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CHAPTER 1

Introduction: Climate, Cocoa and Trees

Mette Fog Olwig, Richard Asare, Henrik Meilby,
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Abstract Climate change is predicted to significantly reduce areas suitable for the cultivation of cocoa, an important cash crop providing a livelihood to over six million smallholders in the humid tropics. Cocoa agroforestry shows potential to increase climate resilience while providing more stable incomes, enhancing biodiversity, supporting healthy ecosystems and reducing the pace at which farms expand into forested areas. Based on the multidisciplinary 'Climate Smart Cocoa Systems for Ghana' research project, this book investigates the case of the biophysical and socioeconomic sustainability of cocoa agroforestry in Ghana, the second largest producer of cocoa in the world. After a brief introduction to the research project, this introductory chapter reviews the literature on the links between climate change, farming and agroforestry, thereby situating

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the study within a wider context. It then presents an in-depth analysis of historical Ghanaian cocoa yields and climate data at both the national and regional levels to establish a foundation for understanding the new climate risks faced by cocoa farmers. The chapter concludes by providing an overview of the chapters that follow and introducing the overall argument that agroforestry can only successfully address climate change impacts on cocoa farming if location-specific biophysical and socioeconomic factors are considered.

Keywords Cocoa systems · Agroforestry · Climate-smart agriculture · Sustainable cocoa · Historical yield and climate data · Smallholders

1.1 INTRODUCTION

Cocoa is not only the key ingredient in chocolate, it is also an important cash crop providing a livelihood to over six million smallholder farmers in the humid tropics. It is cultivated on an estimated area of about 11.54 million ha in over sixty countries (FAOSTAT, 2021). However, being particularly sensitive to drought and high temperatures, the area suitable

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for cocoa cultivation is predicted to decline substantially in the coming years due to climate change, with serious consequences for farmers' livelihoods and the cocoa industry. The potential of growing certain crops under shade, in particular coffee, as a form of agroforestry, has been given much attention as it is believed to be more climate-resilient, and hence more sustainable than growing these crops in the open (Vaast et al., 2016). This book investigates both the biophysical and socioeconomic sustainability of agroforestry in relation to cocoa in times of climate change. It focuses on Ghana, the second largest producer of cocoa in the world.

Cocoa agroforestry entails the growing of cocoa together with shade trees and food crops for agronomic, economic and environmental benefits. Cocoa agroforestry is thus part of a larger trend to encourage forestry as a tool for climate change mitigation and adaptation. Thus far, research on cocoa agroforestry is generally positive regarding its potential to increase farms' resilience to climate change while providing additional, diversified and more stable incomes, enhancing biodiversity, supporting healthy ecosystems and reducing the pace at which farms expand into forested areas (Andres et al., 2018; Asare et al., 2014, 2019; Blaser et al., 2018; Djokoto et al., 2017). Yet, in practice, it is difficult to implement cocoa agroforestry, because integrating shade trees into cocoa farming systems is no simple matter. It requires a good understanding of institutional and social factors, such as land- and tree-use rights and differentiated access to inputs and training. It is also crucial to have locally specific biophysical and socioeconomic knowledge of crop combinations and the types and densities of tree species that, when configured properly, improve complementarity and minimize competition for resources (nutrients, water, solar radiation), manage pests and diseases efficiently, and enhance yields of cocoa, as well as timber, firewood, fruits and other non-timber products. Cocoa agroforestry research, however, often focuses mainly on the health of cocoa, the export crop, and pays little attention to the complex interaction of different plant species and their environmental and societal attributes (Vaast & Somarriba, 2014).

This book addresses these gaps to better inform research, policy and practice. It does so by providing a comprehensive and novel understanding of agroforestry and cocoa production under changing climates through:

1. analysis of historical data on cocoa yields and climate in Ghana

2. on-farm studies and controlled experiments investigating the impact of not only shade levels, but different shade tree species on key factors such as pests and diseases, cocoa ecophysiology and cocoa yields
3. analysis of quantitative and qualitative data that elucidate the socioeconomic factors influencing cocoa farmers' ability and willingness to adopt cocoa agroforestry, paying attention to the importance of particular shade tree species, as well as shade tree species diversity.

The book thus provides a multidisciplinary perspective on the potential of trees to mitigate the negative impacts of climate change through agroforestry.

Focusing on cocoa agroforestry in Ghana, the book compares findings across a climate gradient from the wet southern to the dry northern parts of the Ghanaian cocoa belt (see Fig. 1.1). The book has three key aims. First, it shows how agroforestry can provide a viable and profitable pathway for addressing the impacts of climate change. Second, it demonstrates the need to pay careful attention to context-specific socioeconomic and biophysical factors to maximize the potential of agroforestry and avoid unintended social and environmental consequences. Third, it demonstrates why multidisciplinary approaches are essential when studying climate change and agricultural sustainability.

This introductory chapter begins by providing a brief introduction to cocoa in Ghana and the multidisciplinary research project 'Climate Smart Cocoa Systems for Ghana (CLIMCOCOA)' from which this book emerges. This is followed by a review of the literature on the links between climate change, farming and agroforestry to situate the study in the broader literature on agroforestry and climate change. It then presents an in-depth analysis of historical cocoa yields and climate data both nationally and regionally to establish a foundation for understanding the new climate risks cocoa farmers must overcome to ensure future sustainable cocoa production in Ghana. The chapter concludes by providing an overview of the chapters that follow.

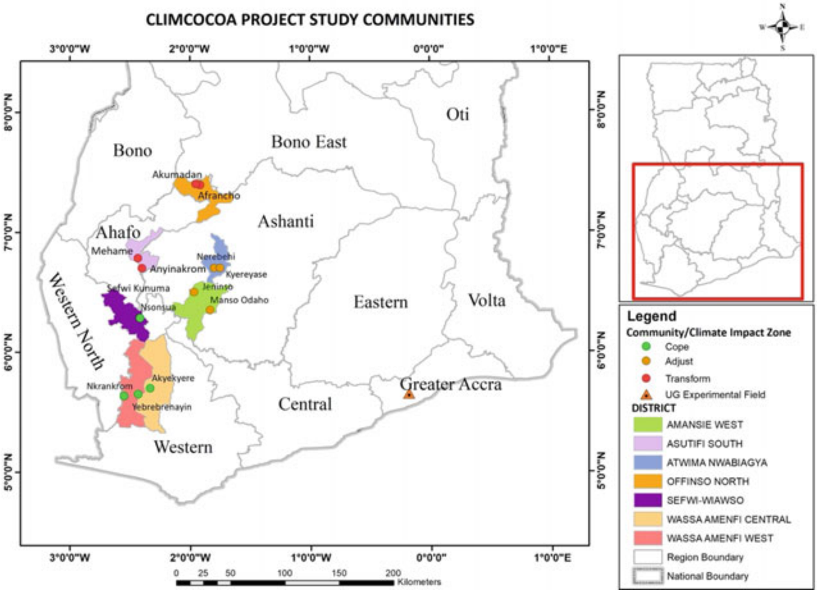

Fig. 1.1 Map of southern Ghana showing the CLIMCOCOA project's study communities

1.2 Cocoa in Ghana and the Multidisciplinary Research Project CLIMCOCOA

This book is based on research conducted between 2016 and 2021 as part of a comprehensive research project entitled 'Climate Smart Cocoa System for Ghana (CLIMCOCOA),' funded by the Danish Ministry of Foreign Affairs/Danida. The project team comprised researchers from the International Institute of Tropical Agriculture (IITA), Ghana; the World Agroforestry Centre (ICRAF), Kenya; the Centre of International Cooperation on Agricultural Research for Development (CIRAD), France; the University of Ghana; the University of Copenhagen, Denmark; and Roskilde University, Denmark. These researchers covered multiple disciplines, including human geography, climatology, development studies, natural resource economics, socioeconomics, ecophysiology, agroforestry, biometry and entomology.

