as climate-smart agriculture (Campbell et al., 2014; Lipper et al., 2014), which is now an aspirational goal for the future of agriculture adopted by many national and international agencies (e.g. UN Food and Agriculture Organization [FAO], World Bank Group, World Agroforestry, Commonwealth Scientific and Industrial Organization [CSIRO], and others).

The inclusion of shade trees in agricultural production systems – a strategy commonly known as agroforestry – is often advocated as a climate-smart solution for some cropping systems (Schroth et al., 2016; Vaast et al., 2016; Blaser et al., 2018). First, this is because shade trees

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may increase long-term production by increasing soil fertility, decreasing effects of pests and disease, and reducing premature aging of crop trees (Schroth et al., 2000; Isaac et al., 2007; Tscharntke et al., 2011; Andres et al., 2018; Wartenberg et al., 2019). Second, shade trees may also promote climate-change adaptation by buffering temperature extremes and maintaining more favorable microclimates (Lin, 2007; Blaser et al., 2018; Niether et al., 2018). And third, shade trees can help to mitigate against future climate change by sequestering atmospheric carbon as biomass (Campbell et al., 2014; Harvey et al., 2014; Blaser et al., 2018; Niether et al., 2020). Nevertheless, net benefits against each of these three climate-smart criteria are not guaranteed. For example, shade trees can also reduce production if they compete with crops for light, water, and nutrients, and shade-trees can have both positive and negative effects on microclimatic variables such as soil moisture, with uncertain consequences for climate-change adaptation under drought (Beer et al., 1998; Lin, 2007; Abdulai et al., 2018; Blaser et al., 2018). Thus, while shade trees are a promising strategy for climate-smart agriculture, their effectiveness depends on how agroforests are implemented.

Existing studies on the implementation of agroforests tend to focus on either the simple presence vs. absence of shade trees (meta-analysis by Niether et al., 2020 and references therein), or assess the effects of shade trees along continuous gradients of shade-tree cover (Bisseleua et al., 2009; Wade et al., 2010; Clough et al., 2011; Andres et al., 2018; Blaser et al., 2018). Both these approaches have led to more refined recommendations for improving agroforestry. However, despite the diversity of shade trees often found in agroforests very few studies assess the influence of shade trees with different types of traits (Isaac et al., 2007; Abdulai et al., 2018; Wartenberg et al., 2019). The relative lack of studies focusing on the effects of shade-tree traits is surprising given that the potential importance of tree traits for agroforestry was suggested more than three decades ago (Beer, 1987), and has been reiterated in several more recent papers (Isaac et al., 2007; Clough et al., 2011; Somarriba et al., 2013, 2018; Isaac and Borden, 2019; Sauvadet et al., 2020).

Circumstantial evidence suggests that shade-tree traits are likely to strongly influence the effectiveness of agroforests. For example, there is compelling evidence from basic ecology that particular traits have consistent effects on the strength of competition between species (Kunstler et al., 2016), and on ecosystem function including on microclimates and biomass production (Lavorel, 2013; Wood et al., 2015). This suggests that shade trees with particular traits could be selected to reduce the negative effects of competition from shade trees on the primary crop, and to increase the climate-change adaptation and mitigation capacity of agroforests. The challenge then is to identify tree traits that improve the effectiveness of agroforests while being sufficiently simple to allow recommendations that are easy to implement for smallholder farmers in particular (Wood et al., 2015). Height of the base of the shade-tree canopy above the primary crop may be one such trait (Fig. 1).

Of the many traits that can vary between shade-tree species, height of the shade-tree canopy above the primary crop is a gross, easily measured trait that is likely to strongly influence climate-smart objectives. For example, while all trees provide some shade, canopy height is likely to influence the amount of light penetration to understory crops, thus influencing the outcome of light competition between trees and crops (Fig. 1, Blank and Carmel, 2012; Blaser et al., 2013). Moreover, trees with canopies well above the primary crop may be less effective at protecting understory crops from ambient high temperatures and low relative humidity, and so may be less effective than low-canopy species at buffering crop microclimates. Finally, for the same amount of shade-tree cover, tall-statured trees that stand well above the understory crop are likely to be more effective at sequestering carbon simply because larger trees tend to have higher biomass (Somarriba et al., 2013; Chave et al., 2014; Schroth et al., 2014). Thus, this single tree trait is likely to be a strong driver of the effectiveness of agroforests for meeting production, and climate-change adaptation and mitigation goals. Despite its potential importance, however, the influence of shade-tree

