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ORIGINAL PAPER

Shade trees and tree pruning alter throughfall and microclimate in cocoa (*Theobroma cacao* L.) production systems

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Abstract

• ***Key message*** **Shade trees in agroforestry systems protect the understory cocoa from climate extremes. Shade tree pruning manages microclimatic conditions in favor of cocoa production while tree diversity is maintained. Adaptation of pruning has to consider seasonal changes in temperature and precipitation to protect the understory cocoa.**

• ***Context*** Structural characteristics of tree stands such as species diversity, tree density, and stratification can affect throughfall and microclimate. Pruning changes the canopy and may therefore modulate internal conditions.

• ***Aims*** The aim of this study is to assess the environmental growing conditions of cocoa trees.

• ***Methods*** We monitored canopy openness and the impact of stand structure on throughfall and microclimate in three cocoa production systems (monoculture, agroforestry, and successional agroforestry) and a natural regrowth in a long-term trial in Bolivia from 2013 to 2015. We further focused on the effect of annual shade tree and cocoa pruning on these variables to evaluate the potential impact of this activity.

• ***Results*** Agroforestry systems buffered extreme climate events like temperature fluctuations compared to monocultures but reduced light and throughfall drastically. Spatial variability of throughfall and transmitted light were low under a high and closed shade tree canopy. Shade tree pruning resulted in higher canopy openness, light transmittance, and throughfall, while the buffer function of the agroforestry systems concerning temperature and humidity fluctuations was reduced.

• ***Conclusion*** Differences between cocoa production systems regarding throughfall and microclimate were overlain by pruning activities. Cocoa agroforestry systems are temporal dynamic systems. Pruning timing and intensity is pivotal for balancing light and water availability under seasonally varying environmental conditions to conserve micro-environments for cocoa production with less exposure to unfavorable climate.

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Contribution of the co-authors W.N. contributed to design the data collection, collected the data, analyzed the data, and had the lead in writing the manuscript. L.A. supported in writing the paper and running the statistical data analysis. C.A. contributed by designing the experimental data collection. M.S. was the coordinator of the long-term trial in Bolivia, and contributed in designing the experimental set-up. G.G. was the supervisor of the study and contributed in designing the experimental data collection. All co-authored contributed to the manuscript by detailed reading and revision.

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Keywords Agroforestry · Pruning · Light · Cocoa · Throughfall · Bolivia

1 Introduction

Cocoa (*Theobroma cacao* L.) production is at a crossroads: deforestation versus intensification to meet the growing demand (Vaast and Somarriba 2014), production under the viewpoint of climate change in vulnerable landscapes, and buffer zone management (Schroth et al. 2004) are contemporary issues. Farmers want to increase yields but also rely on benefits from ecosystem services for sustainable production and local livelihoods (Vaast and Somarriba 2014). The relationships between biodiversity and crop performance are under discussion for cocoa (Tscharntke et al. 2011) as well as for coffee (Perfecto et al. 2005) and other tropical crops.

Production systems with cocoa vary from full-sun monocultures to multi-strata agroforestry systems, where cocoa trees are planted together with fruit, timber, firewood, and leguminous trees, or within thinned forests (Rice and Greenberg 2000). Although full-sun monocultures may produce high cocoa yields in the short term (Ahenkorah et al. 1974), agroforestry systems provide other benefits such as conservation of biodiversity, associated ecosystems services and improving farmers' food security (Jacobi et al. 2014), and offer competitive business opportunities (Armengot et al. 2016). In this context, the shade quality, i.e., the diversity of shade trees and associated ecosystem services, offered by the agroforestry trees is as important as the shade quantity that is represented by the percentage of cover (Clough et al. 2011).

The effect of shade trees on light reduction is obvious. Cocoa has a low light saturation: 95% of the maximum photosynthesis occurs at already 200 μmol m^{-2} s^{-1} (Baligar et al. 2008). That makes cocoa a suitable crop to be produced under shade in areas with high radiation around the equator.

Cocoa trees need a stable warm and humid climate (Wood and Lass 2001) and are vulnerable to climate extremes. Temperatures should not fall below 15 °C (Carr and Lockwood 2011) while high ambient temperatures have a negative impact on yield. For instance, higher incidence of cherelle wilt has been reported in a simulated environment with mean temperature of 26.6 °C compared with 23.0 °C (Daymond and Hadley 2008). High temperature can also cause stress indirectly by a higher evapotranspirative demand of the air (Läderach et al. 2013). Cocoa is also sensitive to high levels of vapor pressure deficit (VPD) (Köhler et al. 2014) and CO_2 assimilation declines when VPD increases above 2 kPa (Balasimha et al. 1991). In forests and agroforestry systems, the microclimate beneath the canopy is cooler and more humid compared to the surroundings (Beer et al. 1998; Martius et al. 2004). This reduces the ecophysiological stress for understory crops in comparison to full-sun (Wood and Lass 2001) and makes conditions more resilient to environmental changes (Lin et al. 2008).

Annual precipitation in the main cocoa producing areas ranges from 1300 to 2800 mm (Carr and Lockwood 2011). The distribution over the year is also important (Wood and Lass 2001) since drought has a negative effect: three consecutive months with less than 100 mm precipitation in total result in reduced cocoa yields and reduced long-term vitality of the cocoa trees (Läderach et al. 2013). During rain events, a part of the rainfall is intercepted by the canopy and evaporates without reaching the soil. Throughfall is the portion of rainfall that enters directly through gaps in the canopy and by dripping from vegetation (Calheiros de Miranda 1994). The throughfall rate depends on canopy openness and stand structure, and is variable according to the rainfall intensity over the season (Crockford and Richardson 2000).

The northern lowlands of Bolivia, involving the region Alto Beni, provide suitable soil and climate for cocoa cultivation (Elbers 2002) although inter-annual variability in precipitation patterns and temperature is common (Seiler et al. 2013a). Additionally, climate change is predicted to heavily affect agriculture (including cocoa production) and ecosystem stability in Bolivia (Seiler et al. 2013b). Already existing constraints in cocoa production will be enhanced by intensification of differences in the rainfall distribution pattern and increasing temperature. Adaptation strategies are therefore needed, not only in Alto Beni but also in other affected cocoa producing areas. The potential of agroforestry systems as suitable production systems for climate change adaptation is already under discussion (Vaast and Somarriba 2014) but until now little attention has been paid to management practices of agroforestry systems beside tree species selection and planting density. Cocoa farmers usually slash trees to reduce shading, while shade tree pruning is not very common due to a lack of knowledge, equipment, and workforce (Andres et al. 2016). Pruning has the potential to modify light availability and regulate humidity to limit pathogens (Schroth et al. 2000), while maintaining biodiversity and associated ecosystem services (Tscharntke et al. 2011).

In this study, we show the influence of stand structure and pruning on throughfall and microclimate in different cocoa production systems and a natural regrowth of the same age in Alto Beni, Bolivia. Stand structure is defined here by the cocoa and shade tree density and planting design, the canopy openness, and the stratification of the different cocoa production systems, while pruning of cocoa and shade trees is an activity to modulate the canopy. We hypothesized (i) that shade trees buffer environmental conditions. Therefore, we were looking at fluctuations of temperature and vapor pressure deficit within in the systems. We further hypothesized (ii) that cocoa and shade tree pruning changes the microclimatic conditions. Adequate pruning could be used to improve the growing conditions in favor of the cocoa.

2 Materials and methods

2.1 Study area, regional climate, and climate trends

The study site Sara Ana is located in Alto Beni at the eastern foothills of the Bolivian Andes. It lies on an alluvial terrace 380 m.a.s.l. at 15° 27′ 36.60″ S and 67° 28′ 20.65″ W, with soil of Lixisols and Luvisols classes (Schneider et al. 2017).

The nearest weather station (Sapecho: 410 m.a.s.l., 15° 33′ 56 ″ S and 67° 19′ 30 ″ W) recorded weather data from 1964 to 2012 (SENAMHI 2015): 1439 mm mean annual precipitation, 25.2 °C mean annual temperature, and 83.0% mean annual relative humidity offer favorable conditions for cocoa production. Restrictions are the distribution of rainfall over the year—78% of total annual precipitation falls in the rainy season from October to April—and temperature extremes that vary between cool nights and hot days.