The CLIMCOCOA research project focused on the case of Ghana. Ghana is important to the global production of cocoa, being the second largest producer in the world, and cocoa is also of key importance to Ghanaian society. Cocoa is one of Ghana's main exports making up 3.9% of Ghana's GDP in 2019 according to FAO statistics, while Sadhu et al. (2020) estimate the contribution much higher, at 7% of GDP. The cocoa sector furthermore employs 17% of the labor force, supporting the livelihoods of more than 550,000 farming households (Sadhu et al., 2020). Cocoa thus represents an important pillar in both rural and urban poverty alleviation and the general development of the Ghanaian economy.

Cocoa was introduced to Ghana in the nineteenth century and was traditionally established as a form of agroforestry on partially cleared forestland by smallholders. Cocoa arrived together with British colonial rule, which was keen to support the development of tradeable commodities. Since cocoa is generally not consumed locally, cocoa farming led to a reorientation from subsistence to labor-intensive cash-cropping, thereby exposing farmers to the risks of external market forces. This, coupled with the increasing use of seasonal migrant workers from the northern, poorer and drier part of Ghana and the use of hazardous and illicit child labor, meant that cocoa farming led to major changes in social, generational and gender relations (Allman, 1994; Sadhu et al., 2020; Yaro et al., 2021). In the 1980s, there was a dramatic drop in cocoa output attributed in part to the El Niño weather phenomenon, which led to a period of severe drought, and bushfires, that destroyed cocoa farms (Kolavalli & Vigneri, 2011). As a response, full-sun cocoa systems were introduced by the government coupled with new and early maturing cocoa varieties that thrived under less shade and in the short term produced higher yields than shaded cocoa (Gockowski et al., 2013). This resulted in the widespread adoption of full-sun cocoa systems by smallholders. Today, for a host of reasons that will be explored further in this book, researchers, extension officers and policymakers are increasingly favoring agroforestry instead of full-sun cocoa systems. This is in part because of financial considerations, as high yields from full-sun systems depend on a high level of inputs, which are expensive and can be difficult to obtain. Environmental concerns are also important because full-sun systems are established at the expense of forestlands, soil fertility, biodiversity and environmental sustainability. The current interest in Ghana, and in West Africa more generally, in reintroducing agroforestry systems is also a result of the new risks posed by climate change. Research indicates that agroforestry may be more resilient than full-sun systems when the correct level of shade and the appropriate combination of shade tree species are implemented. For example, this growing interest was apparent at the 2022 International Symposium on Cocoa Research in Montpellier, France (https://www.iscrsymposium.org/oral-presentations).

The CLIMCOCOA research project had two objectives: (1) to develop a comprehensive understanding of the impacts of climate change on the socio-biophysical bases of cocoa systems in Ghana; and (2) to assess the role of agroforestry as a model for climate-smart cocoa production. It utilized a multidisciplinary approach to investigate the biophysical and socioeconomic opportunities for and limitations of cocoa agroforestry under climate change. The project therefore employed multiple and varied methods, including analysis of historical yields and climate data; on-farm studies and eco-physiological experiments; literature reviews; field observations; twenty focus-group discussions and a household survey of 402 households in twelve cocoa communities. Data were collected in the Ashanti, Ahafo, Western and Western North Regions across the three delineated climate impact zones projected to have different degrees of climate suitability for cocoa production in Ghana (see Fig. 1.1). These three 'climate impact zones' are categorized as (1) the Cope Zone, which has the most favorable climate currently for cocoa and the lowest climate-related vulnerability, indicating the ability for cocoa farming to *cope* with climate change; (2) the Adjust Zone, with a moderately favorable current climate and moderate climate vulnerability, indicating the need for cocoa farming to make some *adjustments* to cope with climate change; and (3) the Transform Zone, which currently has the least favorable climate and the greatest climate vulnerability, indicating the need to replace or radically *transform* cocoa farming (Bunn et al., 2019).

This book presents the key findings from the CLIMCOCOA research project and discusses their implications for the future of cocoa cultivation in this current era of climate change.

1.3 CLIMATE CHANGE, FARMING AND AGROFORESTRY

The United Nations Framework Convention on Climate Change (UNFCCC) attributes climate change directly or indirectly to anthropogenic activities that change the composition of the global atmosphere leading to climatic changes that exceed the natural climate variability observed over comparable time periods (https://unfccc.int/). Similarly, the Intergovernmental Panel on Climate Change (IPCC) defines climate change as a change in the state of the climate identifiable by alterations in the mean and/or the variability of its properties persisting for an extended period—typically decades or longer (IPCC, 2013). Moreover, climate variability is attributed to all temporal and spatial scales beyond that of individual weather events in terms of the deviations of climatic statistics over a given period (e.g., a month, season or year) from the long-term statistics relating to the corresponding calendar period. In effect, climate variability is measured by deviations, which are usually termed anomalies.

Climate change adversely affects the conditions under which agricultural production in sub-Saharan Africa operates. In this region, as in other areas around the world, plants, animals and ecosystems are all experiencing the impact of the ongoing changes in climatic conditions. Some of these impacts, such as the direct impact of heat waves, droughts and floods, are affecting value chains of specific commodities in specific stages of the cultivation cycle. The effects of some of these impacts can be predicted with high confidence, whereas other impacts, such as the effect of climatic change on a whole ecosystem, are more complex to predict, since each element may react differently and interact with the others.

Cocoa is highly sensitive to changes in climatic conditions like drought and high temperatures (Ameyaw et al., 2018; Schroth et al., 2016). Changes in climatic conditions such as rainfall distribution and temperature fluctuations affect evapotranspiration and abiotic stress. According to Anim-Kwapong and Frimpong (2008), climate change can alter the development and incidence of cocoa diseases and pests, modify host tolerance and result in changes in the host's interactions with pests and diseases. This, the authors argue, could shift the geographical distribution of host–pathogen/pest interactions with negative effects on yields, subsequently affecting socioeconomic variables such as farm incomes, livelihoods and farm-level decision-making. Climate change, combined with the use of poor planting material, low soil-fertility management, the prevalence of diseases and pests, and the limited adoption of good agricultural practices have led to average cocoa yields stagnating in the four largest cocoa-producing countries in West Africa (Cameroon, Côte d'Ivoire, Ghana and Nigeria) over the last decade (Fig. 1.2). Nevertheless, in Ghana national production has increased due to the area under cocoa cultivation expanding at the expense of crop lands and natural forests (Ajagun et al., 2021; Forestry Commission, 2010).

