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Copyright Year	2024	
Copyright HolderName	The Author(s)	
Corresponding Author	Family Name	**Mensah**
	Particle	
	Given Name	**Eric Opoku**
	Prefix	
	Suffix	
	Role	
	Division	Department of Crop Science
	Organization	University of Ghana
	Address	Accra, Ghana
	Division	Department of Geosciences and Natural Resource Management
	Organization	University of Copenhagen
	Address	Frederiksberg, Denmark
	Division	
	Organization	CSIR-Plant Genetic Resources Research Institute
	Address	Bunso, Ghana
	Email	eom@ign.ku.dk
		omedjin@gmail.com
	ORCID	http://orcid.org/0000-0002-7964-5180
Author	Family Name	**Vaast**
	Particle	
	Given Name	**Philippe**
	Prefix	
	Suffix	
	Role	
	Division	UMR Eco & Sols, Centre de Coopération Internationale en Recherche Agronomique Pour Le Développement (CIRAD)
	Organization	Université Montpellier
	Address	Montpellier, France
	Division	
	Organization	World Agroforestry Center
	Address	Nairobi, Kenya
	Email	philippe.vaast@cirad.fr
	ORCID	http://orcid.org/0000-0002-2971-3210
Author	Family Name	**Asare**
	Particle	
	Given Name	**Richard**

	Prefix	
	Suffix	
	Role	
	Division	
	Organization	International Institute of Tropical Agriculture (IITA)
	Address	Accra, Ghana
	Email	r.asare@cgiar.org
	ORCID	http://orcid.org/0000-0002-5557-9190
Author	Family Name	**Amoatey**
	Particle	
	Given Name	**Christiana A.**
	Prefix	
	Suffix	
	Role	
	Division	Department of Crop Science
	Organization	University of Ghana
	Address	Accra, Ghana
	Email	camoatey@ug.edu.gh
	ORCID	http://orcid.org/0000-0002-1468-5800
Author	Family Name	**Owusu**
	Particle	
	Given Name	**Kwadwo**
	Prefix	
	Suffix	
	Role	
	Division	Department of Geography and Resource Development
	Organization	University of Ghana
	Address	Accra, Ghana
	Email	kowusu@ug.edu.gh
	ORCID	http://orcid.org/0000-0003-1322-0566
Author	Family Name	**Asitoakor**
	Particle	
	Given Name	**Bismark Kwesi**
	Prefix	
	Suffix	
	Role	
	Division	Department of Crop Science
	Organization	University of Ghana
	Address	Accra, Ghana
	Division	Department of Geosciences and Natural Resource Management
	Organization	University of Copenhagen
	Address	Frederiksberg, Denmark
	Division	
	Organization	CSIR-Plant Genetic Resources Research Institute
	Address	Bunso, Ghana

	Email	bkasitoakor001@st.ug.edu.gh bka@ign.ku.dk
	ORCID	http://orcid.org/0000-0002-6507-6706
Author	Family Name	**Ræbild**
	Particle	
	Given Name	**Anders**
	Prefix	
	Suffix	
	Role	
	Division	Department of Geosciences and Natural Resource Management
	Organization	University of Copenhagen
	Address	Frederiksberg, Denmark
	Email	are@ign.ku.dk
	ORCID	http://orcid.org/0000-0002-8793-5663

Abstract	Cocoa (*Theobroma cacao* L.) is an important cash crop in many tropical countries, particularly in West Africa. Heat and drought are both known to affect the physiology of cocoa plants through reduced rates of photosynthesis and transpiration, as well as changed physiological processes such as the functions of photosystems, chlorophyll synthesis, stomatal conductance and expression of heat-shock proteins. This in turn leads to decreased yields and increased risks of mortality under severe heat and drought. To help cocoa plants adapt to climate change, the literature suggests agroforestry as a potential farm management practice. It has been argued that the lack of tree cover in cocoa cultivation systems exposes the crop to heat and direct solar radiation, thus increasing evapotranspiration and the risk of drought. Drawing on data generated from two on-field studies, this chapter assesses the shade effect on cocoa's physiological responses to drought and heat stress to determine whether shade would be beneficial under climate change scenarios. We conclude that shade improves the physiology of cocoa, but that this may not be sufficient to compensate for the negative effects of high temperatures and severe drought exacerbated by climate change in sub-optimal conditions.