The weather records showed that in several years, annual precipitation was below 1250 mm, which was set as the minimum value for cocoa production (Zuidema et al. 2005) and in some years even below 1000 mm (Fig. 1a). Trend analyses a slight decrease in annual precipitation over time. A more pronounced decrease in monthly precipitation was observed in the months of the dry season, e.g., in August (Fig. 1b). Mean annual temperature increased over time (Fig. 1c).

2.2 Experimental plot description

In 2008, the Research Institute of Organic Agriculture (FiBL) and local partners established a long-term trial with experimental cocoa plots using a randomized complete block design with four repetitions to compare five different cocoa production systems (Fig. 2): full-sun monocultures and agroforestry systems both under organic and conventional farming and a highly diverse successional agroforestry system under organic farming. Non-cultivated plots (natural regrowth, fallow) of the same age following a natural succession were also included in the trial. Each plot had a size of 48 by 48 m, while data collection took place in the inner 24 by 24 m net-plot (Schneider et al. 2017).

2.3 Tree distribution and management

Cocoa was spaced 4 by 4 m resulting in a stem density of 625 stems ha^{-1} (Table 1). Plantains were cultivated between the cocoa rows in all cocoa production systems to provide shade during the establishment phase, but were removed from the monoculture after 3 years. Both the agroforestry system and the successional agroforestry system combine cocoa with woody shade trees and banana or plantain, forming two canopy layers above the cocoa tree layer. In the agroforestry system, shade trees include timber and fruit trees (spaced 16 by 8 m) and leguminous trees (evenly spaced 8 by 8 m). Seventy-eight fruit palms per hectare were planted. In the successional agroforestry system, tree seedlings were planted like in the agroforestry system, additionally various tree seeds were dispersed and others grew due to natural succession (lists of species in the agroforestry system and the successional agroforestry system are provided in Tables 5 and 6 in Appendices). Sweet bananas (*Musa x paradisiaca* L.) in the agroforestry system and various *Musa* spp. in the successional agroforestry system were cultivated between the cocoa rows with an initial spacing of 4 by 4 m (Schneider et al. 2017). Plantains and banana in the agroforestry system and the successional agroforestry system are hereafter collectively termed *Musa*.

Cocoa tree management included three types of pruning: phytosanitary pruning to control diseases, removal of tree suckers, and annual maintenance pruning for crown formation. Maintenance pruning of shade trees in the agroforestry system took place for the first time in 2013 and was continued thereafter annually before the cocoa maintenance pruning in the late dry season between August and September. In the successional agroforestry system, maintenance pruning followed the same strategy as in the agroforestry system, but the closed shade tree layer was principally pruned in 2012. Additionally, selective weeding and growth control were done manually as required over the year. *Musa* were managed by cutting leaves and replacement of pseudostems as required.

The fallow plots without cropping and management were dominated by fast growing pioneer succession species like *Cecropia* spp., forming a canopy at a mean height of 13 m.

2.4 Measurements of stand characteristics, canopy openness, and light

The total crown height of cocoa trees, shade trees, and *Musa* was estimated in 2014 and 2015 before pruning. Cocoa crown volume was calculated before the pruning intervention in 2015 by applying the ellipsoid volume formula: $v = \frac{2}{9}\pi * a * b * c$, where a and b are horizontal expansions of the crown and c is the crown height that is the difference between total and basal crown height. The stem circumference of cocoa trees was measured at 0.3 m height, and of woody shade trees and *Musa* at 1.3 m to calculate the basal area. Trees and *Musa* smaller than 1.3 m were not evaluated.

Hemispherical photographs (24 pictures per plot) were taken using a Nikon CoolPix5400 equipped with a FC-E8 converter lens with a 180° angle before (July) and after the cocoa and shade tree maintenance pruning (October) in 2013, 2014,

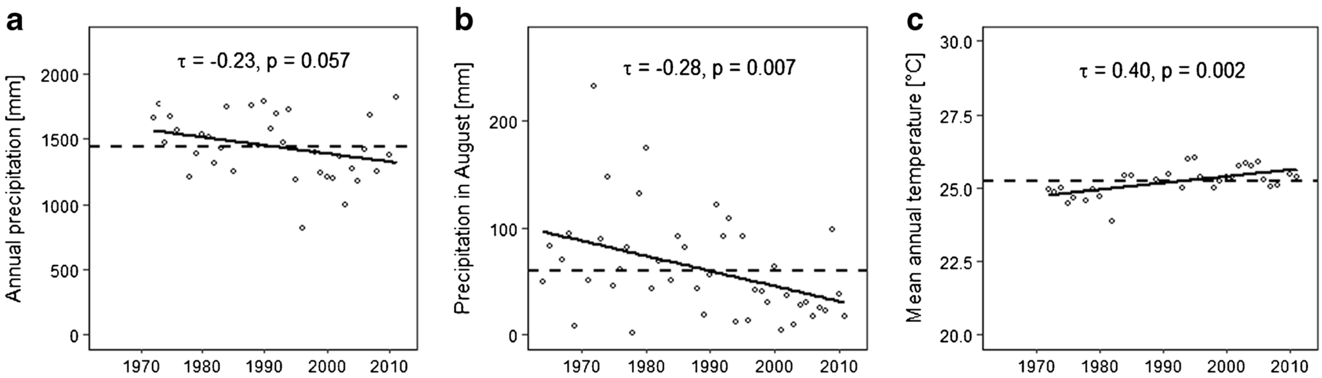

Fig. 1 Annual precipitation (**a**), precipitation in August (**b**), and mean annual temperature (**c**) for the period from 1964 to 2012. The long-term means are indicated as a dashed line, the solid line shows the trend with the coefficient τ and the *p* value. Data were obtained from SENAMHI (2015)

and 2015 at 1.3 m above the soil to estimate total crown canopy openness (%) of the cocoa and the shade trees. Additionally, pictures were taken at 3.2 m in the agroforestry system and the successional agroforestry system to estimate the canopy openness above the cocoa. Pictures and further data were collected along a V-shaped transect of 52 m within the net plot that crossed the cocoa and shade tree rows (Fig. 1; Niether et al. 2017). In the natural regrowth, 24 pictures were taken in 2013 and 2014 in July along two straight transects of 26 m each crossing the plots randomly, since tree distribution was not structured as in the cocoa plots. Pictures were analyzed using Gap Light Analyzer (Frazer et al. 1999) by a single person to avoid any bias in the threshold levels.

Photosynthetically active photon flux density (PPFD, μmol m^{-2} s^{-1}) was measured from photosynthetic active radiation using an AccuPAR PAR/LAI-Ceptometer (LP-80, Decagon Devices, Inc., Pullman WA, USA) before (July) and after (October) pruning in 2014. Measurements were taken at midday between 1100 and 1300 h on cloudless days to avoid bias by the influence of varying diffuse radiation.

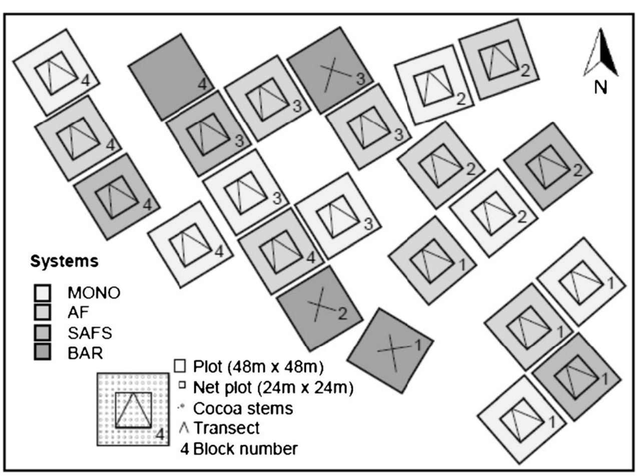

Fig. 2 Set-up of the trial in Alto Beni, Bolivia, showing the location of the plots and the transect for data collection in the cocoa production systems, i.e., monoculture (MONO), agroforestry system (AF), and successional agroforestry system (SAFS), and in the natural regrowth (BAR)

Transmitted PPFD below the canopy was measured on 24 locations along the transect at 1.3 m, while the transmitted PPFD above the canopy was measured outside the plot on 5 spots immediately before and after the corresponding within-plot measurements. The PPFD above the canopy was 1580 μmol m^{-2} s^{-1} in July (solar zenith angle: $\Theta = 35.1°$) and 2028 μmol m^{-2} s^{-1} in October ($\Theta = 12.4°$) with no differences between the systems (F value = 2.1, p value = 0.121). The ratio of radiation directly coming from the solar beam was $f_B = 0.86$ (July) and $f_B = 0.90$ (October). The PPFD at 3.2 m was calculated from the leaf area index (LAI) obtained by the analysis of the canopy openness (pictures at 3.2 m) using the equations and default set-ups from Decagon (2013):

$$\tau = exp\left[\frac{(0.283 + 0.785a - 0.159a^2)(1 - 0.47f_B)\mathrm{LAI}}{1 - \frac{1}{2K}f_B - 1}\right]$$

where τ gives the fraction of transmitted PPFD with transmited PPFD = $\tau *$ PPFD above the canopy, a is the leaf absorption with $a = 0.9$, f_B is the ratio of radiation, and K is the extinction coefficient of the canopy with:

$$K = \frac{\sqrt{X^2 + \tan\Theta^2}}{X + 1.744(X + 1.182)^{-0.733}}$$

where X is the leaf angle distribution parameter with $X = 1$ and Θ is the zenith angle of the sun.