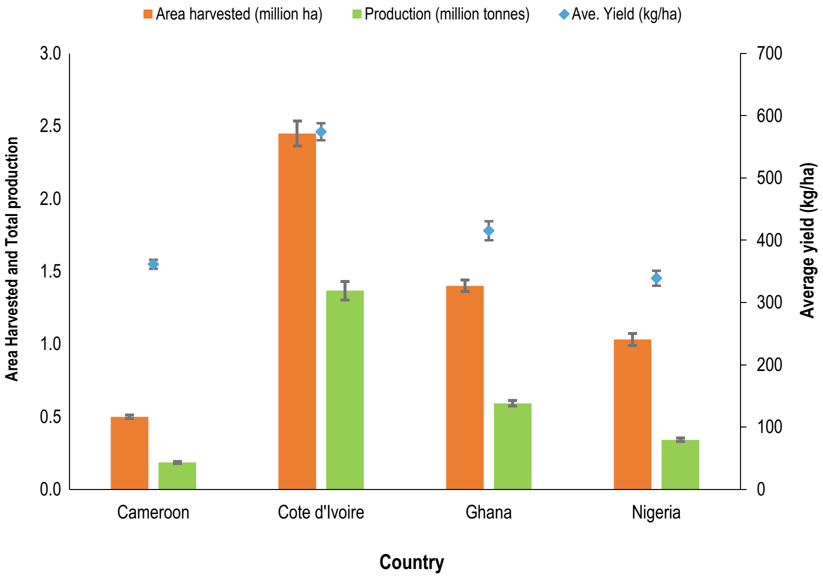

Fig. 1.2 Area harvested, total production and average yields (error bars indicate SE of the mean) of cocoa, 2010–2020 (FAOSTAT, 2021)

Cocoa smallholders have used forest areas as land banks to take advantage of the available nutrients stored in the organic-rich forest soils of newly cleared areas to compensate for falling yields on old cocoa farms (Asare & Ræbild, 2016; Gockowski et al., 2013; Ruf & Zadi, 1998). This is exemplified for Ghana in Fig. 1.3, which shows the annual gross tree cover loss between 2010 and 2020 at a >30% canopy density cover threshold. Currently, about 80% of the Upper Guinean Forest in West Africa has been lost because of cocoa production combined with other land use conversion, such as large-scale surface mining and increasing urbanization (Asare, 2019).

Various studies predict that the West African cocoa belt will experience longer dry seasons and increases in temperatures by 2050 (Läderach et al., 2013; Schroth et al., 2016). This is aggravated by other factors, such as decreased soil moisture and a build-up of pests and diseases, leading to a decrease in land suitable for cocoa cultivation and forcing farmers to expand into forested areas, causing further forest degradation

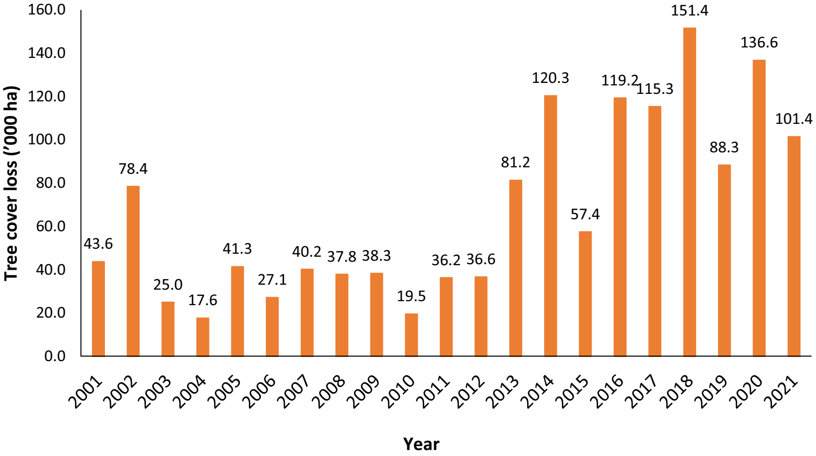

Fig. 1.3 Estimated gross tree cover loss at >30% ('000 ha) canopy density cover threshold in Ghana, 2001–2021 (www.globalforestwatch.org)

(Ruf et al., 2015). It is projected that climate change will have a significant negative impact on many agricultural commodities and communities, including smallholders with a limited capacity to adapt to adverse shocks, further exacerbating global poverty and food insecurity (Howden et al., 2007; Morton, 2007). Thus, both mitigation efforts to reduce greenhouse gas (GHG) emissions and adaptation measures to sustain crop yields are important.

Projected climate change scenarios in West Africa predict a marginal decrease in rainfall along the coastal cocoa-growing areas in countries like Liberia, Côte d'Ivoire and Sierra Leone by 2050 (Läderach et al., 2013; Schroth et al., 2016). Also, longer dry periods are projected in the cocoa belt, with Côte d'Ivoire expecting a gradual drying, and a projected decrease in precipitation in areas beyond Ghana's transition zone (Läderach et al., 2013). The driest parts of Côte d'Ivoire, Ghana, Sierra Leone and Liberia are projected to experience further increases in drought from now toward 2050, which will also affect the forest zones of all cocoa-growing areas along the West African cocoa belt (Schroth et al., 2016). Further, it is argued that changes in the timing of the wet and dry seasons will impact both the cropping patterns of mature cocoa and the successful establishment of cocoa seedlings (Black et al., 2020).

For the West African region, including Ghana, results obtained by the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the high carbon emissions scenario SSP585 indicate that for 2070–2099 compared to the 1985–2014 reference period, overall precipitation in the wet and dry seasons will change very little, but the number of wet days in the rainy season will decrease, implying that the amount of rainfall per rainy day will increase. In the dry season, the number of wet days and the amount of rain per rainy day may increase a little, but these changes are not significant (Wainwright et al., 2021). In the wet season, the mean length of wet spells is expected to decline. Results for the dry season are not significant but indicate a slight decline in the mean length of wet spells. Overall, the simulation results thus indicate that fluctuations tend to become more frequent and more extreme (Wainwright et al., 2021).

Predicting future climatic conditions in West Africa has been difficult, and climate change impacts on cocoa cultivation keep being manifested in different ways (Bunn et al., 2019). For instance, Läderach et al. (2013) and Schroth et al. (2016) predict a gradual decrease in climate suitability for cocoa cultivation in West Africa in the coming decades, with more favorable conditions for cocoa cultivation in the southern cocoa belt compared to the north, which represents the transition zone to the savannah. Modeling work has also shown a likely increase in the annual mean temperature of 2.1 °C by 2050.

1.3.1 Climate-Smart Agriculture

The projected decrease in cocoa-growing suitability in West Africa may be further aggravated by deforestation and soil degradation, but on the other hand, it can be buffered by potential adaptive innovations co-developed by farmers, development partners and scientists, and adopted by rural cocoa-growing communities. Several management strategies have been suggested for simultaneously achieving adaptation and mitigation benefits at the plot, farm and landscape levels. For example, soil conservation practices and the use of conservation agriculture, such as the incorporation of crop residues and cover crops, use of composts, and minimum tillage to increase organic carbon in soils and improve soil moisture through mulching, can all maintain soil fertility and reduce erosion during extreme weather events (Delgado et al., 2011; Hobbs, 2007).