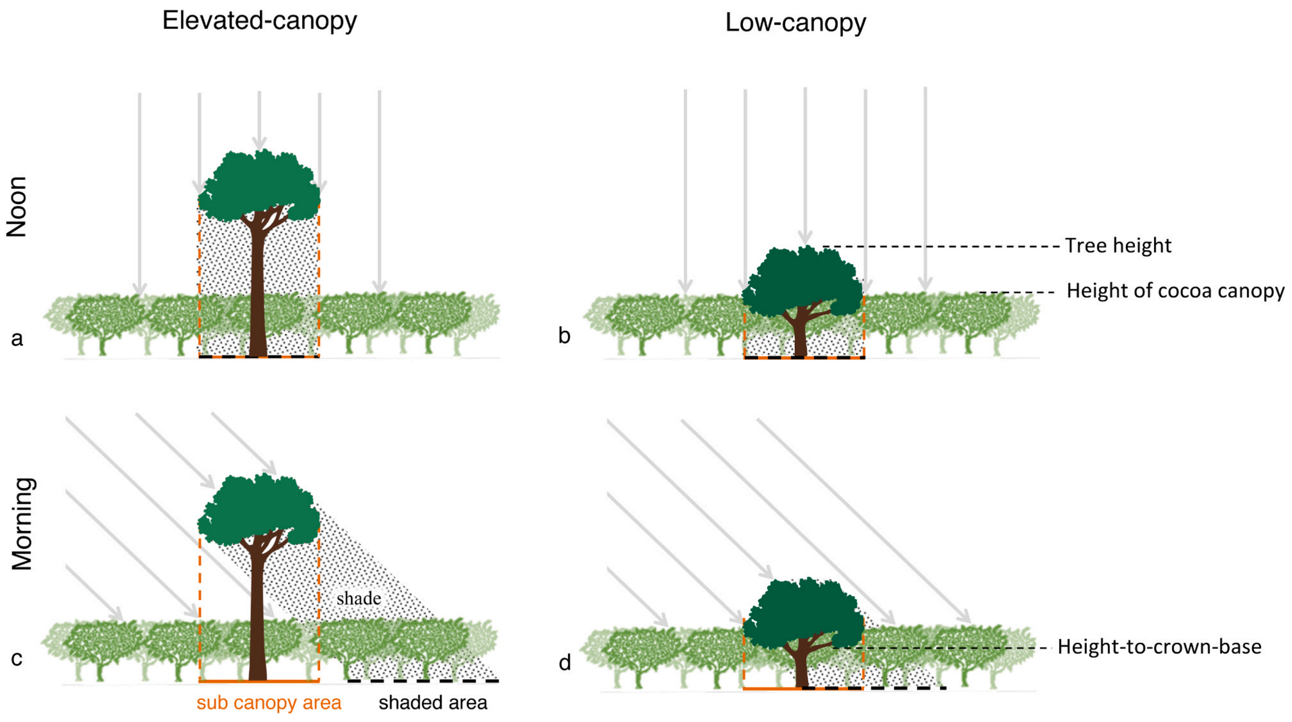

Fig. 1. Schematic profile view of ‘elevated-canopy’ and ‘low-canopy’ shade trees, defined with respect to the cocoa canopy. ‘Elevated-canopy’ species were defined as shade-tree species with canopies elevated above the cocoa canopy and ‘low-canopy’ species as shade-tree species with canopies within the cocoa canopy. Trees with elevated canopies might reduce physiological stress in cocoa by casting significant shade when the sun is directly overhead (noon, a and b), while allowing light to penetrate to the understory during mornings and afternoons (c and d). Under ‘low-canopy’ shade-tree species, on the other hand, most light will not reach the cocoa trees in the subcanopy independent of the angle of the sun (i.e., time of the day).

canopy height on the effectiveness of agroforests has received little empirical attention.

Here we quantify how shade trees with different canopy heights influence the effectiveness of agroforests to meet production, and climate-change adaptation and mitigation goals in a major cocoa (*Theobroma cacao* L.) growing region in West Africa. We quantified the effects of individual shade trees from nine different species across two canopy-height classes (Fig. 1) on several response variables directly related to production (cocoa yields, incoming photosynthetically active radiation [PAR]), climate-change adaptation (sub-canopy temperature, relative humidity, vapor pressure deficit [VPD], and soil moisture), and climate-change mitigation (aboveground carbon stocks). We focused our assessment on cocoa agroforests in Ghana, West Africa, noting that this region produces approximately 70% of the world's cocoa and the suitability for cocoa production across large parts of the West African cocoa belt is expected to decrease with climate change (Läderach et al., 2013; Schroth et al., 2016; Bunn et al., 2018). Thus, improving the ability of agroforests to buffer climate extremes and sequester carbon may be particularly important for guaranteeing the long-term sustainability of cocoa production in this region (Blaser et al., 2018; Bunn et al., 2018).

2. Methods

2.1. Study area

We conducted our study in the Atwima Nwabiagya District of the Ashanti Region, located in the moist, semi-deciduous tropical zone of Ghana (06°40′ N and 01°57′ W). Much of the former semi-deciduous tropical forests in this region have been converted to agricultural land (Acheampong et al., 2019). Cocoa, grown by smallholders under variable shade-tree cover including monocultures, is the dominant perennial crop in this region. Mean annual precipitation ranges between 1700 mm and 1850 mm, with rain distributed in two separate rainy seasons (March to July and September to November). The months between the rains are marked by a short, dry season in August and a long, dry season from December to February. Mean monthly temperatures during our study period (September 2015 - October 2016) ranged between 24 and 28 °C and mean relative humidity was generally high throughout the year (62–89%). The area is expected to become less suitable for cocoa production due to predicted increases in maximum dry season temperatures (Schroth et al., 2016).

2.2. Shade-tree canopy classes

Our main focus was on the effect of the crown architecture of shade trees on the effectiveness of agroforestry for production and climate goals. Specifically, the main independent variable in our study was shade-tree species' 'height-to-crown-base' measured as the distance between the ground and the base of the crown of the shade tree (Fig. 1). 'Low-canopy' species were defined as shade-tree species that tend to have canopies at least partially within the cocoa canopy and 'elevated-canopy' species as shade-tree species with canopies clearly elevated above the canopy of cocoa trees (Fig. 1). Hereafter, for simplicity and readability, we will refer to 'canopy height' as our independent variable rather than 'height to crown base'.

For our assessment we included multiple individuals of each of nine different shade-tree species commonly found in cocoa farms in the study area (Anglaaere et al., 2011; Blaser et al., 2017). Each species was classified as either a 'low-canopy' species or an 'elevated-canopy' species. The 'low-canopy' species in our study were *Citrus sinensis* (orange), *Mangifera indica* (mango), *Persea americana* (avocado), and *Morinda lucida* (konkroma). The 'elevated-canopy' species in our study were *Alstonia boonei* (nyamedua), *Spathodea campanulata* (kuakuanisuo), *Antiaris toxicaria* (kyenkyen), *Ficus capensis* (odoma), and *Terminalia superba* (ofram).

These canopy height classifications were done a priori based on our observations of the canopy heights of mature unpruned individuals of each shade-tree species from an earlier study in 2014 (Blaser et al., 2017). These classifications are supported by data on the rank 'vegetative tree height' of each of our shade-tree species in a widely used global database of plant traits (TRY, Kattge et al., 2020), and in estimates of mature tree heights provided in multiple references to the trees of Ghana (Poorter et al., 2004; Hawthorne and Gyakari, 2006; Oteng-Amoako, 2006). As such, while canopy height can be influenced by age, ontogeny, intraspecific variation, and farm management including pruning (points we return to in the discussion), our canopy-height classification reflects differences in the canopy height of mature shade trees. We also note that farmers do not prune shade trees in the farms we studied. As described below, we measured the canopy height of all focal shade-tree individuals in our study and these measurements were consistent with our a priori species-level canopy-height classification (Fig. A.1). The shade-tree species in our study cover a wide-range of canopy heights, although only represent a subset of the species of shade-trees in the study area.

2.3. Selection of shade trees

To assess the effect of the canopy classes defined above, we selected individual shade trees from a mix of planted, remnant or naturally regenerated trees across 25 low-shade (~15–20% cover), relatively well-maintained, low-fertilizer-input, mature smallholder cocoa farms spread over an area of approximately 20 km^2. We deliberately selected mature isolated individual shade-trees so that we could assess the effects of canopy height independent of potentially confounding variables such as differences in shade-tree density. All focal individuals were located in existing cocoa farms and were therefore surrounded by cocoa in their subcanopy. However, each focal shade tree was isolated from the canopy of other shade trees by at least 20 m. According to information from farmers, cocoa trees in the farms we worked on ranged between 14 and 27 years of age, with an average of 19.3 years.