2.5 Throughfall measurements

Total rainfall and throughfall (mm) within the plots were measured with rain gauges at 1 m height during the dry season with transition to the rainy season from June to November in 2013 and 2014. Bulk deposition was collected weekly and monthly totals were calculated. Evaporation from rain gauges was limited by the white color of the

Table 1 Canopy and stand characteristics (mean ± standard error) of monoculture, agroforestry system, and successional agroforestry system before pruning, and results from the linear mixed-effects models. Letters indicate differences between the production systems

Parameter	Monoculture	Agroforestry system	Successional agroforestry system	*F* value	*P* value
Total crown height [m]					
Cocoa	3.2 ± 0.1[a]	3.3 ± 0.1ab	3.5 ± 0.1b	3.8	0.047
Musa		4.4 ± 0.1a	5.0 ± 0.1b	24.5	< 0.001
Woody shade trees		7.4 ± 0.1a	4.7 ± 0.1b	152.2	< 0.001
Crown volume cocoa [m^3]	18.8 ± 1.1[a]	17.6 ± 0.8ab	14.4 ± 1.6b	5.7	0.015
Basal area [m^2 ha^{-1}]					
Cocoa	6.5 ± 0.3[a]	4.3 ± 0.2b	3.1 ± 0.3c	141.0	< 0.001
Musa		12.2 ± 1.2a	16.1 ± 4.3a	1.8	0.222
Woody shade trees		5.1 ± 0.4a	4.1 ± 1.6a	0.9	0.385
Mean stem diameter [cm]					
Cocoa	11.0 ± 0.2[a]	9.1 ± 0.3b	7.4 ± 0.6c	69.25	< 0.001
Musa		13.9 ± 1.5a	17.3 ± 0.9a	2.41	0.152
Woody shade trees		13.6 ± 0.6a	5.3 ± 0.8b	88.97	< 0.001
Stem density [n ha^{-1}]					
Cocoa	625	625	625		
Musa		668 ± 81a	625 ± 142a	0.1	0.780
Woody shade trees		243 ± 0a	1181 ± 216b	44.0	< 0.001

gauges and the reduced bottle neck opening (Ø < 1 cm) of the container. Throughfall was measured in three blocks with eight rain gauges (Ø = 17 cm) per plot (Unece 2010) along the transect and total rainfall with four rain gauges on a pasture in proximity to the plots. The throughfall rate (%) was calculated from total rainfall and throughfall. Throughfall rates above 100% could occur due to the funneling effect of broad leaves and branches (Siles et al. 2010a; Cattan et al. 2007). Stemflow was not measured in this study since it accounts for < 1% of total rainfall in cocoa production systems (Dietz et al. 2006). The influence of pruning on throughfall was evaluated by comparing the throughfall rates from the month before pruning (July) and after pruning (October).

2.6 Microclimate measurements

Dataloggers (Hobo Pro Series, Onset Computer Corporation, Bourne MA, USA) recorded temperature (°C) and relative humidity (%) hourly at 1 m height. Loggers were cross-calibrated prior to installation in the field. From corresponding temperature and relative humidity data, VPD (kPa), evaporation (E_{within}; mm day^{-1}), and cocoa evapotranspiration ($ET_{\text{cocoa-within}}$; mm day^{-1}) within the systems at 1 m height were calculated according to Allen et al. (1998) to describe not the whole stand evaporation and evapotranspiration, but the microclimatic situation inside the different cocoa stands; therefore, we used the fraction of transmitted PPFD (τ) that entered each systems at 1 m height before and after pruning, respectively (Sections 2.4 and 3.1), to calculate the fraction of shortwave ($R_{\text{ns-within}}$) and longwave radiation ($R_{\text{nl-within}}$) that entered the systems as $R_{ns-\text{within}} = R_{ns} * \tau$ and $R_{nl-\text{within}} = R_{nl} * \tau$. $R_{\text{n-within}}$ is the fraction of net radiation that entered the systems, which was calculated as $R_{n-\text{within}} = R_{ns-\text{within}} - R_{nl-\text{within}}$ (Allen et al. 1998).

E_{within} was calculated applying the equation for equivalent evaporation (Allen et al. 1998): $E_{\text{within}} = 0.408 * R_{nl-\text{within}}$. $ET_{\text{cocoa-within}}$ was calculated using the FAO Penman-Monteith equation with the crop coefficient for cocoa $K_{\text{cocoa}} = 1.05$ (Allen et al. 1998):

$$ET_{\text{cocoa-within}} = \left(\frac{0.408*\Delta*(R_{n-within}-G) + \gamma*\frac{900}{\left(T_{mean}+273\right)}*u*(e_s-e_a)}{\Delta+\gamma*(1+0.34*u)} \right) *K_{\text{cocoa}}$$

where Δ represents the slope of the saturation vapor pressure temperature relationship, G is the soil heat flux (estimated as $G = 0$ according to Allen et al. 1998), γ is the psychrometric constant, T_{mean} is the mean temperature within the respective system, the wind speed u within the system was estimated as $u = 0.5$ m s^{-1} from wind speed data from the region (SENAMHI 2015) and according to Allen et al. (1998), and (e_s-e_a) represents the vapor pressure deficit of the air.

In 2013, three to four dataloggers were placed in each plot of one block and one to two dataloggers per plot in three blocks in 2014. Statistical analyses were performed with data from 2014.

2.7 Statistical analysis

We applied linear mixed-effect models using R (R Core Team 2016) to describe the effects of system, pruning, and the interaction (*system*:*pruning*) on the response variables, i.e., mean of in-field data of canopy openness, PPFD, basal area, height, crown volume, throughfall rate, temperature, relative humidity, VPD, evaporation and evapotranspiration, and spatial variability (expressed as standard deviation of in-field data) of canopy openness, PPFD, and throughfall rate. *Block* nested to *year* were included as random factors. The significances of the effects were tested and when significant differences were observed, post-hoc tests of pairwise comparison with differences of least significant means were applied (*lmerTest* R package, Kuznetsova et al. 2016). When necessary, data were transformed to meet the normality and homoscedasticity of the residuals. Data are shown as mean ± standard error.

We used Spearman's rank correlation (ρ) for non-normally distributed data to evaluate correlations between throughfall and stand structural parameters. Climate trends using data from SENAMHI (2015) were calculated as Kendall's tau (τ) according to the Mann-Kendall trend test (*Kendall* R package, McLeod 2011; *boot* R package, Canty and Ripley 2015). Data frames were managed with the *plyr* R package (Wickham 2011) and graphs were designed with the *ggplot2* R package (Wickham 2009).

Preliminary analyses showed that organic and conventional farming practices in the monoculture and the agroforestry system had no influence on model variables (Table 7 in Appendices). Therefore, data of organic and conventional management were pooled and are not discussed here.

2.8 Data availability

The datasets generated and analyzed during the current study are available in the Zenodo repository (Niether et al. 2018) https://doi.org/10.5281/zenodo.1185579.