Compared to full-sun cocoa systems, agroforestry leads to increased soil carbon stocks and above-ground biomass, provides shade for protection of the cocoa crop against rising temperatures, diversifies farmers' incomes and helps reduce financial risk (e.g., Matocha et al., 2012; Verchot et al., 2007). Practices like agroforestry that address both adaptation and mitigation goals are referred to as 'climate-smart.' In addition to agroforestry, other climate-smart practices include conservation agriculture, sustainable agriculture, evergreen agriculture, silvopastoral systems, sustainable land management and best-management practices (FAO, 2010; Garrity et al., 2010; Hobbs, 2007; McNeely & Scherr, 2003; Vaast et al., 2016; Vaast & Somarriba, 2014).

FAO (2013) refers to climate-smart agriculture (CSA) as agricultural production with the aim of sustainably increasing productivity and resilience (adaptation), reducing or removing GHG emissions (mitigation) and enhancing the achievement of national food security and development goals. Within the cocoa sector, the concept of CSA is referred to as climate-smart cocoa (CSC) and is defined as a strategy with the potential to sustainably increase yields and incomes while reducing rates of deforestation and forest degradation, as well as enhancing carbon stocks on farms (Asare, 2014; CSCWG, 2011; Vaast et al., 2016). According to Asare et al. (2019), synergies between CSA and the cocoa and forestry sectors include the focus on increasing productivity, the goal of resilience in the face of predicted changes in temperature and rainfall patterns (Läderach et al., 2013), and the mitigation potential from increasing shade tree cover in the cocoa system (Ruf & Zadi, 1998).

1.3.2 Does Cocoa Agroforestry Fit the Bill?

Cocoa agroforestry involves the strategic integration of suitable and valuable non-cocoa tree species and other plants into a cocoa farm at various stages, and management of cocoa farms through the three-dimensional arrangement of trees on the ground and in the canopy (Asare, 2006). Recent studies show positive impacts of this practice on yields (Andres et al., 2018; Asare et al., 2019; Blaser et al., 2018), income (Djokoto et al., 2017) and improvements to environmental integrity (Asare et al., 2014). The role of cocoa agroforestry is influenced by the composition and structural pattern of the agroforestry system, which to a large extent is the result of farmers' decisions to retain tree species according to their perceived values (Abdulai et al., 2018b; Graefe et al., 2017; Smith

Dumont et al., 2014). Food crops, fruit and timber trees in cocoa agroforestry systems are used to give both temporary and permanent shade to the young and mature cocoa plants (Asare & David, 2011). As climate change impacts increase in severity, it becomes more urgent to consider ways to reduce the negative impacts. This could include planting of shade trees since increases in the degree of shade are hypothesized to decrease effects of climatic stress. It is necessary to select shade trees according to farmer preference (Asare, 2005). Furthermore, the selected trees should be compatible with cocoa (Sauvadet et al., 2020) in terms of avoidance of disease and pest attacks (Asitoakor et al., 2022), minimal competition for resources such as nutrients and water (Abdulai et al., 2018a) while providing improvements of the microclimate (Graefe et al., 2017; Sauvadet et al., 2020; Smith Dumont et al., 2014).

Integrating diverse non-cocoa crops potentially provides food for farmers due to higher cropping intensities and diversities. According to Djokoto et al. (2017), farm households engaged in cocoa agroforestry benefit by producing food crops consumed by the household and earn additional incomes from the sale of food produce, including plantains, yams, fruit, honey and vegetables. Recent research (Andres et al., 2018; Asare et al., 2019; Blaser et al., 2018) has shown that cocoa yields reach a maximum at a shade cover of 30–50% due to the efficient use of nutrients and moisture (Isaac et al., 2007) and the reduction in the incidence of pests and diseases (Andres et al., 2018; Asitoakor et al., 2022).

In addition, cocoa agroforestry practices can increase on-farm carbon stocks (Afele et al., 2021) and thereby serve as a potential source of additional household income from carbon credits. The drive for agroforestry can trigger tree-planting practices by farmers in line with ongoing global initiatives like the United Nations' program on Reducing Emissions from Deforestation and forest Degradation (REDD), the Voluntary Carbon Market, the Cocoa and Forest Initiative, and the chocolate industry Cocoa Certification Initiative. These initiatives develop various policies on payment mechanisms to reward farmers for their environmental stewardship. By bundling several sources of revenues, including cocoa, timber, fuelwood, fruits and non-timber products, together with local and international payments for environmental services (carbon sequestration, biodiversity conservation, etc.), cocoa agroforestry can be made attractive and economically rewarding for both young and older farmers. However, some authors (Akrofi-Atitianti et al., 2018; Asare et al., 2014) have raised questions regarding issues of equality concerning how cocoa farmers can be fairly rewarded by carbon credits and other payment schemes, and how doing so could improve adoption. There is not yet sufficient clarity on key issues concerning the development of a fair and transparent benefit-sharing scheme or a definition of carbon rights.

Another important factor to consider is that, when land and tree tenure are not aligned with farmers' indigenous practices, undesirable consequences may result. For example, naturally occurring shade trees in cocoa landscapes have been designated as timber concessions without consideration of their shade function. In Ghana, the Concession Act No. 124, 1962, section 16 (4) states that 'All rights with respect to timber trees on any land is vested in the president in trust for the stools concerned.' This means that naturally occurring timber trees are in principle 'owned' by the community held in trust by the chief and vested in the president. This has led to cocoa farmers removing naturally occurring shade trees by, for example, ringbarking (making deep rings around trunks) or setting fires at the base of trees to avoid damages to their cocoa farms from lumbering (Asare & Prah, 2011). Furthermore, due to customary rights, possession of valuable timber trees, such as timber trees serving as shade trees on cocoa farms, can generate challenges when these trees need to be protected from powerful timber concessionaires or there is a need to negotiate compensation when such trees are harvested by the state (Asare & Ræbild, 2016). This is particularly the case for women, who generally have more insecure land and tree rights than men.

If farmers' tree tenure is ensured, it will become attractive for farmers to nurture naturally occurring shade trees, including shade trees that could eventually be harvested for timber. This could offer significant economic benefits to both farmers and the Ghanaian economy by improving household livelihoods and foreign exchange earnings through timber sales, while providing an environmental resource that helps to ensure a healthy and productive cocoa farm and provide ecological services. Shade trees suitable for timber on farms could also serve as collateral for future retirement benefits (e.g., as a pension scheme) to promote cocoa farmers' investment in trees on farmland.

Projections concerning the reduced suitability for cocoa production in some parts of the West African cocoa-growing belt call for a concerted effort to demonstrate how to combine adaptive strategies, resilience building in farming systems and mitigation practices. According to Harvey et al. (2014), there are substantial opportunities to simultaneously pursue adaptation and mitigation goals in tropical agriculture and adopt integrated landscape approaches that contribute to climate change goals for food security and ecosystem service provision. To ensure the sustainability of cocoa agroforestry, it is important to move beyond a narrow concern with climate change adaptation and mitigation and consider broader social and institutional challenges (Boadi et al., 2022).