Keywords (separated by '-')	Shade - Cocoa - Heat - Stomatal conductance - Water potential - Photosynthesis

CHAPTER 2

Cocoa Under Heat and Drought Stress

Eric Opoku Mensah, Philippe Vaast, Richard Asare,
Christiana A. Amoatey, Kwadwo Owusu,
Bismark Kwesi Asitoakor, and Anders Ræbild

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Abstract Cocoa (*Theobroma cacao* L.) is an important cash crop in many tropical countries, particularly in West Africa. Heat and drought are both known to affect the physiology of cocoa plants through reduced rates of photosynthesis and transpiration, as well as changed physiological processes such as the functions of photosystems, chlorophyll synthesis, stomatal conductance and expression of heat-shock proteins. This in turn leads to decreased yields and increased risks of mortality under severe heat and drought. To help cocoa plants adapt to climate change, the literature suggests agroforestry as a potential farm management practice. It has been argued that the lack of tree cover in cocoa cultivation systems exposes

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E. O. Mensah (✉) · C. A. Amoatey · B. K. Asitoakor
Department of Crop Science, University of Ghana, Accra, Ghana
e-mail: eom@ign.ku.dk

C. A. Amoatey
e-mail: camoatey@ug.edu.gh

B. K. Asitoakor
e-mail: bkasitoakor001@st.ug.edu.gh; bka@ign.ku.dk

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the crop to heat and direct solar radiation, thus increasing evapotranspiration and the risk of drought. Drawing on data generated from two on-field studies, this chapter assesses the shade effect on cocoa's physiological responses to drought and heat stress to determine whether shade would be beneficial under climate change scenarios. We conclude that shade improves the physiology of cocoa, but that this may not be sufficient to compensate for the negative effects of high temperatures and severe drought exacerbated by climate change in sub-optimal conditions.

Keywords Shade · Cocoa · Heat · Stomatal conductance · Water potential · Photosynthesis

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E. O. Mensah · B. K. Asitoakor · A. Ræbild
Department of Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg, Denmark
e-mail: are@ign.ku.dk

E. O. Mensah · B. K. Asitoakor
CSIR-Plant Genetic Resources Research Institute, Bunso, Ghana

P. Vaast
UMR Eco & Sols, Centre de Coopération Internationale en Recherche Agronomique Pour Le Développement (CIRAD), Université Montpellier, Montpellier, France

World Agroforestry Center, Nairobi, Kenya

P. Vaast
e-mail: philippe.vaast@cirad.fr

R. Asare
International Institute of Tropical Agriculture (IITA), Accra, Ghana
e-mail: r.asare@cgiar.org

K. Owusu
Department of Geography and Resource Development, University of Ghana, Accra, Ghana
e-mail: kowusu@ug.edu.gh

2.1 INTRODUCTION

Cocoa (*Theobroma cacao* L.) is native to South America and belongs to the Malvaceae family (formerly Sterculiaceae). For this species, three main genetic groups are recognized based on physical, sensory quality and associated botanical traits: Forastero, Criollo and Trinitario (Bartley, 2005; Cheesman, 1944). Around 95% of all cocoa production comes from the Forastero and the Trinitario groups, which are high-yielding, more vigorous and less susceptible to pests and diseases than the Criollo group (Loor et al., 2009; Umaharan, 2018).

Cocoa is mostly grown in a narrow belt 20 degrees north and south of the equator with warm and humid tropical climates, regular rains and short dry seasons (Mattyasovszky, 2017). It is mostly planted in smallholder plantations in West Africa, Southeast Asia and Latin America (Lahive et al., 2019). Cocoa plants grow well within a temperature range of 18–32 °C, with regular rainfall of 1000–2500 mm per year and at altitudes as high as 1000 m above sea level (Ameyaw et al., 2018; ICCO, 2020; Wood & Lass, 1992). Under shade, cocoa physiology is changed, and yields may increase (Asare et al., 2017; Tee et al., 2018). Cultivation under full sun without any vegetation cover increases the risk of exposing the crop to the negative consequences of high radiation, elevated temperatures and drought. Recent predictions of future climate conditions foresee increases in temperature and a decline in rainfall periods at crucial times for cocoa production in the current production zones in West Africa (IPCC, 2021; Schroth et al., 2016; Stocker et al., 2013). The global average air temperature is expected to increase by between 0.8 and 5.4 °C, while annual rainfall may decline by 1.1–20.5% between 2020 and 2080 depending on the emission scenario (IPCC, 2021; NCCAS, 2012; Pielke et al., 2022). This is a cause for concern, since elevated temperatures, reduced rainfall, longer dry seasons and higher incidences of pests and diseases are expected to reduce cocoa yields (Cilas & Bastide, 2020; Gachene et al., 2014; Muller et al., 2014, see also Chapter 1).