3 Results

3.1 Canopy structure, dynamics, and the influence on light transmittance

The monoculture had a single canopy layer formed by the cocoa crown, whereas the agroforestry system and the successional agroforestry system had two additional canopy layers above the cocoa, one of woody trees, the other one of *Musa* (Table 1). In the agroforestry system, the woody shade tree canopy built the top layer of the system, while *Musa* (here: only sweet banana) formed the second layer below. The opposite was found in the successional agroforestry system where the *Musa* (here: various varieties from banana and plantain) layer was higher than the woody tree canopy. Cocoa basal area and crown volume were higher in the monoculture than in the agroforestry system and the successional agroforestry system. Shade tree density was higher in the successional agroforestry system than in the agroforestry system, while no difference was observed in the basal area of the trees.

Canopy openness measured below the cocoa at 1.3 m before the pruning was highest in the monoculture and lowest in the agroforestry system (Table 2). Canopy openness in the agroforestry system was even lower than in the non-managed natural regrowth. After pruning of both cocoa and shade trees, canopy openness increased from 36.4 to 54.0% in the monoculture (+ 17.7%), from 11.6 to 28.9% in the agroforestry system (+ 17.3%), and from 13.6 to 22.5% in the successional agroforestry system (+ 8.7%). The subsequent canopy growth in the 10 months before the pruning session of the following year decreased canopy openness again in the monoculture (− 18.6%), in the agroforestry system (− 16.3%), and in the successional agroforestry system (− 5.4%).

The spatial variability of the canopy openness increased with canopy openness in the agroforestry system, the opposite was observed in the monoculture where heterogeneity decreased with increasing canopy openness, i.e., with pruning of the cocoa trees. The dense canopy of the natural regrowth resulted in a low spatial variability of canopy openness.

In comparison to the full-sun monoculture, canopy openness measured at 3.2 m was low in the agroforestry system and the successional agroforestry system due to the shade tree canopy (Table 2). Canopy openness increased from 25.6 to 54.6% in the agroforestry system (+ 29.0%) and from 24.2 to 44.2% in the successional agroforestry system (+ 21.2%) because of the pruning activities. At the same time, spatial variability of canopy openness increased compared to the spatial variability before pruning, especially in the agroforestry system. In the following months, the leaves and branches of the shade trees expanded and canopy openness decreased again in the agroforestry system (− 27.3%) and in the successional agroforestry system (− 23.6%).

PPFD measured in full-sun was 1580 ± 12 μmol m^{-2} s^{-1} in July and 2028 ± 17 μmol m^{-2} s^{-1} in October at midday between 1100 and 1300 h. In July, the shade tree canopy transmitted only 39% of the light in the agroforestry system and 50% in the successional agroforestry system measured at 3.2 m (Table 2). The fraction of transmitted light below the shade tree canopy and the cocoa canopy was 62% in the monoculture, 15% in the agroforestry system, and 20% in the successional agroforestry system. In the natural regrowth, the fraction of transmitted light was reduced to 7%. After pruning, the fraction of transmitted light increased up to 83% in the agroforestry system and 65% in the successional agroforestry system below the shade tree canopy at 3.2 m and

Table 2 Field average and spatial variability (mean ± standard error) of canopy openness and photosynthetic active radiation (PPFD) at 1.3 m (below the cocoa crown) and 3.2 m (above the cocoa crown), and throughfall rate of monoculture, agroforestry system, successional agroforestry system, and natural regrowth before (July) and after pruning (October), and results from the linear mixed-effect models. Letters indicate differences for one parameter when significant interactions (*system:pruning*) were observed

Parameter		Monoculture	Agroforestry system	Successional agroforestry system	Natural regrowth		*System*	*Pruning*	*System: pruning*
Average canopy openness at 1.3 m [%]	Before	36.4 ± 1.6a	11.6 ± 0.6b	13.6 ± 1.6c	13.1 ± 0.6c	*F* value	258.1	155.1	4.8
	After	54.0 ± 1.4d	28.9 ± 1.3e	22.5 ± 3.0f		*P* value	< 0.001	< 0.001	0.011
Spatial variability of canopy openness at 1.3 m [%]	Before	18.0 ± 0.4a	4.5 ± 0.3b	4.7 ± 0.6b	1.7 ± 0.1c	*F* value	282.9	2.6	74.1
	After	11.9 ± 0.5d	8.6 ± 0.5e	4.8 ± 0.5b		*P* value	< 0.001	0.107	< 0.001
Average canopy openness at 3.2 m [%]	Before		25.6 ± 1.0a	24.2 ± 3.9a		*F* value	8.1	139.1	4.7
	After		54.6 ± 1.2b	44.2 ± 3.4c		*P* value	0.007	< 0.001	0.037
Spatial variability of canopy openness at 3.2 m [%]	Before		10.2 ± 0.5a	9.5 ± 1.2a		*F* value	13.5	16.8	10.3
	After		16.0 ± 0.8b	9.9 ± 1.1a		*P* value	< 0.001	< 0.001	0.002
Average PPFD at 1.3 m [μmol m^{-2} s^{-1}]	Before	985 ± 61a	243 ± 37bc	317 ± 15b	116 ± 28c	*F* value	130.9	175.9	35.3
	After	1546 ± 73d	1273 ± 70a	949 ± 75e	233 ± 16bc	*P* value	< 0.001	< 0.001	< 0.001
Spatial variability of PPFD at 1.3 m [μmol m−2 s−1]	Before	609 ± 21a	316 ± 31b	327 ± 20b	169 ± 46c	*F* value	48.7	53.1	15.4
	After	614 ± 35a	624 ± 18a	606 ± 43a	233 ± 16bc	*P* value	< 0.001	< 0.001	< 0.001
Average PPFD at 3.2 m [μmol m^{-2} s^{-1}]	Before		619 ± 24a	792 ± 109a		*F* value	1.4	972.2	106.2
	After		1680 ± 32b	1326 ± 107c		*P* value	0.275	< 0.001	< 0.001
Spatial variability of PPFD at 3.2 m [μmol m−2 s−1]	Before		260 ± 23a	307 ± 32a		*F* value	0.02	6.5	3.9
	After		379 ± 41a	322 ± 27a		*P* value	0.874	0.023	0.076
Throughfall rate [%]	Before	94.5 ± 4.6a	54.8 ± 3.9b	74.7 ± 7.3c	91.2 ± 1.7ac	*F* value	14.7	3.4	9.4
	After	91.5 ± 3.3a	81.4 ± 3.1a	77.6 ± 3.3c	85.0 ± 4.4ac	*P* value	< 0.001	0.08	< 0.001
Spatial variability of throughfall rate [%]	Before	41.1 ± 6.6	38.8 ± 3.3	57.4 ± 11.2	27.6 ± 5.4	*F* value	3.9	15.1	1.4
	After	18.3 ± 2.9	35.4 ± 5.3	33.0 ± 8.0	20.1 ± 4.0	*P* value	0.014	< 0.001	0.255

up to 76% in the monoculture, 63% in the agroforestry system, and 47% in the successional agroforestry system below the pruned shade and cocoa trees at 1.3 m.

The spatial variability of transmitted light within the field was higher in the monoculture than in shaded cocoa production systems at 1.3 m (Table 2). It increased in the agroforestry system and the successional agroforestry system after pruning slightly below the shade tree canopy at 3.2 m and even more below the canopies of shade and cocoa trees at 1.3 m. However, cocoa pruning did not affect spatial variability of transmitted light in the monoculture. After pruning, all cocoa production systems had the same spatial variability of transmitted light below the canopies at 1.3 m. The spatial variability of transmitted light below the shade tree canopy in the agroforestry system and the successional agroforestry system was still 58% of the variability below the shade and cocoa tree canopies.

The fraction of transmitted light and their spatial variability was systematically lower in the natural regrowth than in the cocoa production systems.

3.2 Precipitation and throughfall

Total rainfall during the dry season until the beginning of the rainy season (June to November) was 683 mm in 2013 and 611 mm in 2014. It changed over the course of the season, with the lowest rainfall recorded in July (38 mm in 2013 and 57 mm in 2014), and the highest in October (209 mm in 2013 and 176 mm in 2014) (Fig. 3a). Consequently, also throughfall changed along the season. The throughfall rate from June to November was 93.6 ± 7.0% in the monoculture, 70.6 ± 6.3% in the agroforestry system, 77.2 ± 6.2% in the successional agroforestry system, and 88.0 ± 5.9% in the natural regrowth (Fig. 3b).