1.4 Historical Cocoa Yields and Climate

We now continue with an analysis of historical cocoa production across the last six decades (1960–2020) and its relationship with climate. We examine the development of climate both nationally and regionally to establish a foundation for understanding the climate risks that cocoa farmers must overcome to ensure future sustainable cocoa production in Ghana. To this end, we draw on a range of data sources and describe patterns using descriptive statistics. Formal prediction of future cocoa production is beyond the scope of the book.

1.4.1 Climate and Weather

Historical data (1960–2020) on daily minimum and maximum temperatures and daily precipitation were obtained from the Ghana Meteorological Agency's synoptic stations.[1] Based on these data, mean minimum and maximum temperatures and accumulated precipitation were calculated for monthly and seasonal periods and are used in the analysis. Country-level spatially averaged time series based on gridded historical

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[1] Data on minimum and maximum temperatures and precipitation were provided by the Ghana Meteorological Agency and originate from a total of 16 synoptic stations, from Axim in the Western Region at 4° 52′ N, 2° 14′ W in the south to Navrongo in the Upper East Region at 10° 53′ N, 1° 5′ W in the far north and from Ada in the Greater Accra Region at 5° 47′ N, 0° 38′ E in the east to Bole in the Savannah Region at 9° 2′ N, 2° 29′ W in the west. Not all stations provide data on all three variables, but from the 1960s data from 10 to 13 stations are available, and from 1981 up to 16 stations have provided data. However, in the years 2013–2020, data are only available from 11 to 15 stations. More specifically, daily minimum temperature data from four stations cover the years 1960–2020 and, except for a few years with missing data, nine stations cover the years 1981–2020. For daily maximum temperature, six stations cover the years 1960–2020 (few exceptions) and 12 stations cover almost all the years 1981–2020. Finally, for precipitation, the years 1960–2020 and 1981–2020 are in most cases covered by three and nine stations, respectively.

data (1960–2020) on monthly mean minimum and maximum temperatures and precipitation were used as a supplement since data from the synoptic stations were not always available.[2]

Previous studies have indicated that the amount and temporal distribution of precipitation is important for cocoa (Anim-Kwapong & Frimpong, 2008). In addition to considering overall trends in precipitation, it is particularly relevant to focus on the drier seasons of the year. Moreover, since both decreasing precipitation and increasing temperatures can cause drought stress, both variables deserve attention. The driest months of the year (in the cocoa-growing areas) are December–February, and the country-level spatially averaged data indicate that, while the mean maximum temperatures in December–February remained stationary with a mean below 34 °C until the early 1990s, an increase to around 34.5 °C on average has been observed since then.

Between 1960 and 1980, country-level annual precipitation showed a declining trend (approx. 1300 mm → 1150 mm) with noticeable year-to-year variation (SD = 138 mm), but since 1980 there has been no clear trend, and the annual variation has been slightly lower (SD = 108 mm). The temporal pattern observed for precipitation in December–February mirrors that of the annual precipitation and shows a decreasing trend from 1960 to 1980, but after then it appears stationary. Particularly dry were December–February in 1981/1982, 1990/1991, 1993/1994 and 2014/2015, with estimated precipitation less than 20 mm.

In Fig. 1.4, the historical development in decadal mean values of monthly precipitation and minimum and maximum temperatures is illustrated for four meteorological stations in the Ashanti, Bono, Eastern and Western Regions (see Fig. 1.1 for the location of these regions) and for the decades 1970–1979 (lighter colors) and 2010–2019 (darker colors). Consistent increases in monthly mean minimum and maximum temperatures (0.5–2 °C) can be observed for all stations and all months of the year, and the increases are typically greatest for maximum temperatures in the dry months of December–January. There is also a slight rainfall decrease in February–July, whereas rainfall has remained approximately unchanged or increased somewhat in September–October. Being

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[2] National-level spatial average time series based on gridded historical data (1901–2021) on monthly mean minimum and maximum temperatures and precipitation were obtained from the Climatic Research Unit (CRU) of the University of East Anglia (CRU-TS, v. 4.06; https://crudata.uea.ac.uk/cru/data/hrg/; Harris et al., 2020).

located at the coast, Axim (4° 52′ N, 2° 14′ W) sets itself apart from the other stations by having particularly high rainfall in May and June of both decades (>200 mm/month on average). The overall bimodal rainfall pattern with a longer dry season in December–February and a shorter dry season around August is consistent across the stations and over the forty years. The minor wet season starts at all the stations in September, except in Axim where it starts in October.

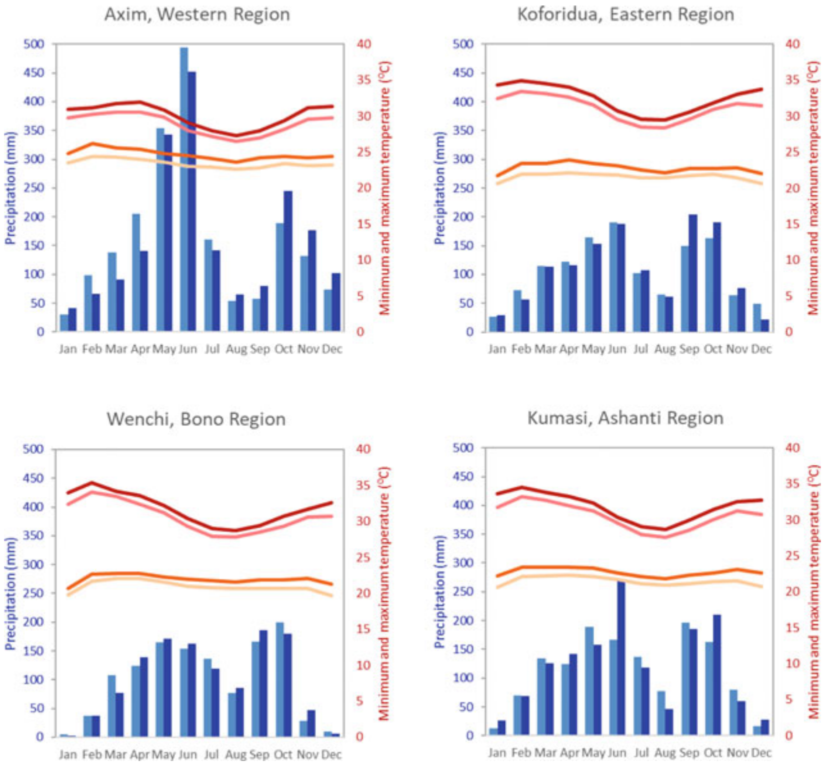

Fig. 1.4 Mean monthly minimum and maximum temperatures (lines) and monthly precipitation (bars), calculated for four meteorological stations in the Ashanti, Bono, Eastern and Western Regions in 1970–1979 (lighter-colored lines and bars) and 2010–2019 (darker-colored lines and bars) (Data courtesy of GMet, Ghana Meteorological Agency)

The diagrams in Fig. 1.4 hide the fact that both the total amount of precipitation and its distribution across the year vary considerably from year to year. To illustrate this, Fig. 1.5 (top panel) shows the monthly precipitation at Kumasi (Ashanti Region). Here, December–February are always fairly dry, March is usually dry but not always, June is usually wet, August is usually dry, and September–October are sometimes wet. However, a severe drought arises when the weather remains dry for a number of consecutive months. Therefore, Fig. 1.5 (bottom panel) also shows cumulative precipitation, calculated for six-month periods. Here, it becomes clear that the cumulative precipitation is mostly low in January–April, whereas in June–November, the cumulative values are high in most years. The most conspicuous exceptions are 1982 and 1983, which is consistent with the incidence of large bushfires, particularly in 1983 linked to El Niño. A few years with particularly high cumulative values in July–November occurred in 1963, 1966 and 1968.