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Breeding resilient varieties has been considered to be a way to increase cocoa yields, especially under future climate scenarios (Vaast & Somarriba, 2014). However, breeding new varieties, especially varieties with increased tolerance to drought and heat, high water-use efficiency and high yields, has been limited by insufficient use of proven breeding methods, limited information on the ecophysiology of cocoa, the plant's long selection cycle, and the heterozygous nature of hybrid parental clones (Efron et al., 2003). Efforts so far have resulted in hybrid cocoa varieties with increased resistance to pests and diseases and reduced time to maturity (Dos Santos et al., 2014; Frimpong-Anin et al., 2015), but more work is urgently needed on their drought and heat tolerances (Judy et al., 2021). Although marker-assisted selection is being used to study drought-resistant cultivars and genes involved in drought tolerance (Bae et al., 2008), the production and dissemination of cocoa materials that are highly tolerant to drought and heat are still some way off. Selecting drought-tolerant cocoa rootstocks, followed by grafting, is another potential pathway (Zasari et al., 2020).

The provision of shade and the promotion of good agroforestry practices are recommended by many plant scientists to ensure the environmental sustainability of cocoa production (Asare et al., 2017; Asitoakor et al., 2022, Vaast et al., 2016). Agroforestry increases species diversity, provides year-round soil cover and ensures high levels of stored carbon in the soil and in vegetation (LobÎo et al., 2007; Sommarriba et al., 2018). It has also been shown that tree growth and cocoa yields, i.e. the mature productive phase, extend over a longer time span under shade than under full-sun conditions (Ahenkorah et al., 1974). Other benefits of agroforestry include reduced evapotranspiration, enhanced soil fertility and protecting cocoa plants from strong winds and other unfavourable ecological factors (Kyereh, 2017; Miyaji et al., 1997). Furthermore, rates of photosynthesis, growth and yields of cocoa are enhanced under shade (Asare et al., 2018; De Almeida & Valle, 2007; Mensah, 2021). For adult cocoa plants, high yields were observed at shade levels between 30 and 40% (Asare et al., 2018), while about 60% shade is recommended for cocoa seedlings.

In agroforestry systems, companion shade trees in cocoa crop systems have been documented to buffer temperature changes, but they may also have other positive or negative consequences. This depends on the associated tree species that are involved, and whether they lead to root-zone complementarity or competition (Abdulai et al., 2017; Critchley et al., 2022; Jaimes-Suarez et al., 2022; Rigal et al., 2022). Studies of cocoa ecophysiology are difficult because of the size and longevity of cocoa trees, making manipulations difficult. This chapter discusses results from the literature in combination with findings from our on-field studies regarding the effects of shade on cocoa performance under drought and high-temperature stress (Fig. 2.1).

Fig. 2.1 **A** Cocoa farm without shade trees. **B** Cocoa agroforestry with remaining shade trees from clearing of the land. **C** Cocoa agroforestry with planted shade trees (*Terminalia sp.* and *Triplochiton scleroxylon*). **D and E** Experiment with a mature cocoa stand under 40% shade using an artificial shade net and with rainwater exclusion. **F** Experiment with cocoa seedlings exposed to heat from non-glowing heaters, with shade (Photos by Eric Opoku Mensah)

The chapter thus draws heavily on two eco-physiological experiments that were conducted in Ghana to study how shade could reduce the effects of drought and elevated temperatures on cocoa physiology (Mensah, 2021). The first experiment took place in the semi-moist region of Ghana investigating the effects of shade and water exclusion on the performance of productive cocoa trees (Fig. 2.1D, E). Plants were monitored over two years for their physiology, growth, litter production and yields. Results from the experiment indicated that shade enhances yields and the physiological performance of cocoa but has limited impacts on water use. The second experiment was conducted at the University of Ghana's Crop Research Farm to test whether shade could reduce the effects of heat on cocoa plants (Mensah et al., 2022). Here, six-month-old cocoa seedlings were exposed to heat provided by 2000W non-glowing infra-red heaters (Fig. 2.1F). The heaters increased the temperature 5–7 °C above the ambient, while 60% shade was provided using black shade nets. Results from the second experiment showed limited effects of shade on the cocoa seedlings under elevated temperature. However, plants kept under shade generally showed enhanced physiology, such as increased chlorophyll fluorescence, chlorophyll pigmentation, stomatal conductance and growth, compared to plants in full-sun conditions.