There were 4–5 focal individuals of each shade-tree species, resulting in a total of 39 focal shade trees (17 focal trees in the 'low-canopy' and 22 in the 'elevated-canopy' category). We characterized each focal shade tree by measuring its diameter at breast height (D), total tree height (H) and the height to crown base (Fig. 1). Diameter at breast height was measured with a diameter tape and height measurements were made with a Vertex IV Hypsometer (Haglöf, Sweden). Linear mixed-effect models with canopy class as a fixed factor and species as a random factor confirmed that our classes differed in their height to crown base ($F_{1,6.9} = 21.6$, $p = 0.002$, Fig. 2a) and total tree height ($F_{1,6.9} = 17.4$, $p = 0.004$). Individuals within species did vary (Supplementary information, Fig. A.1), but our canopy-height classifications, and the effects of canopy height that we demonstrate, emerged despite this intraspecific variation. Total tree height was a good predictor of height to crown base in our study (Supplementary information, Fig. A.1; linear regression: $R^2 = 0.53$, $F_{1,36} = 40.1$, $p > 0.001$).

2.4. Sampling design

We used a paired sampling design, comparing the effects of each focal shade tree on microclimate (Section 2.4.1) and cocoa production (Section 2.4.2) with measurements of the same response variables in nearby open control plots (20 m distance). These open control plots were located within the cocoa crop, but in the absence of a shade tree. This paired design enabled us to isolate the effects of shade trees, independent of confounding factors such as differences in soil type, farm management and local micro-climate between distant farms (see Blaser et al., 2018 for a previous implementation of this approach). We note that the cocoa in each set of paired plots was managed, grown and harvested by the same farmers.

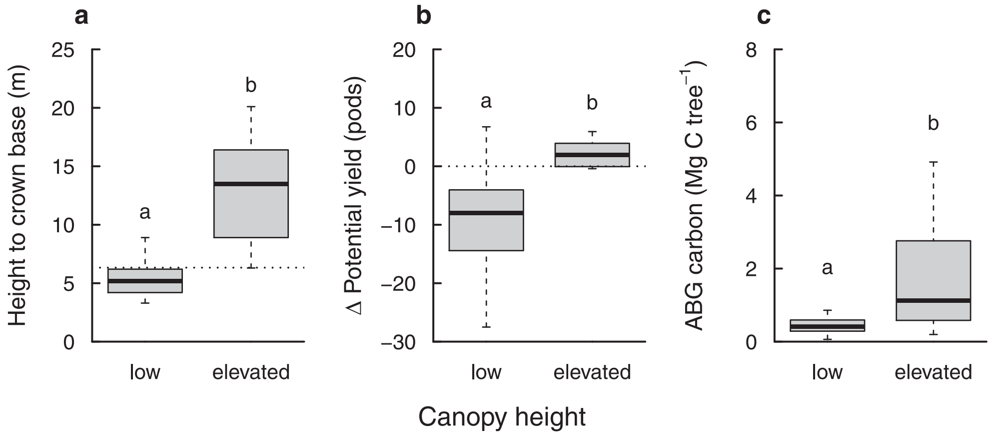

Fig. 2. (a) Differences between our canopy-height classes in measured height-to-crown-base, (b) effects of canopy height on potential cocoa yields, and (c) effects of canopy height on aboveground (ABG) carbon stocks of individual shade trees. Height-to-crown-base and ABG carbon stocks (in mega grams [Mg]) are displayed as absolute values, whereas potential yields are shown as the difference (Δ) in the average pod count per cocoa tree between cocoa trees growing in areas under shade-tree canopies and open control plots at the beginning of the main harvesting season (mean of 2015 and 2016 main season counts). The dashed horizontal line in panel (a) represents the average height of the cocoa canopy. The dashed horizontal line in panel (b) represents no difference in potential yield between areas under shade-tree canopies and open control areas. All data are displayed as boxplots with thick horizontal lines representing the median, the box representing the 25th and 75th percentiles, and the whiskers the 5th and 95th percentiles. Different letters indicate significant differences between the two canopy-height classes.

2.4.1. Effects of shade trees on climate-change adaptation: light & microclimate measurements

To assess the effects of shade trees on microclimate, we placed a temperature and relative-humidity data logger protected with a radiation shield (HOBO Pro v2 U23-001), as well as one light sensor (photosynthetically active radiation [PAR], QSO-S PAR Photon Flux sensor attached to a Em50 data logger, Decagon Devices Inc.), 0.5 m above the cocoa canopy on a bamboo pole. One bamboo pole with all loggers was located two meters directly north of the trunk of each focal shade tree, as well as in each of 15 open control plots (i.e. with cocoa trees, but no shade tree). We measured volumetric water content in topsoil (0–10 cm) using soil moisture sensors (10-HS, Decagon Devices Inc.) attached to a digital data logger (Em50, Decagon Devices Inc.). Three soil moisture sensors were spread evenly at a distance of 1.5 m around each shade tree, and in each of 15 open control plots. All loggers were installed on almost flat terrain. If the area had a gentle slope, attention was paid to locating all open loggers in the same exposition as the paired focal shade trees. All loggers (light, temperature, soil moisture) recorded measurements every 15 min for one year (September 2015 to October 2016).

In total, we installed 54 sets of light, temperature, and soil moisture loggers, with 17 sets under 'low-canopy' shade-tree individuals, 22 sets under the 'elevated-canopy' shade-tree individuals, and 15 sets in open control plots. Because microclimate sensors and loggers are expensive, we were forced to limit the number of open control plots to 15 locations in our study. We therefore assigned an average of 2–3 focal shade trees that were in relatively close proximity to each other to each control plot. Therefore, the control plots used to assess microclimate were not always positioned in exactly the same location as the control plots used to assess cocoa biomass and yields (see Section 2.4.2) but were nevertheless located in relatively close proximity (the average distance from loggers associated with a focal shade tree to loggers in open control plots was 162 ± 29 m). In our statistical analyses we included a random blocking factor to account for the different sets of focal shade trees associated with each open control plot (see Section 2.5, and Appendix A - Supplementary Materials). We also verified that the magnitude of the observed effects on microclimate measurements was not related to the distance of shade trees to the location of the open loggers (all $p > 0.25$). Unfortunately, one logger under an *Alstonia boonei* shade-tree individual was destroyed during the study such that the data could not be accessed.