Before pruning, throughfall was only 54.8% in the agroforestry system and 74.7% in the successional agroforestry system (Table 2). Further, 94.5% of total rainfall entered the cocoa canopy in the monoculture. Throughfall rate increased with pruning to 81.4% in the agroforestry system (+ 26.7%), while the pruning did not change throughfall rate in the other systems. In the successional agroforestry system, the non-significant result was caused by combining data from a very light pruning in 2013 and a stronger pruning in 2014 (data not shown). In October, after pruning, throughfall in the agroforestry system was as high as in the monoculture. Throughfall in the natural regrowth was high year round.

The throughfall rate was positively correlated with canopy openness before and after pruning (Fig. 4a, b). Pruning reduced the correlation coefficient. Throughfall rate decreased with increasing stem basal area before pruning (Fig. 4c), but no correlation was observed after pruning (Fig. 4d). The same effect was observed for the influence of total crown height on throughfall rate of the systems before (Fig. 4e) and after pruning (Fig. 4f).

In contrast to the spatial variability of transmitted light, the spatial variability of throughfall decreased with pruning (Table 2).

3.3 Microclimate

Annual mean temperature was identical in the monoculture and the agroforestry system, but the mean annual temperature amplitude was reduced in the agroforestry system by 1.1 °C compared to the monoculture (Table 3). Annual mean relative humidity was 2.7% higher and VPD was 11 kPa lower in the agroforestry system than in the monoculture. Microclimate in the natural regrowth control was even more buffered than in the agroforestry system, mean annual temperature, temperature amplitude, and VPD were lower, while the relative humidity was higher compared to the agroforestry system and the monoculture.

Differences of monthly means in temperature, temperature amplitude, relative humidity, and VPD were distinguishable between the systems (Fig. 5) and even more pronounced on a daily time scale: during daytime, VPD increased above 2 kPa on 381, 226, and 62 days of a total of 651 measured days in the monoculture, the agroforestry system, and the natural regrowth, respectively (data not shown).

In July, before pruning, the temperature fluctuations were higher in the monoculture than in the agroforestry system, the successional agroforestry system, and the natural regrowth, while at the same time relative humidity was lower

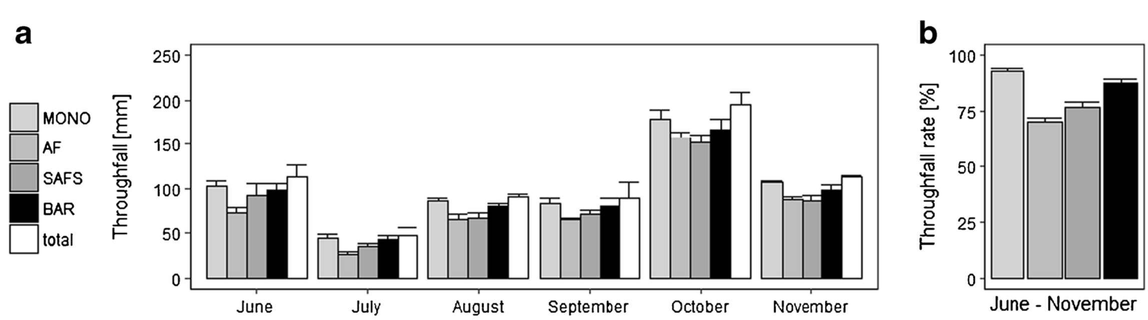

Fig. 3 Total rain (total) and throughfall per month (**a**) and throughfall rate over the period June to November (**b**) in monoculture (MONO), agroforestry system (AF), successional agroforestry systems (SAFS), and natural regrowth (BAR) for the years 2013 and 2014

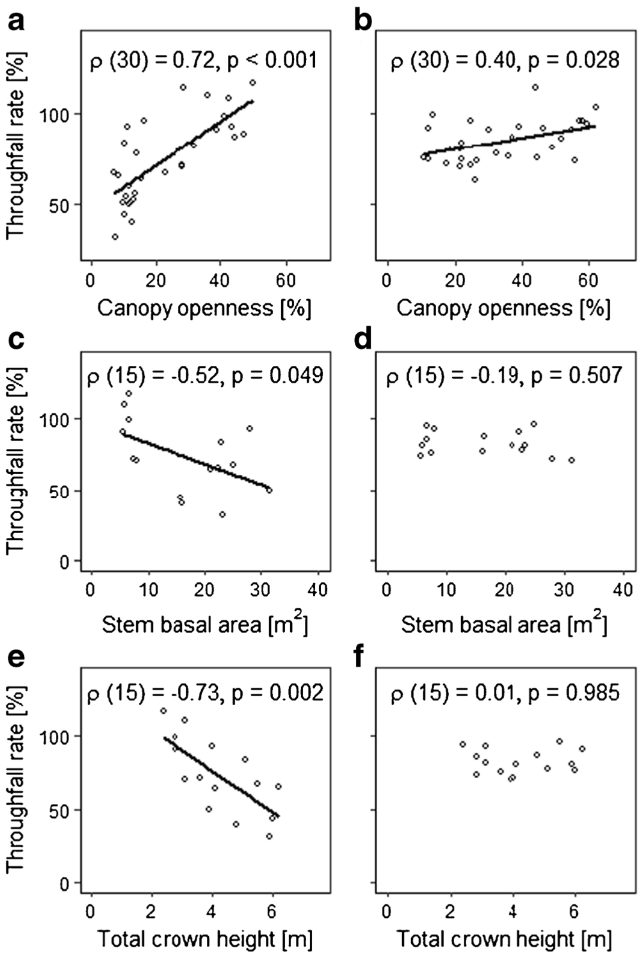

Fig. 4 Throughfall rate influenced by canopy openness (**a**, **b**), stem basal area (**c**, **d**), and total crown height (**e**, **f**) for the conditions before (left column) and after pruning (right column)

(Table 4, Fig. 5). Therefore, also the VPD was higher in the monoculture than in the other systems. Due to the shading effect on the microclimate, the lowest evaporation was calculated for the natural regrowth and increased with decreasing shading from the agroforestry system and the successional agroforestry system to the monoculture. Cocoa evapotranspiration was lowest in the agroforestry system, followed by the successional agroforestry system and the monoculture.

From July to October, season changed from dry winter to spring at the beginning of the rainy season, coming along with increasing temperature (Fig. 5a) and an increase in temperature amplitude (Fig. 5b) that was highest in the agroforestry system (+ 7.9 °C), followed by the successional agroforestry system (+ 6.5 °C) and the monoculture (+ 4.2 °C), and lowest in the natural regrowth (+ 3.6 °C) (Table 4). Relative humidity decreased from July to October (Fig. 5c), the most in the agroforestry system (− 13.2%), followed by the monoculture (− 11.3%), the successional agroforestry system (− 11.2%), and the natural regrowth (− 11.9%) (Table 4). Consequently, VPD (Fig. 5d), evaporation, and cocoa evapotranspiration increased with highest values in the agroforestry system, followed by the monoculture and the successional agroforestry system (Table 4). VPD and evaporation in the natural regrowth increased less than in the cocoa production systems. The different responses of the systems to the seasonal changes were related to the influence of the pruning, while microclimatic changes in the natural regrowth were related only to seasonal changes.

After pruning of the shade and cocoa trees, microclimatic differences were not observed any more between the monoculture and the other cocoa production systems, i.e., the agroforestry system and the successional agroforestry system. However, these parameters were still significantly different in the natural regrowth (Table 4). Despite the same microclimatic conditions in the cocoa production systems, evaporation and cocoa evapotranspiration, which also depend on the radiation, were still highest in the monoculture, followed by the agroforestry system and the successional agroforestry system.

4 Discussion

4.1 Agroforestry systems buffer climate extremes but reduce throughfall

Agroforestry systems with a high number of associated trees and a low canopy openness maintained balanced microclimatic conditions with smaller fluctuations of temperature and relative humidity in comparison to full-sun monocultures. The same buffering effects of shade on microclimate and extreme conditions are shown for shaded and unshaded coffee production systems (Siles et al. 2010a) and forests, poly- and monoculture tree stands (Martius et al. 2004). However, the annual mean temperature was not reduced in the agroforestry system compared to the monoculture, limiting the resilience effect of growing cocoa under shade with the predicted increases in mean temperature.