2.2 DROUGHT AND COCOA PRODUCTION

Drought is a period in which moisture content in the soil is limited so that plants cannot extract sufficient water for growth and physiological activities (Coder, 1999). It occurs under conditions of low soil and atmospheric humidity when the transpiration flux exceeds the plant uptake of water from the soil. Drought has severe effects on cocoa physiology and restricts stomatal conductance and photosynthesis, and hence vegetative and reproductive plant growth.

2.2.1 Soil Moisture

Soil water content (SWC) is the amount of water present in the soil (Datta et al., 2018). At low SWC, leaves start drooping and may reach the Permanent Wilting Point (PWP), the threshold where plants can no longer recover even if re-watered (Datta et al., 2018).

Cocoa plants have shallow rooting systems (Carr & Lockwood, 2011), with most of the roots concentrated within the first 80 cm of the soil profile, and with over 80% of the root biomass within the top 40 cm, restricting the possibility for water extraction from deep soil layers (Lahive et al., 2019; Moser et al., 2010). The amount of soil water obviously depends on rainfall patterns and evapotranspiration, but also on the soil type and soil depth. For example, clayey soils hold larger amounts of water than sandy soils, and deep soils conserve more available water than shallow soils. In most cocoa-producing countries in West Africa, soil water is depleted in the top 60 cm of soil depth during extended dry seasons, thus exposing the plants to drought (Abdulai et al., 2017).

Under shade, the temperature may fall to 5 °C lower than outside the canopy during the day, maintaining shaded cocoa plants under conditions of relatively high humidity. This means a lower vapour pressure deficit (which is the driving force for transpiration), and it has been suggested that agroforestry reduces cocoa evapotranspiration and allows cocoa to survive under sub-optimal climate conditions (Acheampong et al., 2013; Neither et al., 2018). However, this depends on complementarity in water use between shade tree species and cocoa and hence works best with deep-rooted shade trees that tap soil water below the cocoa root zone. Species selection for cocoa production is very important under drought conditions, as some shade trees, such as *Albizia ferruginea* and *Antiaris toxicaria* (leguminous tree species), have been found to compete with cocoa plants for soil moisture during the dry season (Abdulai et al., 2017; Adams et al., 2016).

2.2.2 Effects of Drought on Plant-Water Potential

Water potential is an expression of the water status of a plant, with negative values indicating a relative absence of water. When soil moisture is reduced, roots may not keep up with the pace of evaporation (also known as transpiration) from the leaves, increasing tension in the water-transporting tissues (the xylem) and making plant-water potential more negative. Under conditions of severe drought, the water potential becomes increasingly negative and may cause the formation of air bubbles in the xylem (known as cavitation), which blocks water transport and may in severe cases be lethal to the plant. It is noted that in cocoa, the stem xylem has a larger diameter than the root xylem, which may contribute to plant sensitivity to cavitation under drought (Kotowska et al., 2015).

The plant-water potential affects many physiological processes, and most importantly, it controls the opening and closing of stomata in leaves. Stomata are the pores through which the plant takes up CO_2 and loses water vapour. Under normal, well-watered conditions, cocoa plants will have a water potential ranging between 0.0 and −0.4 MPa (Deloire & Heyns, 2011; Zanetti et al., 2016), whereas values below −0.8 MPa indicate a water deficit (Deloire & Heyns, 2011). In a through-fall displacement study in Indonesia, after six months of drought, roots experienced declining water potential, falling below −1.5 MPa (Moser et al., 2010) that caused permanent closure of stomata. In a study from Ghana during the dry season, most of the cocoa plants died in response to very low soil moisture because of competition with shade trees (Abdulai et al., 2017).

Shade increases relative humidity around the cocoa plants, thereby reducing transpiration and thus potentially maintaining plant-water potential at a high level. In our field experiment, water exclusion reduced the predawn water potential of cocoa plants, with lower values observed during the dry season (Table 2.1). However, shade resulted in slightly higher water potentials, confirming that shade has a positive impact on the water status of cocoa trees. Reduced plant-water potential in full sun may be the result of increased evapotranspiration resulting from higher leaf temperatures and dryer air.