After downloading the data, we calculated average daily mean temperature and relative humidity, daily minimum and maximum temperatures, daily minimum relative humidity and daily mean soil moisture across the whole year (September 2015 to October 2016). Vapor pressure deficit (VPD), which assesses the drying power the air exerts upon plants and is a critical variable in determining plant photosynthesis, was calculated from temperature and relative humidity recordings following Allen et al. (1998). Briefly, we calculated mean VPD values for both subcanopy and open areas as the difference between the saturation pressure (e_s) and actual vapor pressure (e_a) over the course of one day based on daily minimum and maximum temperature and daily minimum and maximum relative humidity. Specific details about our VPD calculations are provided in the Supplementary Materials (Appendix A - Supplementary Materials). Data from the light sensors were used to calculate average daily light integrals (mol m^{-2} day^{-1}) assuming constant PAR values over each 15-minute measurement interval.

2.4.2. Effects of shade trees on production: cocoa yield and losses to disease

In our study area there is a major cocoa crop that is harvested between September and December and minor cocoa crop that is harvested between January and August. Under these circumstances, direct measurements of total annual yield for the 874 cocoa trees associated with our 39 individual shade-trees and open paired plots was prohibitive because of the need to coordinate yield measurements across multiple farms, cocoa trees within farms, and harvest times across multiple years. Therefore, we used an estimate of potential cocoa yield in our study. Potential yield was estimated by counting the number of healthy cocoa pods greater than 10 cm long for all cocoa trees that occurred under the crown area of each focal shade tree (i.e., in the shade-tree 'subcanopy') and for eight cocoa trees in the paired open control plot located on the same cocoa farm at least 20 m from any shade tree. These counts were done just before commencement of the major harvest in both years (in late September in 2015 and 2016). Our counts excluded small pods that could fall off before reaching 10 cm (e.g., due to cherelle wilt). From these counts we calculated the average number of pods per cocoa tree across the two sampling years, providing an estimate of *potential* cocoa yield.

While there may be some differences between our estimates of potential cocoa yield and the actual cocoa yield for each tree, our conclusions will remain accurate under the assumption that pod numbers immediately prior to the major harvest positively correlate with the total number of pods harvested during the major harvest (Chandran et al., 2015). We note that similar methods and assumptions using partial harvest data to assess potential yield have been made in previously published work (Koko et al., 2013; Andres et al., 2018; Gateau-Rey et al., 2018). We also emphasize that the effects of year-to-year variation are also likely to be mitigated because we estimated potential yield across multiple years.

In addition to estimates of yield, we also assessed potential losses to disease by counting the number of diseased cocoa pods greater than 10 cm long for the same 874 cocoa trees. All pods showing signs of black pod (*Phytophthora* sp.) or other pests or pathogens (mostly mirid bugs *Sahlbergella singularis* and *Distantiella theobroma*) were classified as diseased pods. Levels of potential losses to disease were expressed as the percentage of all mature pods (healthy plus diseased pods) lost to disease. From these measurements we calculated the average percent loss to disease per cocoa tree across the two sampling years.

We were not able to assess potential cocoa yields and losses to disease associated with four individual focal trees (each of a different species). This was because discussions with farmers revealed that cocoa in the open control areas that we had selected for these focal trees was planted earlier and so cocoa trees were not of a comparable age between shade tree and control plots. Our decision to not collect data associated with these trees was conservative and was done to avoid spurious conclusions that could have arisen not because of the effect of shade trees but rather because of differences in the age (and therefore the productive capacity) of cocoa itself.

2.4.3. *Potential of shade trees for climate-change mitigation: carbon stocks*

To assess the carbon-storage potential of shade trees we estimated their aboveground biomass (AGB) using the allometric equation of Chave et al. (2014) developed for tropical trees: $AGB_{tree} = 0.0673 \times \left(\rho D^2 H^2\right)^{0.976}$, where ρ is specific wood density, D is diameter at breast height and H is total tree height. We used our measurements of D and H for each tree (see Section 2.3). Values for the specific wood density (ρ) of each shade-tree species were obtained from the global wood density database (Chave et al., 2009; Zanne et al., 2009). For one shade-tree species (*Morinda lucida*) for which no record of species-specific wood density was found, we used the mean wood density of the genus. Aboveground biomass values of all shade trees were converted into aboveground carbon stocks by multiplying shade-tree aboveground biomass by a factor of 0.49 as recommended by the IPCC (2006).

2.5. *Statistical analyses*

For all microclimate and production measurements we used the difference in the value of each measured variable between subcanopy and open control plots (Δvariable = measurement in subcanopy – measurement in open control plots) as the response variable in our analyses. With this difference metric as our response variable, we used linear mixed-effects models with canopy class ('low-canopy' and 'elevated-canopy') as a fixed independent variable and species as a random independent variable in our analyses. When the difference in a microclimate variable was the response variable, we extended the basic model to include a random blocking factor to account for focal trees that share a single control plot (as per our sampling design described in Section 2.4.1). To compare carbon stocks between shade trees with low- and elevated-canopies we used a linear mixed-effects model with canopy height as a fixed independent variable and species as a random independent variable.

We also assessed the effects of shade-tree species on microclimate, production, and carbon stocks. We did this by using models with the same structure as described for canopy height, except that we included species instead of canopy height as the main fixed independent variable in our analyses. Finally, independent of the effects of canopy architecture and shade-tree species, we also did *t*-tests to evaluate if the observed differences in our response variables between the presence and absence of shade trees was significantly different from zero. This allowed us to evaluate if the simple presence or absence of shade trees had a significant effect on production and climate-change adaptation measurements. The form of our statistical models for each analysis is provided in Appendix A - Supplementary Materials.

We note that for the microclimate analyses, data points associated with one *Citrus sinensis* tree and one *Mangifera indica* tree were often outliers that had a large influence on the statistical significance of our results. Therefore, we took the conservative approach of excluding these data points from all our microclimate analyses. All analyses were performed in R 3.6.2 (R Core Team, 2019). Linear mixed-effects models were implemented using the *lme4* package (Bates et al., 2015), together with *lmerTest* (Kuznetsova et al., 2017).