Monthly mean VPD in all systems was low due to continuously high relative humidity during the night, but VPD increased regularly during daytime above 2 kPa, where the net photosynthetic rate of cocoa decreases (Balasimha et al. 1991). This happened regularly in the monoculture and was less observed in the agroforestry system. Shade trees therefore play an important role in reducing ecophysiological stresses for cocoa trees and maintaining photosynthesis at high temperatures. The light saturation point for photosynthesis of cocoa as mentioned by Baligar et al. (2008) was exceeded for all measurements in the monoculture, even when including the self-shading effect of the cocoa by measuring at the height of the lower boundary of the cocoa crown. PPFD measured at the same height in the agroforestry system was sufficient for photosynthesis under the measurement conditions (midday, cloudless), but light limitations for the lower, self-shaded leaves of the cocoa under different radiation intensities in the

Table 3 Microclimatic parameters at 1 m height (temporal mean ± standard error) within monoculture, agroforestry system, and in the natural regrowth in 2014, and results from the linear mixed-effects models. Letters indicate differences between the systems

Microclimatic parameters	Monoculture	Agroforestry system	Natural regrowth	*F* value	*P* value
Temperature [°C]					
Annual mean	24.7 ± 0.4a	24.6 ± 0.5a	23.7 ± 0.4b	96.5	< 0.001
Annual mean amplitude	19.9 ± 0.6a	18.8 ± 0.9b	14.6 ± 0.8c	75.0	< 0.001
Relative humidity [%]					
Annual mean	88.3 ± 0.9a	91.0 ± 1.2b	94.0 ± 1.2c	85.5	< 0.001
Vapor pressure deficit [kPa]					
Annual mean	0.50 ± 0.06a	0.39 ± 0.07b	0.23 ± 0.06c	47.9	< 0.001

course of the day (Siles et al. 2010a) and with clouded sky were possible. Limited photosynthesis might therefore be the explanation for lower yields in the agroforestry system compared to the monoculture (Schneider et al. 2017) and of higher crown volume and basal area of full-sun compared to shaded cocoa trees. Smaller cocoa trees in the successional agroforestry system than in the agroforestry system enforce the idea of competition not only for light but also for nutrients by a high stem density (Schroth et al. 2001).

Increasing canopy openness and light transmittance were accompanied by increasing temperature and VPD. Both are correlated with an increase in transpiration (Lin 2010), that will finally cause a decrease in net photosynthetic rate (Balasimha et al. 1991). Below the canopies, evaporation and cocoa evapotranspiration were lower in the agroforestry system than in the monoculture, as it is already described for cocoa transpiration in a multi-species stand (Köhler et al. 2014) and for shaded coffee (van Kanten and Vaast 2006; Lin 2007). Reduced transpiration

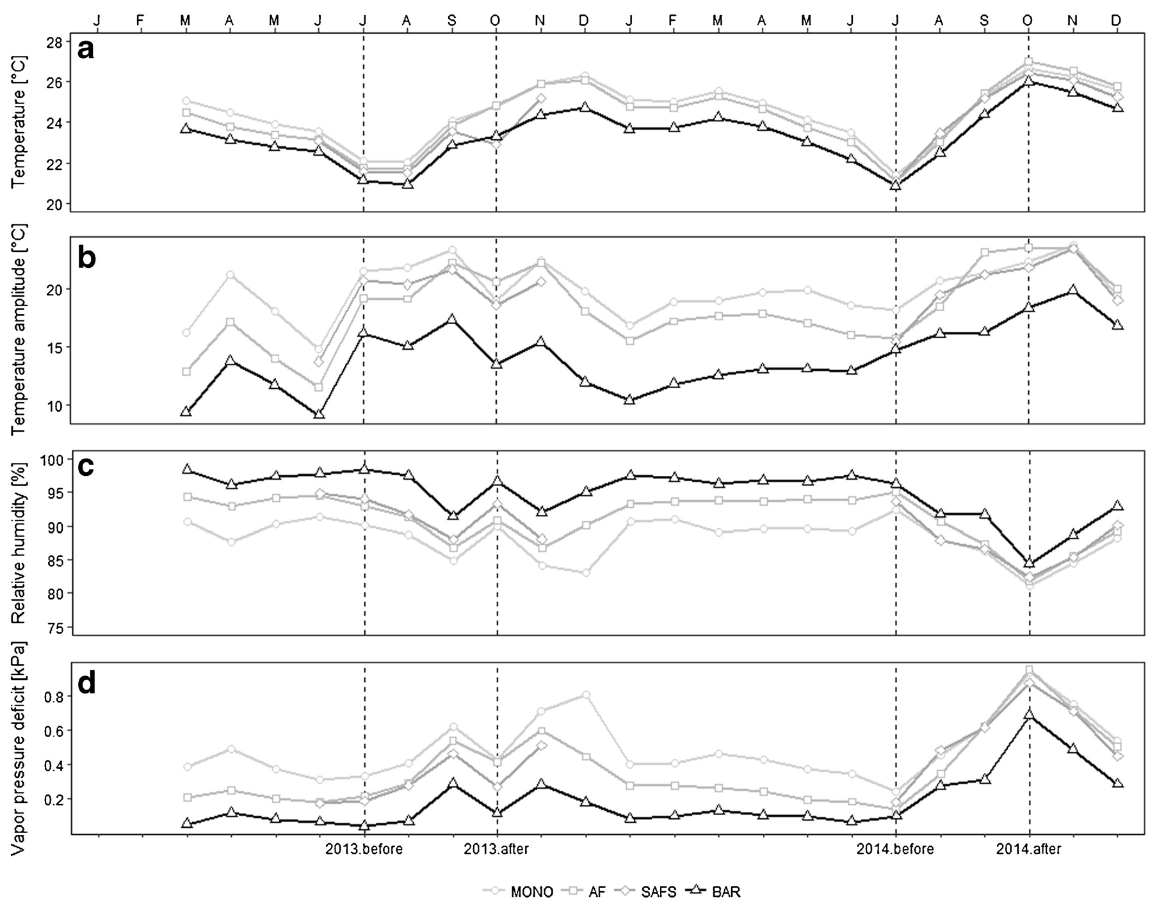

Fig. 5 Monthly mean temperature (**a**), temperature amplitude (**b**), relative humidity (**c**), and vapor pressure deficit (**d**) from March 2013 to December 2014 in monoculture (MONO), agroforestry system (AF), successional agroforestry system (SAFS), and natural regrowth (BAR). The dashed lines highlight the months before (July) and after pruning (October)

Table 4 Microclimatic parameters at 1 m height (mean ± standard error) within monoculture, agroforestry system, successional agroforestry system, and natural regrowth before (July) and after pruning (October), and results from the linear mixed-effect models. Letters indicate differences for one parameter when significant interactions (*system:pruning*) were observed. Evaporation (E_{within}) and cocoa evapotranspiration ($ET_{cocoa\text{-}within}$) where calculated according to Allen et al. (1998)

Parameter		Monoculture	Agroforestry system	Successional agroforestry system	Natural regrowth		*System*	*Pruning*	*System: pruning*
Temperature amplitude [°C]	Before	18.1 ± 0.4a	15.7 ± 0.2b	15.4 ± 0.3b	14.7 ± 0.4b	*F* value	22.4	396.7	13.4
	After	22.3 ± 0.5c	23.6 ± 0.4c	21.9 ± 0.4c	18.3 ± 0.5a	*P* value	< 0.001	< 0.001	< 0.001
Relative humidity [%]	Before	92.4 ± 0.3a	95.1 ± 0.4b	93.7 ± 0.8bc	96.3 ± 0.3c	*F* value	4.9	1964.5	3.9
	After	81.0 ± 0.8d	81.9 ± 0.5d	82.4 ± 1.3de	84.4 ± 1.1e	*P* value	0.015	< 0.001	0.033
Vapor pressure deficit [kPa]	Before	0.24 ± 0.01a	0.14 ± 0.01b	0.18 ± 0.03b	0.10 ± 0.01b	*F* value	6.2	1005.2	4.6
	After	0.94 ± 0.04c	0.95 ± 0.03c	0.88 ± 0.09cd	0.69 ± 0.06d	*P* value	0.007	< 0.001	0.020
E_{within} [mm day^{-1}]	Before	0.59 ± 0.01a	0.11 ± 0.00b	0.16 ± 0.00c	0.04 ± 0.00d	*F* value	2503.1	5035.7	313.3
	After	1.24 ± 0.04e	1.05 ± 0.01f	0.73 ± 0.03g	0.14 ± 0.01h	*P* value	< 0.001	< 0.001	< 0.001
$ET_{cocoa\text{-}within}$ [mm day^{-1}]	Before	1.91 ± 0.02a	0.54 ± 0.01b	0.70 ± 0.03c		*F* value	1179.9	7605.3	241.7
	After	5.12 ± 0.05d	4.51 ± 0.02e	3.35 ± 0.04f		*P* value	< 0.001	< 0.001	< 0.001