Across the cocoa belt, the year-to-year variation of mean minimum and maximum temperatures in December–February are mostly in synchrony. The mean maximum temperatures (Fig. 1.6) are highest toward the north and east (33–35 °C) and lowest toward the southwest (30–32 °C). The mean regional precipitation in December–February varied somewhat (10–41 mm) within the cocoa belt, with an overall mean of 19 mm for the Bono Region and 35–41 mm for the Eastern, Western and Ashanti Regions. Across the 61 years covered by the data, the mean minimum and maximum temperatures for December–February generally increased by about 0.1–0.4 °C per decade on average, whereas the precipitation in the same three months decreased by 0.7–2.2 mm per decade. On average, a slight increase in aridity can therefore be observed in the three driest months of the year. Moreover, in agreement with the development of the country-level temperature average, it appears that the regional mean maximum temperatures increased slowly or remained almost stationary until around 1990 and then started increasing more rapidly (Fig. 1.6).

1.4.2 *Production and Yields*

Historical production data were obtained from the Ghana Cocoa Board (Cocobod), which regulates the pricing, purchasing, marketing and exportation of cocoa beans in Ghana. The data covers national (1960/1961–2019/2020), regional (1960/1961–2019/2020) and district

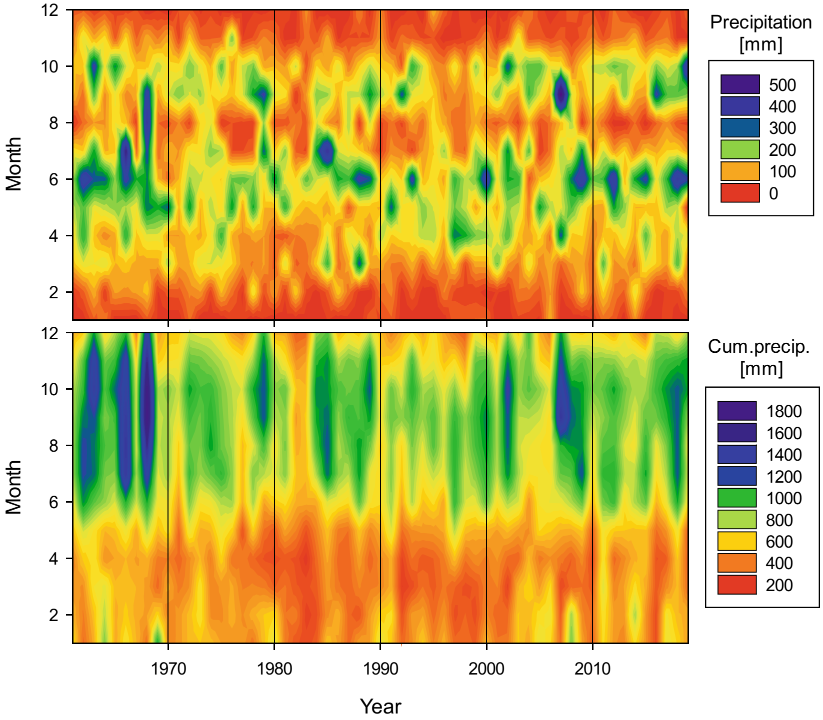

Fig. 1.5 Precipitation in Kumasi (6° 40′ N, 1° 37′ W), Ashanti Region, 1960–2020. Top: monthly precipitation; Bottom: cumulative precipitation calculated for a six-month period, including the current and the five preceding months (Data courtesy of GMet, Ghana Meteorological Agency)

(2000/2001–2014/2015) levels.[3] Historical data on the total area harvested and on average national yields (1961–2020) were obtained from FAOSTAT.[4]

According to Cocobod, the total annual production of cocoa beans was around 400,000 tons from 1961 to the mid-1970s. From 1976, a

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[3] Regional and national production data (1947/1948–2019/2020) are available at the Ghana Cocoa Board's (Cocobod) webpage (https://cocobod.gh/cocoa-purchases).

[4] FAOSTAT, Statistics Division of the Food and Agriculture Organization of the United Nations (https://www.fao.org/faostat/en/#home).

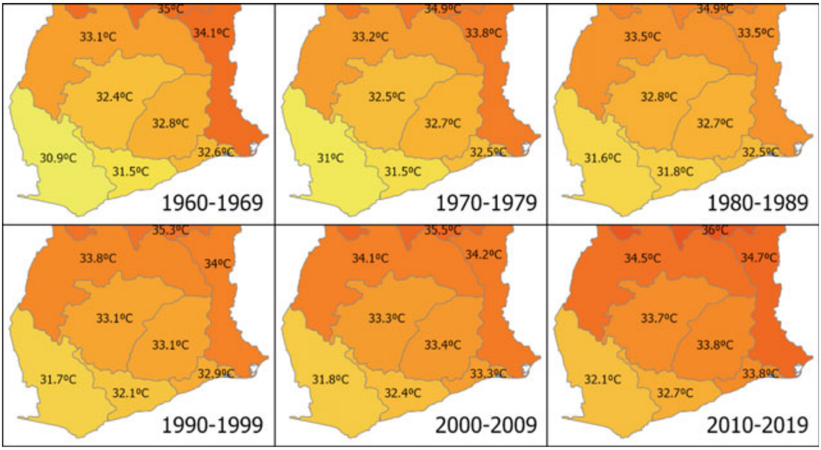

Fig. 1.6 Mean maximum temperatures for December–February in the cocoa belt of Ghana interpolated using data from between five (1960–1969) and fifteen (2010–2019) meteorological stations (Data courtesy of GMet, Ghana Meteorological Agency)

marked decline set in, and a historical minimum of 159,000 tons was reached in 1983/1984, consistent with the droughts experienced in 1982 and 1983. The low production in these years is at least to some extent also affected by cocoa being sold illegally via Côte d'Ivoire and Togo due to the low value of the Ghana Cedi at the time. In the following twenty years, production slowly increased, and from 2004, a harvest of about 700,000 tons was reached. In the years after 2012, production reached a level of 800–900,000 tons annually. According to Cocobod, production peaked in 2010/2011 and again in 2020/2021 at slightly above a million tons.