3. Results

3.1. *Effects of shade-tree crown architecture on light and microclimate*

3.1.1. *Light*

Light was lower when shade trees were present vs. when they were absent ($t_{38} = 18.8$, $p < 0.001$). The effect of shade trees on light was mediated by the height of the shade-tree canopy (Fig. 3a–c). In particular, daily light sums and the maximum light levels were lower under shade trees with low canopies than under shade trees with elevated canopies (light sums: $F_{1,7.1} = 6.0$, $p = 0.04$; maximum light: $F_{1,7.1} = 5.7$, $p = 0.05$; Fig. 3a–c). Light levels were also significantly different under different shade-tree species ($F_{8,30} = 12.9$, $p > 0.001$) with the biggest reductions in daily light sums found under *Citrus sinensis* and *Mangifera indica* and the smallest reductions under *Terminalia superba* and *Antiaris toxicaria* (Supplementary materials Fig. A.2a).

3.1.2. *Temperature*

Mean temperatures were lower and temperature extremes were buffered (lower maximum and higher minimum temperatures) when shade trees were present vs. when they were absent (mean - 0.17 °C: $t_{37} = 6.3$, $p < 0.001$; maximum - 0.9 °C: $t_{37} = 7.8$, $p < 0.001$; minimum + 0.14 °C: $t_{37} = 5.9$, $p > 0.001$, Fig. 3d–f). The effects on temperature, however, were not mediated by shade-tree canopy height (mean: $F_{1,10} = 2.0$, $p = 0.19$, maximum.: $F_{1,8.9} = 1.04$, $p = 0.33$; minimum: $F_{1,35.0} = 1.45$, $p = 0.23$; Fig. 3f) and did not differ between shade-tree species (mean: $F_{8,25.9} = 0.68$, $p = 0.70$; maximum: $F_{8,21.4} = 1.9$, $p = 0.12$; minimum: $F_{8,2.2} = 17.5$, $p = 0.09$; Fig. A.2b).

3.1.3. *Humidity*

Mean relative humidity was higher, and minimum and maximum relative humidity levels were buffered when shade trees were present vs. when they were absent (mean: +0.44%, $t_{37} = 3.2$, $p = 0.003$; minimum: +2.5%, $t_{38} = 8.6$, $p < 0.001$; maximum: −0.32%, $t_{37} = 3.6$, $p < 0.001$; Fig. 3g–i). The effect of shade trees on mean relative humidity was mediated by shade-tree canopy height (Fig. 3g–i). In particular, higher mean relative humidity levels occurred under shade trees with low canopies ($F_{1,11.4} = 9.0$, $p = 0.01$). However, there was no effect of canopy height on minimum ($F_{1,9.2} = 1.9$, $p = 0.2$) or maximum ($F_{1,36} = 0.13$, $p = 0.72$) levels of relative humidity (Fig. 3g–h). There were also indications that shade-tree species tended to cause differences in mean relative humidity ($F_{8,20} = 2.1$, $p = 0.08$), with the largest increases observed under *Mangifera indica* and the smallest increases observed under *Terminalia superba* (Fig. A.2c).

3.1.4. *Vapor-pressure deficit*

Mean and maximum daily vapor-pressure deficits were lower when shade trees were present vs. when they were absent (mean: −0.1 kPa, $t_{37} = 8.0$, $p < 0.001$; maximum: −0.2 kPa, $t_{37} = 8.4$, $p < 0.001$; Fig. 3j–l). However, there was no evidence that canopy height (mean: $F_{1,10.5} = 1.1$, $p = 0.31$; maximum: $F_{1,10.3} = 0.81$, $p = 0.39$, Fig. 3j–l) or shade-tree species (mean: $F_{8,19.8} = 1.3$, $p = 0.30$; maximum: $F_{8,19.8} = 1.28$, $p = 0.31$, Fig. A.2d) mediated the effects of shade trees on vapor-pressure deficit.