Table 2.1 Average predawn leaf water potential of cocoa plants at three different levels of rainwater exclusion and two levels of shade measured over two year

Shade	*Rainwater exclusion*	*Predawn water potential (MPa)*	
		Rainy season	*Dry season*
Shade	Full rainwater (0/3W)	-0.24 ± 0.12^{a}	-0.40 ± 0.17^{a}
	Moderate rainwater exclusion (1/3W)	-0.30 ± 0.13^{b}	-0.46 ± 0.15^{bc}
	Severe rainwater exclusion (2/3W)	-0.36 ± 0.15^{c}	-0.51 ± 0.14^{bc}
Sun	Full rainwater (0/3W)	-0.31 ± 0.16^{bc}	-0.46 ± 0.16^{b}
	Moderate rainwater exclusion (1/3W)	-0.36 ± 0.15^{c}	-0.52 ± 0.14^{c}
	Severe rainwater exclusion (2/3W)	-0.43 ± 0.17^{d}	-0.59 ± 0.14^{d}

Note Numbers indicate means ± s.d. ($n = 3$). Means followed by different letters are significantly different according to Tukey's multiple range test ($P < 0.05$)

2.2.3 Effects of Drought on Photosynthesis

Photosynthesis, the process by which plants use sunlight, water and carbon dioxide to create oxygen and energy in the form of carbohydrates, is impaired when soil–water content is decreasing (Carr & Lockwood, 2011; Datta et al., 2018; Kirschbaum, 2004). Reduced rates of photosynthesis may be due to partial closure of stomata but can also be due to biochemical limitations (Liang et al., 2019) (see Sect. 2.4). Stomata regulates both transpirational water loss and CO_2 diffusion into the leaves (Barbour, 2016). As discussed above, under drought stress, many plants reduce their stomatal opening to conserve water, at the cost of reducing plant absorption of CO_2 for photosynthesis. The closure of the stomata reduces cooling of the leaves through evaporation, thus increasing leaf temperature. Very high leaf temperatures may harm the leaves and cause leaf wilting. Cocoa plants have low stomatal conductance under water stress and low relative humidity (De Almeida & Valle, 2007) compared to large stomatal opening under non-limiting water conditions and high relative humidity (Sena et al., 1987). Stomatal opening is often assessed in terms of stomatal conductance, a standardized measure of opening. In our field study, stomatal conductance showed a strong seasonal trend, being especially low during the dry season (Fig. 2.2). Surprisingly, the effects of shade vs. sun appeared to have a larger effect on stomatal conductance compared to water exclusion, with shaded cocoa plants having larger stomatal conductance than sun plants.

Despite the differences in stomatal conductance, rates of photosynthesis were comparable between sun and shade plants, with a tendency towards slightly higher values for the former (Fig. 2.2). Since photosynthesis is driven by light, it would be natural to expect a large decrease in photosynthesis in shaded plants. However, in addition to having larger stomatal opening, shaded cocoa plants were able to use the available light and achieve relatively high rates of photosynthesis. Cocoa plants have low light-saturation points, meaning that they reach saturation for photosynthesis at relatively low levels of light, corresponding to 500 μmol photons m^{-2} s^{-1} or ca. 20% of the natural sunlight (Anim-Kwapong & Frimpong, 2004; Salazar et al., 2018). Hence, plants in full sun may not be able to take advantage of the extra radiation available to them. The ability to capture light in shade may also be a result of a reorganization of the photosynthetic system development of large leaves with longer lifespans and increased chlorophyll pigments in the leaves.