The regional development in production is illustrated in Fig. 1.7. Until around 1970, the annual production was 50–100% of the historical maxima in the Ashanti, Brong Ahafo, Central, Eastern and Volta Regions, but in the following years, production in these regions declined toward a historical minimum in the early 1980s and then increased again, first slowly in the 1980s and 1990s, and then more rapidly from around 2000. By contrast, in the Western Region annual production was only 20–40,000 tons until the mid-1980s, but it then increased to about ten times as much by 2010 through the establishment of cocoa farms in the virgin forests of this region (Ruf & Schroth, 2004; Ruf et al., 2015). In fact, since the middle of the 1990s, 50–60% of Ghana's annual cocoa production has taken place in the Western Region. In the Volta Region production decreased from 20–30,000 tons annually in the 1960s to 1–4,000 tons annually between 1980 and 2010. Only in the most recent decade has it increased slightly again to 5–8,000 tons/year. The westward shift in cocoa production was partly a consequence of the spreading of the Cocoa Swollen Shoot Virus (CSSV), which started in the 1930s and ultimately led to the abandonment of huge areas of plantations in the east and encouraged cocoa farmers to migrate and establish new plantations in the west (Danquah, 2003).

Aside from the different long-term developments in cocoa production within the regions, clear similarities in the year-to-year short-term fluctuations can be observed across the regions from 1960/1961 to 2019/2020. A year of comparatively high production in one region was typically also a good year in other regions, and coefficients of correlation

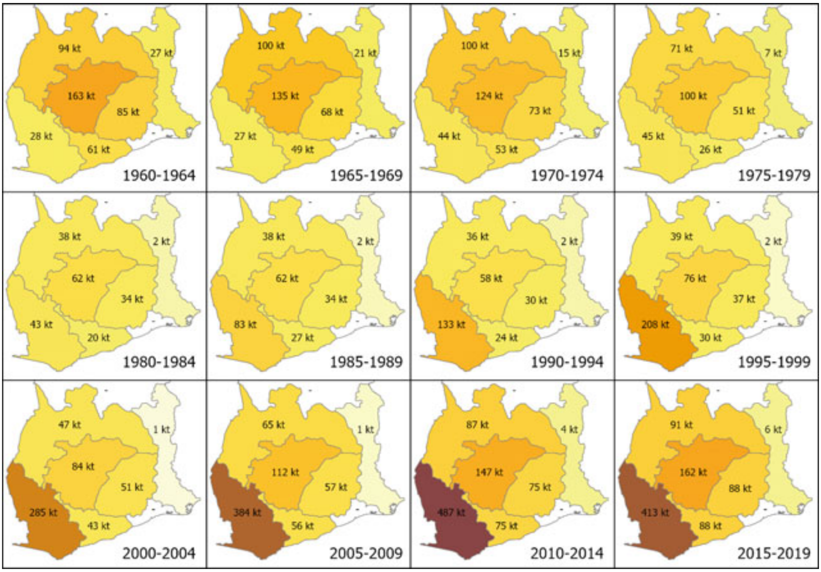

Fig. 1.7 Average production of cocoa beans in the cocoa belt of Ghana, calculated for five-year periods (1960–1964, ..., 2015–2019) by region based on Cocobod purchases. Unit: kilo tons, kt = 1,000,000 kg

between detrended annual production figures for different regions typically exceeded 0.6. This indicates that, at least in the short term, the production is affected by one or more common factors, of which the weather could be an important one. For the Volta Region, the similarity with other regions is only clear in the 1960s, before its production began declining to its current low level.

According to FAOSTAT, the total area harvested in Ghana first peaked in 1964, where it reached 1.85 million ha. In the following 24 years, the area gradually declined and reached a minimum of about 0.7 million ha in 1989–1994. The long decline was due to increasing cocoa taxation, the Ghanaian government's main source of income, an over-valued Ghana Cedi and high inflation rates, which made cocoa cultivation a poor business for farmers (Kolavalli, 2019). The decline was further exacerbated by low precipitation, widespread disease and bushfires in the early 1980s. In the decade following 1994, as a result of increasing world market prices and renewed political efforts to strengthen and promote the Ghanaian cocoa sector both domestically and in global markets, the areas under cocoa increased and peaked at the historical maximum of 2.0 million ha. Since then the area harvested has seemingly stabilized at 1.6–1.7 million ha. From 1961 to the late 1980s, the estimated yield varied between 200 and 300 kg/ha, and over the next few years, it increased to 300–400 kg/ha in 1990–2010, and since 2012 it has been slightly above 500 kg/ha.

1.4.3 Producer Prices

Producer prices were obtained from Cocobod and cover the crop years 1980/1981 to 2017/2018. Export prices for cocoa beans were obtained from FAOSTAT, and real prices in Ghanaian Cedi were calculated using annual consumer price indices and annual average exchange rates from the World Bank.[5]

The real producer price and the export price of cocoa beans were highly correlated ($r = 0.92$), and in most years the producer price remained approximately 1,000–2,000 Cedi (real 2010 prices) below the

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[5] Annual average consumer price indices (1964–2017) and annual average exchange rates (Ghanaian Cedi per US dollar, 1964–2017) were obtained from the World Bank (World Development Indicators, https://data.worldbank.org/). Export prices for cocoa beans (1961–2020) were obtained from FAOSTAT (https://www.fao.org/faostat/en/#home).

export price. In the second half of the 1980s, producer prices were 40–50% of the mean export price, but during the 1990s, Cocobod gradually increased the producer price to a level corresponding to about 60–70% of the mean export price. This reflects Cocobod's partial liberalization of the cocoa-bean market and a price policy that enables farmers to plan under the assumption that they will not experience a drop in price.

While short-term fluctuations in production may be related to variations in the annual weather conditions, variations in the longer term could partly be explained by changing prices. Hence, it emerges that across the 37 years covered by the dataset, the real producer price was highly correlated with annual production ($r = 0.82$), the area harvested ($r = 0.70$) and the yield of beans per hectare ($r = 0.67$).

1.4.4 Association Between Production and Climate Variables

To examine correlations between year-to-year fluctuations in climate variables and in regional or national cocoa production, the time series were first detrended using polynomial trend models. This eliminated long-term variation not related to the weather but also helped stabilizing the variance. Next, year-to-year changes were calculated to reduce the serial correlation. The analysis was carried out for both the interpolated regional climate series and the national-level spatially averaged series. Correlation patterns were mostly similar but results for precipitation turned out to be more consistent for the national average series, and therefore these are used here.

Across all six regions in the dataset (Ashanti, Brong Ahafo, Eastern, Central, Western and Volta), the year-to-year changes in production were correlated with changes in dry-season precipitation, especially in November. Hence, except for the Volta Region, which was hit very hard by bushfires in the early 1980s and has had very low production levels since then (cf. Fig. 1.7), the correlation of changes in regional production with changes in November's precipitation generally exceeded 0.30 ($0.30 < r < 0.43$, $p < 0.05$). Similarly, the positive correlation with precipitation in the three-month period December–February was in most cases significant at the 5% level.