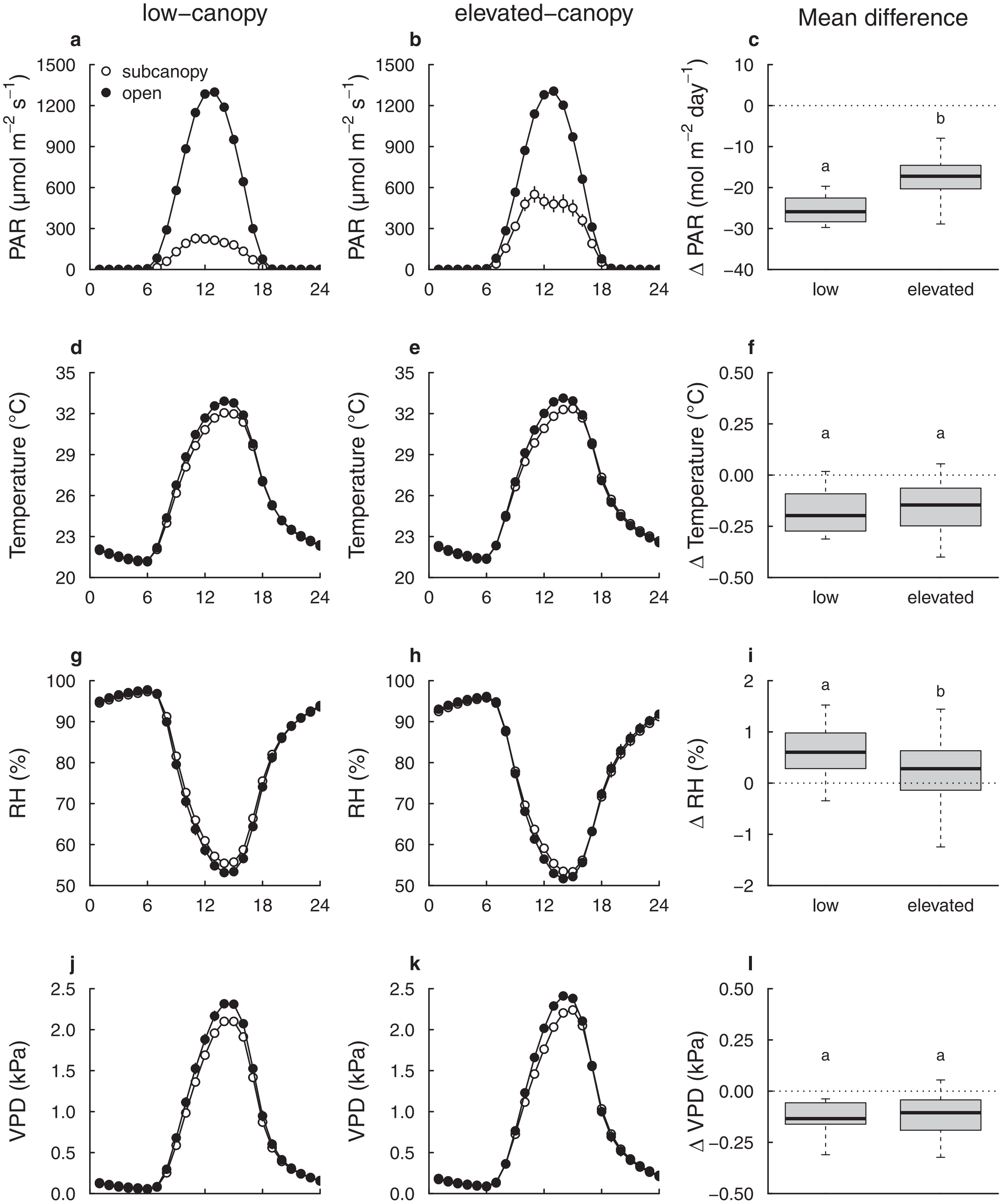

Fig. 3. The effect of shade trees with different canopy heights (low and elevated canopies) on microclimate parameters. The first two columns of panels show the diurnal pattern of the mean hourly measurements of each response variable for low- and elevated-canopy shade trees, respectively. Open dots show measurements under the canopy of shade trees and filled dots show measurements from open control areas. The final column of panels shows the difference (Δ) in the measurements of each response variable between shade-tree and open control plots for low- and elevated-canopy shade trees. Positive values in these panels indicate higher values observed under shade trees. (a) and (b) show results for PAR, and (c) shows the difference in mean daily PAR sum. (d) and (e) show results for temperature, and (f) shows the difference in mean annual temperature. (g-) and (h) shows results for relative humidity (RH), and (i) shows the difference in mean annual relative humidity. (j) and (k) shows results for vapor pressure deficit (VPD), and (l) shows the difference in mean annual VPD. In the first two columns of panels, standard errors are plotted for each value but are only visible where they exceed the size of the dots. In the final column of panels, thick horizontal lines in boxplots represent the median, the box represents the 25th and 75th percentiles, and the whiskers the 5th and 95th percentiles, and different letters indicate significant differences between the two canopy-height classes. Data were recorded over the course of one year from September 2015 to September 2016.

3.1.5. Soil moisture

Average soil moisture levels in topsoils (0–10 cm) were lower when shade trees were present vs. when they were absent (mean −3.8%, $t_{37} = 6.5$, $p < 0.001$). However, there was no evidence that canopy height ($F_{1,35.8} = 0.55$, $p = 0.46$) or shade-tree species ($F_{8,26.8} = 1.5$, $p = 0.19$) mediated the effects of shade trees on soil moisture.

3.2. Effects of shade-tree crown architecture on potential yield

Potential cocoa yield was lower when shade trees were present compared to when shade trees were absent ($t_{34} = 2.9$, $p = 0.006$). However, the negative effects of shade trees on yield were driven by shade trees with low canopies (Fig. 2b). In particular, significant differences in yield under low vs. elevated canopies showed that while low canopies had large negative effects on yield, there was no evidence for a similar reduction in yield under shade trees with elevated canopies ($F_{1,6.7} = 7.2$, $p = 0.03$, Fig. 2b). Lower yields tended to be associated with lower daily light sums reaching the cocoa canopy (linear regression, $R^2 = 0.12$, $F_{1,33} = 4.4$, $p = 0.04$).

Shade-tree species also caused differences in cocoa yield ($F_{8,26} = 2.9$, $p = 0.02$, Fig. A.2e), with the biggest reductions occurring under *Mangifera indica* (−13 ± 4 pods) and *Citrus sinensis* trees (−12 ± 4 pods) and the biggest increases under *Spathodea campanulata* (+3 ± 2 pods) and *Terminalia superba* (+3 ± 1 pods).

Potential losses to diseases were not affected by the presence or absence of shade trees ($t_{34} = 0.56$, $p = 0.58$) and did not differ between the two shade-tree canopy classes ($F_{1,8.2} = 0.02$, $p = 0.9$) or between species ($F_{8,26} = 0.74$, $p = 0.66$).

3.3. Effects of shade-tree crown architecture on aboveground carbon stocks

Shade trees with elevated canopies had higher aboveground carbon stocks than shade trees with low canopies ($F_{1,7.0} = 5.4$, $p = 0.05$; Fig. 2c). Removing one exceptionally tall shade-tree species (*Alstonia boonei,* Fig. A.1) confirmed the general trend but weakened the relationship ($F_{1,5.9} = 4.7$, $p = 0.07$). Aboveground carbon stocks also differed between shade-tree species (Fig. A.2f, $F_{8,30} = 9.5$, $p > 0.001$) with the highest carbon stocks in *Alstonia boonei* (6.9 ± 1.9 Mg C tree^{-1}) and *Antiaris toxicaria* (2.1 ± 0.8 Mg C tree^{-1}) and the lowest carbon stocks in *Citrus sinensis* (0.2 ± 0.1 Mg C tree^{-1}) and *Persea americana* (0.4 ± 0.1 Mg C tree^{-1}).

4. Discussion

The ability of agroforests to meet the objectives of climate smart agriculture may be difficult if shade trees have a mix of costs and benefits for production, and climate-change adaptation and mitigation. Therefore, a key challenge for agroforestry is to maximize the benefits of shade trees while minimizing the costs (Sanchez, 1995; Holmgren et al., 1997; Blaser et al., 2018). We investigated how the benefits and costs of shade trees for production, and climate-change adaptation and mitigation are mediated by the height of the canopy of the shade trees included in cocoa agroforestry systems. Our results demonstrate that while shade trees tend to reduce potential cocoa yields (a cost of shade trees), this effect is most strongly driven by a large negative effect on potential yield of shade trees with low canopies. By contrast, there was no evidence in our study that shade trees with elevated canopies reduce potential cocoa yields (Fig. 2b). Meanwhile, shade trees with different canopy heights were similarly capable of buffering temperature, humidity, and vapor-pressure deficit means and extremes (maxima and minima), suggesting similar abilities to confer benefits for the adaptation of cocoa production to climate change. However, in addition to mediating microclimate, shade trees with elevated canopies also have significantly higher carbon-storage potential (Fig. 2c), and so have a greater ability to benefit climate-change mitigation than shade trees with low canopies. In sum, our results suggest that agroforests may be best able to meet the multidimensional demands of climate-smart agriculture if shade trees are selected and/or managed for elevated canopies.