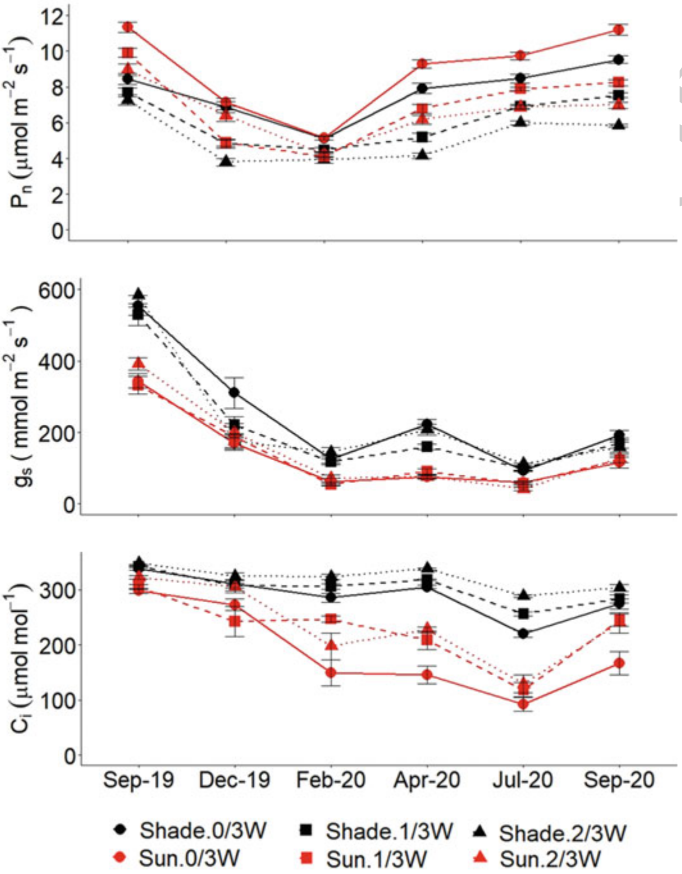

Fig. 2.2 Effects of shade and rainwater exclusion on photosynthesis rate (P_n), stomatal conductance (g_S) and sub-stomatal CO_2 concentration (C_i) of a 12-year-old cocoa plant. Codes indicate water availability: 0/3W—full rainwater; 1/3W—partial water exclusion; 2/3W—severe water exclusion

Responses to drought may be dependent on genotypes. Some reports indicate different responses of stomatal conductance and transpiration among cocoa cultivars (Daymond et al., 2011; De Almeida et al., 2015), suggesting that it may be possible to identify cultivars that perform better under drought stress than others. Further research on the varietal differences of stomata regulation and water use in cocoa plants is needed. This also includes studies of whether cocoa has a predominantly anisohydric behaviour (i.e. a variable water content because of continued transpiration at low soil moisture, due to limited stomatal adjustment) or an isohydric tendency (with more stable water contents due to closure of stomata after sensing low soil–water potential).

2.2.4 Biochemical Limitations to Photosynthesis

In addition to limitations caused by light availability and stomatal limitations to the diffusion of CO_2, photosynthesis may also be limited by biochemical factors. The presence of such biochemical limitations can be detected by increased levels of CO_2 inside the leaf (C_i). In our rainwater-exclusion experiment, C_i increased in highly stressed plants compared to non-stressed control plants, and the concentration was proportional to the level of stress (Fig. 1.2). Paradoxically, biochemical limitations may in the first instance be caused by high light and limited diffusion of CO_2, caused by closed stomata (Tholen et al., 2012; Haworth et al., 2018). Energy from high light may be directed to toxic oxygen compounds that will react with enzymes and other substances in the cell, thus reducing the capacity of the plant for photosynthesis. Conversely, high sub-stomatal CO_2 concentrations observed in shade, rather than indicating damage to the photosynthetic system, may be caused by plants maintaining high stomatal conductance and in effect facilitating carbon absorption. Shade thus has positive effects on CO_2 absorption and distribution in the leaves, reflecting increased carboxylation.

The study of sub-stomatal CO_2 concentration is also important because CO_2 gradients within the leaf affect the efficiency of the enzyme fixing CO_2 into sugars (RubisCO) and the nitrogen use efficiency (Evans & von Caemmerer, 1996). Limited information is available on the effect of environmental conditions on sub-stomatal CO_2 concentration in cocoa.

2.3 Heat and Cocoa

High temperature is one of the main limiting factors for cocoa production (De Almeida & Valle, 2007). High temperature affects the physiology of plants, including the effects of changed stomatal frequency, chlorophyll synthesis (the green pigments in the leaf), enzyme activity and sugar transport (Lamaoui et al., 2018; Wiser et al., 2004).