For temperature, particularly high and significant ($p < 0.05$, except for the Volta Region) negative correlations were observed between year-to-year changes in regional production and changes in July's maximum temperature. Correlations of year-to-year changes in production with changes in temperature for June, August and September were also negative but not always significant at the 5% level. Correlations with changes in maximum temperature for the three-month periods June–August and July–September were similar to those observed for July. Correlations estimated for the three-month period December–February were also negative but slightly weaker than those observed for July and June–August. For the months June–September, correlations estimated for minimum temperatures turned out to be similar to those obtained for the maximum temperatures, but for the three-month period December–February the correlations were not significant.

1.4.5 Consistency of the Correlation Patterns

Previous studies have observed that increasing temperatures and reduced precipitation tend to reduce cocoa production (e.g., Ofori-Boateng & Insah, 2014). In agreement with the assumption that cocoa production is affected the most at times of the year when precipitation is low or absent for an extended period of time, we found significant and positive correlations between year-to-year variation in production and precipitation in and around the major dry season, particularly in the month of November, as also reported by Asante et al. (2022), and in the three-month period December–February. In addition, and in agreement with the possible incidence of heat stress, we found significant and negative correlations with variations in maximum and minimum temperatures in July and in the three-month periods June–August and July–September. In agreement with the results of Schroth et al. (2016), clear negative correlations were also observed with maximum temperature in the December–February period. Since maximum temperature and precipitation in December–February are negatively correlated, the negative correlation of production with maximum temperature may essentially reflect the same response as the positive correlation with precipitation. Furthermore, the correlation between minimum temperatures and precipitation in the dry season is much weaker than for maximum temperatures and precipitation, thus presumably explaining why the correlation between production and minimum temperatures in December–February was not significant.

In agreement with the trend observed over the last sixty years (cf. Fig. 1.6), climate projections consistently indicate that increasing temperatures can be expected, but for Ghana, the forecasted changes in precipitation patterns are less clear and likely to be small (e.g., Wainwright et al., 2021), including during the dry season, and in agreement with historical patterns (cf. Figs. 1.4 and 1.5). Thus, increasing temperatures and the associated evaporative demand, leading to water stress and possibly also to heat stress, may be more direct causes of a likely decline in cocoa production than the precipitation as such.

1.5 Overview of Chapters

This chapter's analysis of historical Ghanaian cocoa yields and climate data has highlighted changes in climate and how these historically have influenced yields. Building on previous cocoa agroforestry research that has largely focused on the health of cocoa as an export crop, the chapters that follow will contribute important findings on the complex of plant species and their environmental and societal attributes, the social and institutional contexts within which agroforestry practices are introduced across a climate gradient, and the impacts of climate change on the socio-biophysical bases of cocoa systems.

Chapter 2 investigates how full-sun cocoa systems versus cocoa agroforestry systems perform under changing climate and soil conditions. The chapter first discusses the impact of soil moisture as well as environmental stress, specifically drought and heat, on cocoa plants. It then examines how the impact of these factors on cocoa plant growth and yield are changed by shade. This chapter thus contributes to the still limited number of studies on the impact of increased heat and drought on the physiology of the cocoa tree and discusses how and if shade trees may reduce these effects. The chapter shows that shade generally reduces stress effects on cocoa plants, but that when temperatures and drought reach a certain level, shade only partially compensates for the negative effects. It draws on data generated from two experiments that were set up to investigate the effects of drought and elevated temperatures on cocoa, one with heat and shade using seedlings, and the other with drought and shade using a mature cocoa stand. The focus is on the physiological responses of cocoa trees to environmental stress and different levels of shade, which is a crucial first step in understanding the different factors that influence the potential of agroforestry as a means of climate change adaptation in cocoa farming.

Chapter 3 focuses on the species-specific effects of shade trees on cocoa, a topic that is in its infancy in cocoa agroforestry research. The chapter examines how various shade tree species impact the general health and productivity of the cocoa tree, including soil fertility and pests and disease infestation. Overall, results confirm that, under low input conditions (of fertilizer and pesticides), shade increases yields compared to full-sun systems. Furthermore, the chapter shows that shade tree species may have different effects on yields and the occurrence of pests and diseases, offering opportunities for improved management by strategically selecting tree species appropriate to the local context. The chapter is based on a four-year on-farm study of eight different agroforestry shade tree species and their effects on cocoa trees and their yields, as well as the prevalence of pests and diseases that damage cocoa pods. This chapter thus provides data to substantiate the overall claim of the book that site-specific and tree-specific biophysical knowledge is important to fully realize the potentials of agroforestry.

Chapter 4 moves from a biophysical to a socioeconomic focus and discusses the social challenges and opportunities linked to agroforestry from the perspective of the cocoa farmers. It describes the different monetary and non-monetary values farmers obtain from shade trees on cocoa farms, but argues that social barriers and institutional factors, such as land and tree rights, can prevent cocoa farmers from engaging in longer-term agroforestry practices and thereby from benefitting from the opportunities shade trees present. Based on focus-group discussions and in-depth interviews with cocoa farmers in twelve different cocoa-growing communities, the chapter shows that to realize the opportunities of agroforestry, it is necessary for farmers to navigate a complex socioeconomic landscape, including issues related to access, rights, ethnicity, migration, gender and other institutional and cross-cutting factors. It focuses specifically on the lesser-known benefits of shaded cocoa fields in the form of mushrooms and snails, and on challenges such as the role of chiefs, who are found to wield unchallenged power over land possessions, as well as the influence of mining activities that literally remove the foundation for investments in trees and cocoa. These and other very tangible challenges to cocoa agroforestry are the result of a mixture of historical land policies and contemporary opportunities for a more secure income.

Chapter 5 looks at another important socioeconomic factor, namely the household economics of cocoa agroforestry. To understand farmers' decision-making in relation to agroforestry, this chapter examines the costs and benefits of cocoa agroforestry along a climate gradient. It is based on household surveys in three different climate zones and is thus able to examine how different climates impact the costs and benefits of agroforestry. The chapter argues that cocoa agroforestry can be more profitable than monocrop systems when combined with income from shade trees, and that agroforestry farms with fruit trees are more profitable and more competitive across all three climate zones. Moreover, cocoa farmers attain a consistent and sustained profit from their cocoa plots if they implement a more tree species-diverse cultivation system that includes fruit trees suitable to local needs and conditions. Importantly, hired labor costs were lower the higher the tree species diversity because suitably shaded cocoa requires less intensive care than full-sun systems. This is important not just for reducing costs, but also because reduced labor inputs free up labor for both on-farm and off-farm diversification activities. The chapter thus further illustrates the complexity of integrating trees into cocoa farming systems, and the importance of not just looking at shade levels, as is commonly done in cocoa agroforestry research, but also paying attention to shade tree species diversity.

In the concluding Chapter 6, the findings presented in the different chapters are brought together in making the overall argument of the book, namely that agroforestry can only successfully address climate change impacts on cocoa farming if site-specific biophysical and socioeconomic factors are considered. The chapter also summarizes and discusses the overall policy and practice implications for cocoa farming that arise from the findings of the book. Finally, the chapter points to important new directions suggested by this study for further and broader research on the potential of climate change adaptation, which considers social and ecological factors in the larger context of agriculture vulnerable to climate change.

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