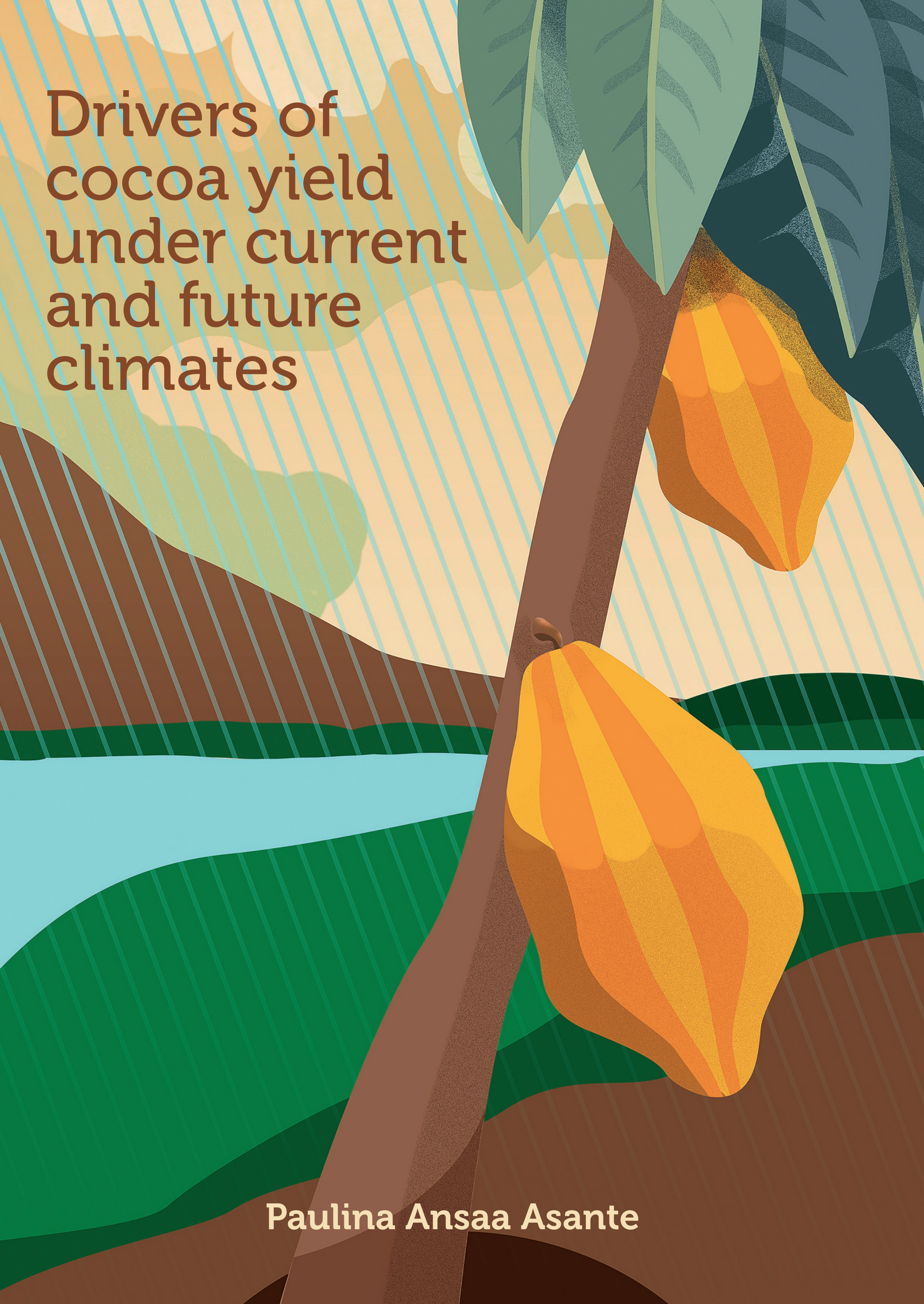
Drivers of cocoa yield under current and future climates



Paulina Ansaa Asante

Propositions

1. For climate change adaptation to be effective for cocoa farms, good agronomic management needs to be in place first.
   (this thesis)

2. Closing the cocoa yield gap depends more strongly on agronomic management than on environmental conditions.
   (this thesis)

3. Providing technological solutions to the poor without proper support will only make them poorer.

4. The most important step in solving people's problems is fully understanding their needs and motivations.

5. In a PhD, struggles are opportunities to build resilience and innovation.

6. Collaborative research provides effective, efficient and more impactful scientific solutions to societal challenges than stand-alone research.

7. Understanding the cultural background of an International PhD student is essential for providing effective supervision.