2.3.1 Photosynthesis

As mentioned, stomata control CO_2 and water movement in and out of the plant through the pore area, the density on the leaf surface and the degree of opening. In cocoa, stomatal densities are higher for leaves developed under mild water stress (Carr & Lockwood, 2011; Huan et al., 1986), but are also higher in leaves developed in full sun compared to shaded leaves (De Almeida & Valle, 2007). In our heat experiment, seedlings in full sun had denser stomata per unit area than seedlings in shade, and heat increased the number of stomata produced per unit area under both full sun and shade. Such differences naturally affect photosynthetic performance, although knowledge on pore size is also needed to accurately assess potential rates of gas flux in and out of leaves.

Most enzymes, including those involved in photosynthesis, work faster with increasing temperatures until they reach the maximum level, where they start uncoiling and lose their function (denaturation). For example, temperatures above 40 °C destroyed the light harvesting complexes in the leaves of perennial plants such as fingered citron and reduced assimilation (Chen et al., 2012; Hasanuzzaman et al., 2013). Another temperature-dependent process affecting rates of photosynthesis is photorespiration. The enzyme fixing CO_2 into sugars, RubisCO, occasionally catalyzes a reaction called photorespiration where O_2 takes the place of CO_2. Photorespiration increases with temperature and leads to a declining net photosynthesis at high temperatures. Furthermore, high temperature inactivates the enzyme system, which transforms sugars into starch, resulting in accumulation of sugars, causing a downregulation of the rate of photosynthesis (Franck et al., 2006; Mathur et al., 2014).

In our heat experiment, we showed that photosynthesis of cocoa is affected by the growing temperature (Fig. 2.3). Temperature optima were between 31 and 33 °C (see also Avila-Lovera et al., 2016; Yapp, 1992) but were almost similar across treatments. The optimum temperature range for photosynthesis coincided with the daily average environmental temperature of 29–33 °C in the experimental site. Having optimum temperature for photosynthesis close to the environmental temperature helps plants to thrive and function well in their environment (Slot & Winter, 2017). Above the optimum, the rate of photosynthesis declines due to photorespiration and, at higher temperatures, the denaturation of enzymes.

On the other hand, the actual levels of photosynthesis were affected by both shade and heat treatments. Photosynthetic capacity was higher for plants growing in full sun compared to shaded plants, and heat reduced the photosynthetic capacity considerably at all temperatures (Fig. 2.3). However, our analysis did not show interactions between sun/shade and heat/no-heat treatments, suggesting that shade could not prevent the loss of photosynthetic capacity caused by the heat treatments (Mensah et al., 2022).

Measurement of chlorophyll fluorescence showed that part of the decrease in photosynthesis seen under heat stress was caused by damages at photosystem II, which is the enzyme complex that fixes the energy from light by removing an electron from oxygen. Chlorophyll fluorescence

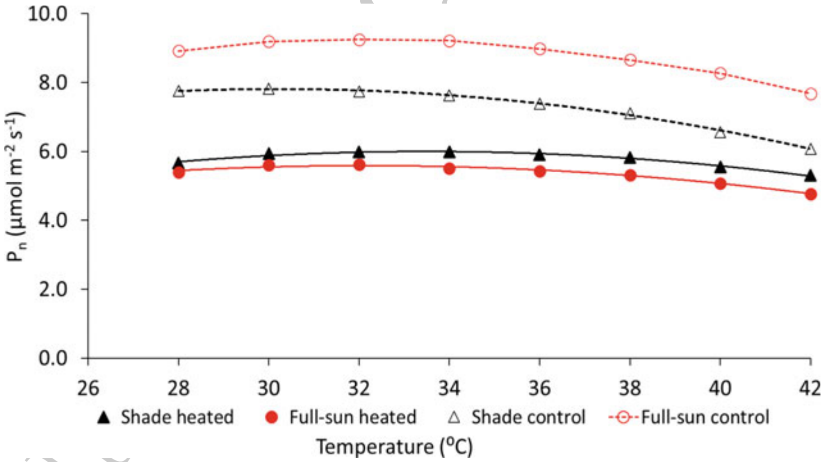

Fig. 2.3 Effects of shade and heat on the photosynthesis rate at different levels of temperature (Adapted from Mensah et al. [2022]. Creative Commons Attribution BY 4.0)

(F_v/F_m) reflects the photochemical activity of photosystem II (PSII) and has previously been used to detect and quantify temperature-induced changes in the photosynthetic system (Chen et al., 2012; Murchie & Lawson, 2013). In our experiment, predawn chlorophyll fluorescence was reduced from 0.80 in control treatments to 0.68 after 28 days of heat imposition, indicating severe stress to the photosynthetic system.