lowers the water needs of cocoa trees growing in the understory. This is indicated by higher soil moisture in agroforestry systems than in monocultures in the main cocoa rooting layer of the soil (Niether et al. 2017). Even though total stand transpiration of agroforestry systems with a high tree density is predicted to be higher than stand transpiration of a low-density tree stand or a monoculture (Köhler et al. 2014), shade trees may not compete for water with the cocoa trees but use it from below the cocoa rooting system (Niether et al. 2017).

At the same time while the water demand by cocoa transpiration was reduced, also water input in cocoa production systems was reduced by rainfall interception of the shade and cocoa tree canopies. Throughfall decreased with increasing crown height (Dietz et al. 2006) and stem basal area as also shown for shaded coffee (Siles et al. 2010b). We found mean throughfall rates similar or slightly lower than those reported for cocoa agroforestry systems in Indonesia with a similar canopy openness as in this study (Dietz et al. 2006). During rainy seasons with a high amount of rainfall and a high kinetic energy of the rain drops, throughfall reduction protects understory crops from strong rainfall events (Gaitán et al. 2016). In dry seasons, however, monthly throughfall can be lower than 100 mm in three consecutive months that is described as a critical value for cocoa production (Läderach et al. 2013), even when total rainfall is still above. This can be problematic in respect to projected changes in precipitation patterns in dry seasons. On the other hand, as described above, the reduction in transpiration of the cocoa under shade (Köhler et al. 2010) may reduce the water needs for cocoa production below the input of 100 mm.

4.2 Spatial variability of canopy openness, light, and throughfall in cocoa production systems

Additionally to the temporal variability of precipitation and radiation over the seasons, we found spatial variability of transmitted light and vertical water distribution in the cocoa production systems. Leaf and branch accumulation caused a concentration of water in the canopy and a funneling was observed (Siles et al. 2010b). Especially leaves of banana are reported to act as funnels (Cattan et al. 2007) or cover other locations completely. Even though leaves were more abundant and leaf shapes more heterogeneous in the agroforestry system and the successional agroforestry system than in the monoculture due to the high species diversity and the high number of *Musa*, spatial throughfall variability did not differ between the different cocoa production systems. This can be explained by the high spatial variability of the cocoa canopy openness in the monoculture: as long as the cocoa canopy was not closed, gaps between the cocoa trees allowed the rain to pass through (Gaitán et al. 2016) while other locations were completely covered by the low cocoa crown. Large gaps also resulted in higher spatial variability of transmitted light below the cocoa in the monoculture than in the agroforestry system and the successional agroforestry system, where gaps were smaller and therefore less radiation reached the ground like in forests with a closed canopy (Denslow 1987). Spatial variability increases, when the distances between stems or crowns become greater (Siles et al. 2010a; Gaitán et al. 2016) because within-gap heterogeneity is high (Denslow 1987). The cocoa canopy itself received homogenous light under full-sun conditions, while light was transmitted with a relatively low spatial variability in the agroforestry system and the successional agroforestry system through the shade tree canopy.

The natural regrowth had the lowest spatial variability of throughfall and of transmitted light, and the most homogenous and closed canopy compared to the managed cocoa production systems. Gaitán et al. (2016) describe a high spatial variability of throughfall in shaded coffee, but not in a secondary forest, due to the natural and randomly distributed stand structure of the forest. In our study, the low variability in the natural regrowth compared to the production systems was caused by the dominance of *Cecropia* spp., early successional species that invest more in height than in strength (Sposito and Santos 2001). After a short time, the canopy is closed, but the crown is thin implying a low water storage capacity and consequently a low rain interception rate (Crockford and Richardson 2000). Temperature and VPD were lower in the natural regrowth than in the agroforestry system, but also the radiation was strongly reduced, implying that cocoa production—if planted directly in a young regrowth stand or secondary forest—would be light-limited.

4.3 Pruning increases temporal dynamics by rapidly reducing system differences

Canopy openness above and below the cocoa canopy was within the range of reported studies (Dietz et al. 2006; Abou Rajab et al. 2016; Schroth et al. 2016). A shade tree cover of 30–40% is mentioned as critical to balance the trade-off between yield and ecosystem services (Clough et al. 2011). However, most studies do not reflect the temporal dynamics of canopy openness that are observed by annual cocoa and shade tree pruning and the following canopy growth. Siles et al. (2010a) describe a reduction of the shade level in the month of pruning by about 12%, but the pruning effect is abrogated already in the following month and shading is even lower in the dry season because of litterfall than after pruning. In this study, pruning increased the canopy openness above the cocoa trees by 29% in the agroforestry system and 20% in the successional agroforestry system. Seasonal leaf shedding was not observed, probably because pruning was conducted at the end of the dry season and replaced the need for the trees for leaf shedding. Temporal dynamics of the canopy continued when leaf and crown growth of cocoa and associated trees were enhanced during the rainy season (Reich and Borchert 1984).

Canopy openness was accompanied by an increase in transmitted light (Siles et al. 2010b), which is reported to be positively correlated with floral bud and open flower production (Adjaloo et al. 2012). Tropical shade-tolerant species, like cocoa, depend on locally enhanced light levels for growth and reproduction and response positively to canopy opening (Denslow 1987). Pruning of shade trees and the cocoa crown might therefore be an option to reduce the shade at that time of the year when flowering and photosynthesis have to be enhanced and diseases controlled by aeration of the stand. Shade reduce cocoa yield (Armengot et al. 2016), but the yield of well-managed and pruned-shaded systems can be higher than of insufficiently managed full-sun cocoa (Jacobi et al. 2015). Transpiration is supposed to increase with stem density (Köhler et al. 2014). But pruning decouples this relation because it decreases the transpiring leaf mass. Lower transpiration also reduces the competition for water (Schroth et al. 2001). Additionally, throughfall increased in the agroforestry system as high as in the monoculture while high tree density and diversity was maintained. In the dry season, even little rain events can rewet the upper soil layer and the cocoa profit from the moisture (Köhler et al. 2010).

At the same time, strong pruning reduced the buffering capacity of the shade tree canopy for temperature fluctuations and humidity. Therefore, ecophysiological stress for cocoa increased (Beer et al. 1998). In contrast to the monoculture, the shade tree canopy expanded after pruning again and reached the same canopy openness and shelter function for the cocoa as before pruning after some months while reducing light transmittance again.

4.4 Structure and development of cocoa production systems

Basal area of cocoa and shade trees were lower while basal area of *Musa* was higher than reported for cocoa production systems across Central America (Somarriba et al. 2013). Differences can be explained by the age of the plantations, i.e., a young plantation in our study, in combination with the high planting density of shade trees in our trial. A lower planting density may also imply more large shade trees with higher diameter (Schroth et al. 2016). This was already the case in the agroforestry system in comparison to the successional agroforestry system. Tree density and tree diversity were not directly related to canopy openness, as also shown by Martius et al. (2004), but pruning of shade and cocoa trees was more effective in controlling canopy openness and microclimatic processes.

In this long-term trial, it is foreseen to reduce the shade tree density in the agroforestry system and the successional agroforestry system: fast growing trees will be slashed when the slow growing fruit and timber species will have developed a shade canopy above the cocoa. The number of *Musa* pseudostems will be reduced, because the leaves take over almost the same stratum as the cocoa canopy and they capture a lot of water and translocate it down the pseudostem (Cattan et al. 2007). We do not expect a strong increase or decrease in canopy openness over the years due to development and thinning of the stands, because canopy openness and temporal dynamic will rather be controlled by adequate shade tree pruning as supposed by Tscharntke et al. (2011), while cocoa pruning will be continued to avoid excessive self-shading.