4.1. The effects of shade trees on light availability and cocoa production

The relationship between cocoa production and light is complex. On the one hand, light is necessary for photosynthesis and so light limitation caused by too much shade from shade trees can limit production via light competition (Lahive et al., 2018). These negative effects on photosynthesis emerge in physiological models of cocoa (Zuidema et al., 2005), and empirical research also shown that heavy shading reduces cocoa yields (Ahenkora.Y et al., 1974; Bisseleua et al., 2009; Clough et al., 2011; Andres et al., 2018; Blaser et al., 2018). The negative effects of shading on cocoa yields are part of the reason why full-sun practices have tended to replace the traditional practice of growing cocoa under shade trees in many parts of West Africa (Ruf, 2011). On the other hand, however, *Theobroma cacao* is an understory tree species in nature and so is most likely adapted to grow best with some shade (Almeida and Valle, 2007). Indeed, photosynthetic capacity in cocoa saturates at low light levels (~400 μmol m^{-2} s^{-1}, which is ~20% of full sunlight; Balasimha et al., 1991; Mielke et al., 2005) and significant photoinhibition occurs if leaves are exposed to high light levels for extended periods of time (Raja Harun and Hardwick, 1988). Furthermore, pollination and pod set have been shown to be highest under light shade (Asomaning et al., 1971), and modeled relationships between cocoa yield and available light suggest that some degree of shading is desirable (Almeida and Valle, 2007). Based on this evidence, maximizing cocoa production is likely to require some shade, but not so much that light limitation occurs.

Our results suggest that this balance between light and shade requirements is best met by selecting shade trees in cocoa agroforests according to canopy height. Both low- and elevated-canopy shade trees reduce photosynthetically active radiation (Fig. 3a–c). However, over the course of a day, low-canopy shade trees reduce light more than elevated-canopy shade trees (Fig. 3c), and only under low-canopy trees is cocoa production compromised (Fig. 2a). While our results are not definitive about mechanism (see Section 4.4 *Limitations*, below), these results are consistent with conceptual arguments suggesting that in some circumstances (including in production systems), tall trees can cast less shade over the course of the day than short trees and so may be less likely to inhibit production of understory species in general, and cocoa in particular (Beer, 1987; Blaser et al., 2013; Somarriba et al., 2013). Thus, while excessive shading under low-canopy trees like *C. sinensis* and *M. indica* can have negative effects on cocoa yields (Figs. 2b, 3a), light shading under trees with elevated crowns, such as *T. superba*, could have the advantage of allowing light levels close to saturating intensity for maximum photosynthesis (Fig. 3b; Raja Harun and Hardwick, 1988). Moreover, the provision of some shade by trees with elevated crowns should also still buffer cocoa from excessive and/or damaging light levels, allowing a longer productive lifetime in shaded cocoa farms compared to full sun monocultures (Obiri et al., 2007; Jagoret et al., 2011).

4.2. Shade trees, but not shade-tree canopy height, influence adaptation to climate change

Many of the world's major cocoa growing regions, particularly those in West Africa, are vulnerable to projected climate changes (Läderach et al., 2013; Schroth et al., 2016; Bunn et al., 2018). In this context, one of the main reasons for promoting cocoa agroforestry is because of the benefits of shade trees for maintaining local microclimates within tolerable ranges, even as macroclimate continues to change (Schroth et al., 2016; Vaast et al., 2016). Our study is one of few studies that empirically support this contention by demonstrating the buffering effect of shade trees in cocoa systems with field data (Asare et al., 2017; Abdulai et al., 2018; Blaser et al., 2018; Niether et al., 2018; Borden et al., 2020). By intercepting solar radiation, shade trees in our study buffered means and extremes (minima and maxima) of temperature and relatively humidity, and reduced vapor-pressure deficit, confirming that shade trees can help to mitigate against stressful environmental conditions (Lahive et al., 2018). Increased minimum and decreased maximum temperatures necessarily result in more stable microclimates. Moreover, our finding that mean and maximum temperatures are lower under shade trees is particularly important for microclimate mediation given evidence that maximum temperatures are projected to become most limiting for cocoa under climate-change projections (Schroth et al., 2016). In contrast to the effects of shade trees on light, however, there tended to be no consistent effect of shade-tree canopy height on microclimate, except for mean relative humidity (Fig. 3i). While the independent variable of interest in our study – canopy height – did not have strong, consistent effects on microclimate variables, this does not mean that other crown characteristics such as 'Plant Area Index',ight not still be important, as has been shown in urban areas (Sanusi et al., 2017).

In general, the effects of shade trees on microclimates that we observed should benefit cocoa production relative to full-sun monocultures. Reducing temperature extremes should help maintain crops in their tolerable temperature range, and higher humidity levels plus lower vapor-pressure deficit during the daytime should reduce evaporative water losses (Lin, 2007, 2010; Lahive et al., 2018). All are key to maintaining high levels of photosynthesis (Balasimha et al., 1991; Niether et al., 2018). In our study, individual shade trees reduced daily maximum temperatures by 0.9 °C, increased minimum relative humidity by 2.5%, and reduced maximum VPD by 0.2 kPa (Fig. 3). Our results for temperature are consistent with some other studies showing reductions in temperature maximums of less than ~1.1 °C (Asare et al., 2017; Blaser et al., 2018; Niether et al., 2018). However, Abdulai et al. (2018) reported decreases in maximum temperatures of up to 7 °C. Together, the relatively few studies with strongly contrasting results highlight that there is still much to learn about the capacity of shade trees to effectively buffer temperature extremes in cocoa and other agroforestry systems. More generally, it remains untested whether these buffering effects are sufficient to enable cocoa production to adapt to projected climate changes, and where other adaptation strategies, such as the gradual replacement of cocoa by systems with more heat and drought adapted crops, could be more suitable (Bunn et al., 2018, 2019).