Another cause for lower photosynthesis seems to be a changed concentration and composition of the chlorophylls, the green pigments responsible for capturing light for photosynthesis. We observed reduced leaf chlorophyll contents under heat stress, suggesting impaired chlorophyll biosynthesis (Datta et al., 2009). Also, the ratio between chlorophylls A and B was affected (Mensah et al., 2022). Reduced chlorophyll contents could reduce photosynthesis, resulting in substantial loss in plant productivity. Again, values under shade were higher, but effects were not strong enough to prevent a decrease for the heated seedlings (Salazar et al., 2018).

2.4 FLOWER AND POD DEVELOPMENT UNDER HEAT AND DROUGHT STRESS

The flowering of cocoa starts eighteen months after planting for some early yielding varieties, while for most varieties, this occurs between three to five years (De Almeida & Valle, 2007). Only 0.5–5% of the flowers develop into mature pods (Carr & Lockwood, 2011). Flowering intensity, pod formation and sizes are affected by drought and heat. Pollen and stigma viability, anthesis, pollen-tube growth and early embryo development are all vulnerable to heat stress (Giorno et al., 2013; Lamaoui et al., 2018). Increased rainfall promotes flushing and flower initiation in cocoa, which is mostly followed by flower and fruit abortion in the dry season (Frimpong-Anin et al., 2014). While flowers and fruits drop during the dry season, mainly because of water stress, flower and fruit abortion in the rainy season is a way for cocoa to manage the resources available for the plants to develop pods (Handley, 2016; Stephenson, 1981). This is affected by plant hormones, the positions of the flowers or the pods on the plant, and rates of cross-pollination (Carr & Lockwood, 2011; Handley, 2016).

Cocoa attains full potential yield between eight to ten years after planting (De Almeida & Valle, 2007). The average yield is between 300 and 500 kg ha^{-1} in West Africa (Bymolt et al., 2018) corresponding to only a third of the potential yield (Aneani & Ofori-Frimpong, 2013; MOFA, 2016). The low yields seem to be partly due to limitations in water supply (Asante et al., 2022). In our study on shade and water-exclusion effects, yields were generally between 200 and 700 kg ha^{-1} per year depending on the suppression and/or the shade levels. Under full rainwater, shade increased yields by about 23% compared to full-sun conditions, while severe water exclusion reduced yields to as low as 59%. While shade was beneficial under all levels of water supply, it was not sufficient to prevent lower yields when water was restricted.

2.5 Conclusion

In West Africa, climate change is already having negative impacts on cocoa production and therefore on cocoa farmers' livelihoods. All stakeholders along the cocoa value chain (from cocoa farmers to purchasing companies) are increasingly being affected, in Ghana as well as in the neighbouring cocoa-producing countries. Field performance and yields are expected to be reduced further due to increasing rainfall variability, longer dry seasons and rising temperatures, making climate change the key challenge faced by cocoa producers. Our results confirm that drought and high temperatures have negative impacts on cocoa physiology, leading to reduced yields. Shade, on the other hand, improves both physiological performance and yields, thus confirming on-field research suggesting that agroforestry systems may increase yields (see Chapter 3). Although we recommend cultivation under shade, shade alone does not reduce the negative impact of stresses sufficiently to prevent damage from extreme climate change. Hence, while agroforestry represents an overall benefit under medium to high rainfall conditions, it will be necessary to refine agroforestry management using other climate-smart management innovations to improve the performance of cocoa under the expected climate change. This could include the following:

- Exploring the effects of irrigation systems under shade
- Selecting and managing tree species according to the local context
- Selecting cocoa rootstocks and varieties that are highly performant under water-limiting conditions
- Studying shade tree-cacao interactions to understand cocoa physiology under agroforestry conditions

- Identifying deep-rooted shade trees with limited competition with cocoa plants' root zones under drought stress.

Aside from climate, yields are influenced by a wide range of factors, including labour costs, diseases and pests, soil fertility, choice of cocoa variety, the age of cocoa trees, and the age and training of farmers (Abdulai et al., 2020). Higher yields may be possible with the use of technologies such as fertilization, pest and disease control, timely harvesting, pruning, supplemental irrigation and planting high-yielding cocoa cultivars (Laven & Boomsma, 2012). Any intervention regarding the use of shade will have to consider these factors, which are explored in more detail in other chapters of this book.

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