Farmers are well aware of the canopy's buffering capacity against drought and heat stress (Jacobi et al. 2015). Pruning is a method that can be applied by the producer to manage the trade-off within different ecosystem services from diversified agroforestry systems and between the ecosystem services and the production goal of the producer (Tscharntke et al. 2011; Vaast and Somarriba 2014). While cocoa pruning is easier and more adapted by the producers to control self-shading, shade tree pruning is rarely applied due to lack of knowledge and tools (Andres et al. 2016). It is very labor-intensive, but maintains tree and crop diversity (Armengot et al. 2016) and should therefore be supported by capacity building and tools for working on high trees. Agroforestry systems with an adequate management will play an important role under the viewpoint of changes in precipitation patterns and increases in temperature extremes in cocoa producing countries (Läderach et al. 2013) to reduce ecophysiological stressful conditions by adapting microclimatic conditions in favor of the cocoa. In Alto Beni, the pruning of cocoa and shade trees, if applied, is commonly conducted at the end of the dry season that is followed by the highest temperatures in the course of the year. Pruning intensity, therefore, has to be adjusted that the cocoa benefits from the enhanced light transmittance while not losing the microclimate buffering effect of the canopy at the same time completely. More frequent partial pruning of the shade trees over the year might be preferred to complete annual or biannual pruning, but demands even higher labor input (Schroth et al. 2001).

5 Conclusions

Cocoa growing in monocultures can be easily exposed to unfavorable conditions when temperature rises and humidity drops. Agroforestry systems buffer extreme climatic conditions and therefore reduce the stress for the cocoa tree. However, reduced throughfall and radiation can also lead to unfavorable conditions for cocoa production. Pruning is a key tool to achieve micro-environmental conditions that favor cocoa production, but has to be adapted in intensity and timing, e.g., to enhance throughfall in dry months without eliminating the buffer function of the canopy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Declaration of ethical issues The manuscript was not published before and is not under consideration elsewhere.

Appendix

Table 5 Shade trees planted in the agroforestry system and the successional agroforestry system (modified from Schneider et al. 2017)

Family	Genus/species, author	Local name	Use	Spacing in agroforestry system
Fabaceae	*Hymenaea courbaril* L.	Paquillo/Paquío	Timber	40 m × 40 m
Meliaceae	*Swietenia macrophylla* King	Mara	Timber	40 m × 40 m
Fabaceae	*Centrolobium ochroxylum* Rose ex Rudd	Huasicucho	Timber	40 m × 40 m
Fabaceae	*Myroxylon balsamum* (L.) Harms	Quina Quina	Timber	40 m × 40 m
Sapindaceae	*Nephelium lappaceum* L.	Rambutan	Fruit	40 m × 40 m
Malvaceae	*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.	Copoazú/Cupuazú	Fruit	40 m × 40 m
Clusiaceae	*Garcinia macrophylla* Mart.	Achachairú	Fruit	40 m × 40 m
Lauraceae	*Persea americana* Mill.	Palto	Fruit	40 m × 40 m
Euphorbiaceae	*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.	Goma	Latex	40 m × 40 m
Fabaceae	*Inga* spp.	Pacay	N-fixation, firewood, fruit	8 m × 16 m
Fabaceae	*Erythrina* spp.	Eritrina/Ceibo	N-fixation	8 m × 16 m
Arecaceae	*Euterpe precatoria* Mart.	Asaí	Fruit	14.1 m × 14.1 m (irregular)

Table 6 Additional trees and herbal plants in the successional agroforestry system and their usages. Various herbal plants already completed their lifespan and were removed from the field (modified from Schneider et al. 2017)

Family	Genus/species, author	Local name	Life-form	Use
Bixaceae	*Bixa orellana*	Achiote/Achuete	Tree/shrub	Biomass, colorant
Malvaceae	*Ceiba* sp.	Flor de mayo	Tree	Timber
Myristicaceae	*Otoba parvifolia*	Sangre de toro/Gabú	Tree	Timber
Moraceae	*Clarisia racemosa*	Mascajo	Tree	timber
Fabaceae	*Stryphnodendron* sp.	Toco colorado	Tree	Timber, N-fixation
Fabaceae	*Amburana cearensis*	Roble	Tree	Timber, N-fixation, medicine
Juglandaceae	*Juglans boliviana*	Nogal	Tree	Timber
Combretaceae	*Terminalia oblonga*	Verdolago	Tree	Timber
Lauraceae	*Nectandra* sp.	Laurel	Tree	Timber
Celastraceae	*Salacia impressifolia*	Chuchuhuasi	Tree	Fruit, medicine
Rutaceae	*Citrus sinensis*	Naranja	Tree	Fruit
Myrtaceae	*Pimenta dioica*	Pimienta gorda	Tree	Spice
Malpighiaceae	*Bunchosia glandulifera*	Mermelada	Tree	Fruit
Myrtaceae	*Eugenia stipitata*	Arazá	Tree	Fruit
Arecaceae	*Bactris gasipaes*	Chima	Tree	Fruit
Arecaceae	*Oenocarpus bataua*	Majo	Tree	Fruit
Oxalidaceae	*Averrhoa carambola*	Carambola	Tree	Fruit
Lecythidaceae	*Bertholletia excelsa*	Castaña	Tree	Fruit
Clusiaceae	*Garcinia madruno*	Ocoró	Tree	Fruit
Moraceae	*Artocarpus heterophyllus*	Yaca	Tree	Fruit
Anacardiaceae	*Mangifera indica*	Mango	Tree	Fruit
Poaceae	*Zea mays* L.	Maíz	Herbaceous	Food
Poaceae	*Oryza sativa* L.	Arroz	Herbaceous	Food
Euphorbiaceae	*Manihot esculenta* Crantz	Yucca	Herbaceous	Food
Malvaceae	*Hibiscus sabdariffa* L.	Hibisco	Herbaceous	Food, medicine
Bromeliaceae	*Ananas comosus* (L.) Merr.	Piña	Herbaceous	Fruit
Fabaceae	*Cajanus cajan* (L.) Millsp.	Chicharilla	Shrub	Food, N-fixation
Araceae	*Xanthosoma sagittifolium* (L.) Schott	Walusa	Herbaceous	Food
Zingiberaceae	*Zingiber officinale* Roscoe	Jengibre	Herbaceaous	Spice, medicine
Zingiberaceae	*Curcuma longa* L.	Pallillo	Herbaceaous	Spice

Table 7 Details about the preliminary analyses on the fixed factor *farming* (organic and conventional farming practices of the cocoa monoculture and the agroforestry system) for all measured parameters

Parameter	*F* value	*P* value
Canopy openness 1.3 m	0.02	0.8767
Spatial variability of canopy openness at 1.3 m	0.00	0.9871
Canopy openness 3.2 m	0.02	0.88764
Spatial variability of canopy openness at 3.2 m	0.65	0.4458
PPFD at 1.3 m	0.07	0.7888
Spatial variability of PPFD at 1.3 m	1.76	0.195565
PPFD at 3.2 m	0.12	0.7329
Spatial variability of PPFD at 3.2 m	3.67	0.087671
Throughfall	0.06	0.8138
Spatial variability of throughfall	0.01	0.9245
Throughfall rate	0.04	0.83989
Spatial variability of throughfall rate	0.03	0.8656
Mean temperature	3.74	0.08902
Minimum temperature	1.94	0.1938
Maximum temperature	0.43	0.5258
Mean relative humidity	2.23	0.1737
Minimum relative humidity	1.59	0.2429
Height		
Cocoa	0.93	0.3501
Woody shade trees[a]	7.47	0.01708
Musa	1.77	0.2043
Basal area		
Cocoa	0.28	0.605
Woody shade trees[a]	14.0	0.03324
Musa	0.26	0.6297
Crown volume cocoa	2.39	0.1503
Stem diameter		
Cocoa	0.52	0.4865
Woody shade trees	8.97	0.05787
Musa	4.20	0.08636

[a] Basal area and height of woody shade trees was slightly higher in conventionally than in organically managed plots. But there was no difference in comparison of the basal area between organically managed, conventionally managed and successional agroforestry systems as indicated in Table 1

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