4.3. Taller shade trees have greater climate-change mitigation potential

Shade trees had consistently higher carbon stocks in their aboveground biomass compared to cocoa trees (1492 vs. 12 kg C tree^{-1}), adding to the many studies that demonstrate the higher climate-change mitigation potential of agroforests compared to cocoa monocultures (Nair et al., 2009; Niether et al., 2020, and references therein). We further demonstrated that shade trees with elevated canopies have significantly higher aboveground carbon stocks than shade trees with low canopies (Fig. 2c). This result is not surprising and can be explained by the taller absolute height of trees with elevated canopies (Fig. A.1a). Nevertheless, combined with our production, light, and microclimate results, the higher climate-change mitigation potential of shade trees with elevated canopies suggests a way to implement agroforests to maximize benefits and minimize costs. In particular, selectively designing agroforests with tall trees that have elevated canopies could allow these systems to generate light and microclimatic conditions most favorable for cocoa production while simultaneously maximizing the carbon storage potential of these systems (Somarriba et al., 2013; Schroth et al., 2014; Blaser et al., 2018).

4.4. Canopy height and farm management through time

Our results suggest that active management of shade-tree canopy height over time could be used to improve the effectiveness of cocoa agroforests. Indeed, shade-tree canopy height is a relatively unique tree trait in the sense that it can be actively manipulated via pruning. Manipulating other tree traits that might also influence tree-crop interactions such as rooting depth, specific leaf area or specific wood density is much more difficult. Our results suggest that pruning to increase the height of the lower canopy of low-canopy shade trees could provide benefits for mature cocoa and so deserves further research attention.

We emphasize that our results show the effects of mature shade trees on mature cocoa trees. It is important to note, however, that agroforestry of perennial crops is a dynamic process where the needs of the crop change over time as the crop plant matures, and the size and effects of shade trees will also change. For example, cocoa seedlings and young cocoa trees are known to have higher shade requirements than mature cocoa trees (Rice and Greenberg, 2000; Wood and Lass, 2001; Tscharntke et al., 2011). In this context, recommendations arising from our results represent a goal to aim for as cocoa trees mature to become productive. This longer-term goal may need to be supported by additional management strategies, including providing appropriate levels of shade for young cocoa trees, to provide optimal conditions for the crop before it reaches maturity. The evaluation of additional management strategies for young cocoa is outside the scope of our current study but certainly deserves further research attention.

4.5. Limitations

We used a mensurative experiment to assess the effect of shade-tree canopy height on cocoa production, and climate-change adaptation and mitigation. For this reason, we cannot rule out effects of potentially confounding variables. While there are good conceptual and empirical arguments supporting our conclusions about canopy height, lower production under low-canopy shade trees may also occur for other reasons such as belowground competition for water and nutrients (Beer, 1987; Abdulai et al., 2018). We cannot rule these and other mechanisms out, although we note that the effect of canopy height on light availability and other potential mechanisms are unlikely to be mutually exclusive. We also note that agroforests in our study area contain shade trees that were actively planted or originated as remnant or naturally regenerated vegetation, which would also cause shade trees themselves to be of different ages. While we are confident our height classification reflects the rank height of mature individuals of each of our shade-tree species, the origin and age of our focal shade trees and its influence on our response variables is unknown. Because of the longevity of both cocoa and shade-trees, long term manipulative experiments including multiple shade-tree species would be required to disentangle these effects. Regardless of the mechanisms involved, our overall conclusions are unchanged; in our study shade trees with elevated canopies are associated with higher production, higher carbon sequestration, and more-or-less equivalent climate-change adaptation benefits compared with shade trees with low canopies.

While our approach comparing cocoa trees directly under shade trees to nearby, open areas provides a good estimate for the effects of single shade trees directly under their canopy, our results do not consider potential positive or negative effects of shade trees beyond the canopy drip line (Norgrove, 2018). Moreover, our approach does not consider how tree-crop competition or microclimatic variables change with increasing shade-tree abundance at the farm scale. Past research along gradients of shade-tree cover show increases in temperature and humidity buffering and a decrease in light as shade-tree cover increases (Lin, 2007; Blaser et al., 2018), and recent work suggests that shade-tree cover beyond 30–40% will likely have negative effects on cocoa yield due to an increase in resource competition (Clough et al., 2011; Andres et al., 2018; Blaser et al., 2018). How these farm/regional scale results would be mediated by the independent and combined effects of shade-tree abundance *and* shade-tree canopy height (and other tree traits) remains unknown. However, our results combined with other studies (Beer, 1987; Isaac et al., 2007; Somarriba et al., 2013) highlight the important possibility that choosing elevated-canopy species might allow higher numbers of shade trees to be maintained in cocoa farms to maximize production, climate, biodiversity, and ecosystem function benefits of agroforests. Improvements in farm management practices will likely only add to these benefits (Clough et al., 2011; Kongor et al., 2017).

Finally, farmers are most likely to adopt recommendations that improve their livelihood. The recommendations stemming from our study address this concern by explicitly focusing on the effects of shade trees on farmers' primary source of income (cocoa production). However, shade trees can also provide farmers with secondary sources of income or provide goods and materials essential for daily life via production of timber, food, or medicine, for example (Herzog, 1994; Cerda et al., 2014; Dumont et al., 2014). We did not assess these livelihood benefits directly, but in our study at least some of the taller trees may be important sources of timber (e.g. *T. superba, A. boonei*), while some of the shorter trees may be important sources of fruit (e.g. *M. indica, P. americana*). In this context, it is important to consider that farmers may gain some livelihood benefits from including low canopy trees that offset the costs to cocoa production that we demonstrate. Therefore, future studies would benefit from assessing the net costs/benefits to farmers' livelihoods via effects of shade trees on both primary and secondary sources of income.

4.6. Conclusion

Much recent work demonstrates the potential of agroforests for climate-smart sustainable agriculture (Vaast et al., 2016; Blaser et al., 2018; Niether et al., 2020). While our understanding of what makes an effective agroforest is improving, we believe there is significant potential to further increase the effectiveness of agroforests through evidence-based approaches. Here we focused on a simple trait of shade trees – canopy height – to demonstrate that careful selection of shade trees for elevated canopy heights can increase some of the manifold benefits of agroforests (production, climate-change adaptation, and climate-change mitigation). We focused on canopy height because there are good ecological reasons why canopy height should mediate interactions between trees and understory species (Blaser et al., 2013; Kunstler et al., 2016), and because it is a simple trait that can be easily assessed and managed by farmers through selective planting and pruning. However, future work should expand the range of potential traits of shade trees (e.g., leaf and root traits) likely to increase the effectiveness of agroforestry systems (e.g. Borden et al., 2020). More generally, we are optimistic that there remains further significant potential to increase the effectiveness of agroforests by increasing our understanding of the independent and combined effects of shade-tree density, shade-tree traits, and other shade-tree characteristics such as potential to provide alternative sources of income and the ability to support high levels of biodiversity.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107676.

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