Propositions belonging to the thesis, entitled

Drivers of cocoa yield under current and future climates

Paulina Ansaa Asante
Wageningen, 23 May 2023

Drivers of cocoa yield under current and future climates

Paulina Ansaa Asante

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This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC).

Drivers of cocoa yield under current and future climates

Paulina Ansaa Asante

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Abstract

Cocoa (Theobroma cacao L.) is one of the world's most important agricultural commodity tree crops with the largest share of global production concentrated in West Africa. Current on-farm yields in this region are low and are expected to decrease in response to climate change through decreasing climate suitability. Previous studies identified numerous climate, soil and agronomic management factors limiting cocoa yields on farmer fields, however, the relative importance of these factors in explaining variation in yields which is relevant for prioritizing interventions is largely unknown. Additionally, effects of temperature, rainfall and atmospheric carbon dioxide concentration [CO_2] on cocoa tree physiology and productivity are poorly understood. As a consequence, possible implications of climate change for cocoa productivity and adaptations have not yet been considered. Climate-induced geographic shifts in the West African cocoa belt may have serious implications for farmers, cocoa supply and forests. This thesis therefore aimed to: (1) assess how current climate, soil and management factors affect current cocoa yields; (2) quantify the cocoa yield gap and the factors that can narrow the gap; and (3) assess the impacts of projected changes in climate and the underlying rise in atmospheric concentration [CO_2] on future cocoa production. In this thesis, on-farm data on cocoa yield were combined with simulations with a cocoa crop growth model.

It was found that under current climate, agronomic management was the dominant determinant of on-farm cocoa yields in Ghana, more so than environmental (climate and soil) conditions whilst climate effects on yields were stronger than soil effects. Nonetheless, the role of environmental conditions on cocoa yield becomes more important with increasing yields, such that the most productive cocoa farms tend to be the ones whose yields are most climate sensitive. Large cocoa yield gaps were found on farms revealing large opportunities to increase yield beyond current levels. Maximum water-limited yield gaps were much larger than yield gaps attainable in high-input and low-input systems. Climate factors were the important drivers of the absolute maximum water-limited and attainable yield gaps in high-input systems, but not in low-input systems. Relative yield gaps (maximum water-limited, attainable in high- and low-input systems) were reduced by management practices, particularly cocoa tree density and black pod control. This shows that improved agronomic practices offer opportunities to substantially increase production of present-day cocoa plantations.

Under future climate by mid-century (2060), large increases in potential water-limited yields and gains in area suitable for growing cocoa were expected, particularly when assuming full effects of elevated CO_2 and under wetter climate-change scenarios. Impacts were expected to follow a (south) east - west gradient with projected yield increases and in area suitable for cocoa being most positive for Cameroon, followed by Nigeria (except the largest increases in land area suitable for cocoa were expected here), Ghana and the least positive for Côte d'Ivoire. In areas with increasing yields, inter-annual yield variability was expected to decrease, but increased variability was predicted in areas with low yields, especially in north-west Côte d'Ivoire. Overall, simulations based on one climate-change scenario showed current country-level production to be maintained within current cocoa growing areas of Côte d'Ivoire and Ghana by mid-century. Projected increases in dry season precipitation by general circulation models (GCMs) was the most important factor explaining increases in potential water-limited yields and gains in suitability whilst projected shortening of the dry season most importantly explained the predicted reduction in yield variability. These modelling results indicate that, despite projected increases in temperature and changes in rainfall distribution by GCMs, projected increases in dry-season precipitation and shorter dry-season length would allow many areas where cocoa is currently grown to either maintain or increase productivity by mid-century, particularly if full elevated [CO_2] effects are assumed.

Keywords: cocoa yield, yield variability, yield gap, climate change, CO_2 effects

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Chapter 1

General Introduction

1.1. Background

Cocoa (*Theobroma cacao L.*) is one of the world's most important agricultural commodity tree crops, grown mainly for its beans, which are used for the production of chocolate, confectionary, cosmetics, pharmaceuticals and other end products (Beg et al., 2017). Production of the crop serves as an important source of revenue for producing countries and supports the livelihoods of about 5-6 million cocoa farmers and 40-50 million people working for industries that utilize cocoa to produce end products worldwide (Beg et al., 2017; Bermudez et al., 2022; CacaoNet, 2022; World Cocoa Foundation, 2014).

Historically, the species *T. cacao* is believed to have evolved in the tropical Amazon rainforest of South America (Motamayor et al., 2002) where several wild populations can be found and in the Guyana region (De Almeida et al., 2007). In its natural state, the tree can grow to a height of about 20-25 m, but when cultivated, tree height is about 3-10 m (De Almeida et al., 2007; van Vliet & Giller, 2017). Trees come to bearing (produce pods typically containing about 20-30 seeds/beans) after 2-3 years depending on the variety and method of propagation (Lahive et al., 2019) and have a typical economic lifespan of 30-40 years (Wessel & Quist-Wessel, 2015).

Traditionally, cocoa trees were cultivated under the shade of thinned forest trees, representing one of the oldest known agroforestry systems in the Americas. It is believed to have been domesticated about 5400 years ago in equatorial South America and introduced to central America roughly 1500 years ago by the Mayan and Olmec people (De Almeida et al., 2007; Zarrillo et al., 2018). However, since the 1980s cocoa farmers have increasingly opted for growing cocoa under full sun or very light shade systems (Ruf, 2011). Cocoa is now grown in diverse agroecological conditions in production systems which range from intensive mono-specific plantations to fully integrated agroforestry systems in over 60 tropical countries (Fig. 1.1) (Carr & Lockwood, 2011; Tridge, 2021). Production has shifted from the Latin American and Trinidad regions, where almost all production occurred in the 19th century (Cunningham et al., 1961), to Africa and Asia (ICCO, 2022). The majority of cocoa beans, over 70%, is currently being produced in West and Central Africa with the main producing countries being Côte d'Ivoire followed by Ghana, Nigeria and Cameroon (Fig. 1.1) (ICCO, 2022). Global annual production currently exceeds 4,800,000 tonnes of which about 95% is produced on small farms with average sizes of between 2 to 5 hectares (World Cocoa Foundation, 2014).

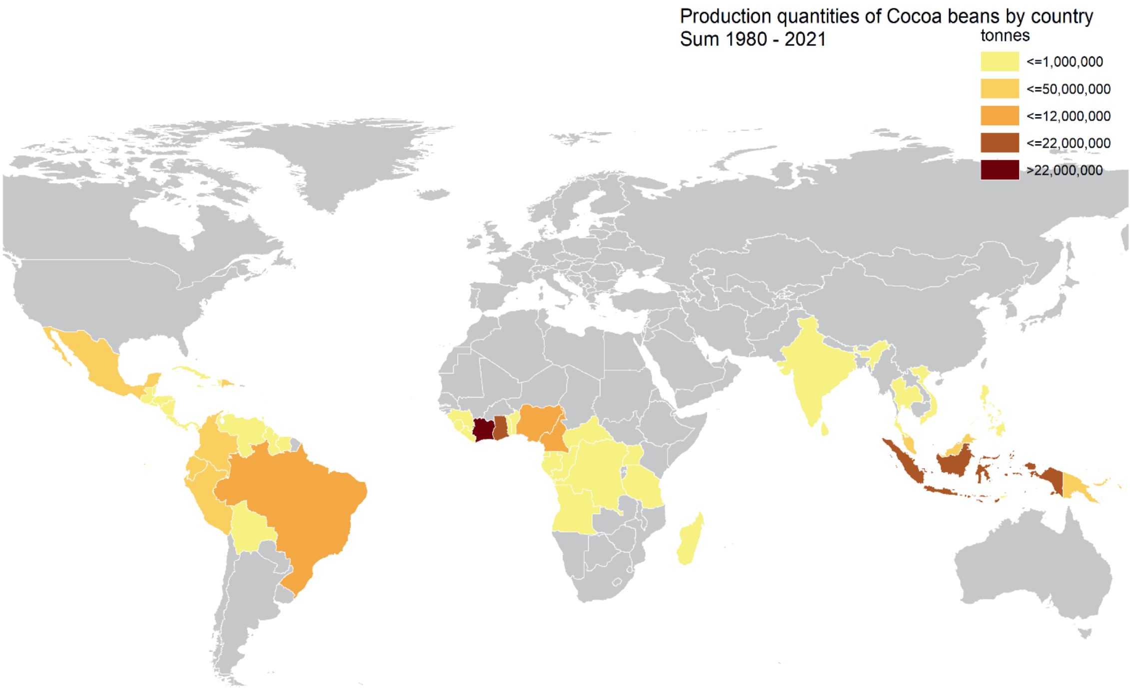

Fig. 1.1. Total cocoa production in tonnes by country for the 1980-2021 period (FAOSTAT, 2023)

Global demand for cocoa has been increasing at an average rate of 3 % per year for the past 100 years (Beg et al., 2017; CacaoNet, 2022), and production has increased more than fourfold since the 1960s (Fig. 1.2) (FAOSTAT, 2023; Fountain & Huetz-Adams, 2018; van Vliet & Giller, 2017). Increases in cocoa production over the past three decades have been driven by a sharp expansion in plantation area with only marginal increases in yields (Fig. 1.2) (FAOSTAT, 2023; van Vliet & Giller, 2017). This is driving deforestation in the major cocoa producing countries (Abu et al., 2021), as cocoa is grown mainly in regions that used to be covered with highly diverse moist tropical forests and cocoa generally replaces forests (Ruf, Schroth, & Doffangui, 2015). For instance, expansion in area planted with cocoa led to the loss of about 2-3 million ha of forest between 1988 and 2008 (European Commission, 2013). In the two major producing countries, Côte d'Ivoire and Ghana, cocoa plantations have been detected in currently forested and protected areas (Abu et al., 2021), increasing the risk of further deforestation. In other areas, cocoa is replacing croplands threatening food security (Ajagun et al., 2021).

Furthermore, there is a growing concern about the potentially negative climate-change effects on the suitability of cocoa growing areas in West and Central Africa due to decreasing climatic suitability (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). These projected shifts in climate suitability of production areas coupled with increasing demand for cocoa could drive producers to new areas which are currently covered with forests (Ruf et al., 2015). This is raising concerns for forest conservation (Jennings et al., 2022; Kroeger et al., 2017). Thus, to avoid further deforestation and expansion of cocoa fields into vulnerable areas, there is a need to evaluate opportunities to increase yields per unit area on existing lands (sustainable intensification) as a means to meet the growing demand for cocoa and at the same time reduce pressure on forest and other land uses.

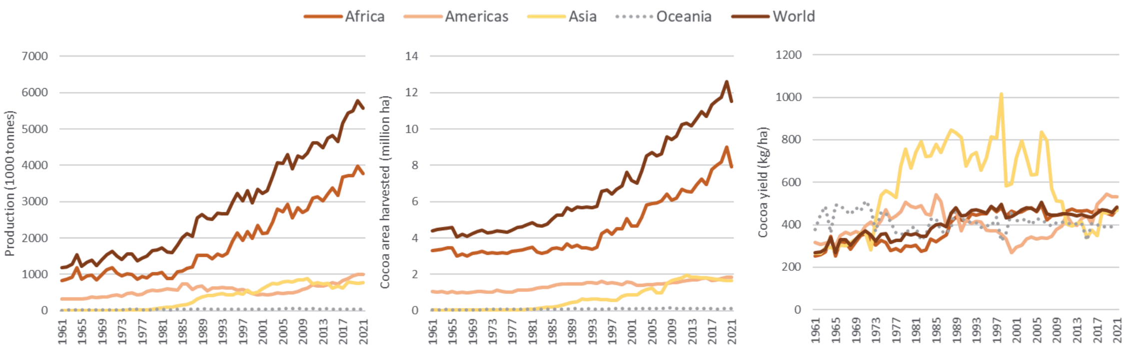

Fig.1.2. Cocoa production, area harvested, and yields worldwide and per continent (FAOSTAT, 2023).

1.2. Cocoa yield variability and drivers

Cocoa farming systems in West and Central Africa are largely rain-fed and low-input with average yields of 300-600 kg ha, which are among the lowest in the world (Wessel & Quist-Wessel, 2015). Numerous factors have been identified to limit current yields. Weather conditions in most cocoa growing areas show yearly fluctuations which often hamper cocoa yields (van Vliet & Giller, 2017) and occurrence of extreme weather events such as droughts and extreme temperatures significantly reduce cocoa yields (Gateau-Rey et al., 2018; Keil et al., 2008; Ruf et al., 2015; Schwendenmann et al., 2010). There is also a high incidence of pests in cocoa growing areas such as capsid bugs, cocoa pod borer and diseases like black pod, which significantly reduce yields and have been shown to account for about 20-40% of annual cocoa yield losses (Akrofi et al., 2015; Mpika et al., 2011; Opoku et al., 2000). Additionally, other factors such as loss of soil fertility partly due to inadequate soil nutrient management (Appiah et al., 2000; Baah et al., 2011), aging farms and trees (Nalley et al., 2014), planting material with low yield potential (Adomako & Adu-Ampomah, 2000; Edwin & Masters, 2005), lack of access to inputs (Aneani & Ofori-Frimpong, 2013), aging farmer population (Dormon et al., 2004), lack of adequate agronomic management practices such as weeding (Aneani & Ofori-Frimpong, 2013), irrigation (Carr & Lockwood, 2011), pruning (Tosto et al., 2022) and planting density issues (Sonwa et al., 2018; Souza et al., 2009) have been identified as major yield-limiting factors. Climate change is also becoming a major driver of cocoa yield variability, by altering temperature and precipitation patterns, increasing the frequency and severity of extreme weather events, and, indirectly, by altering pest and disease dynamics (Anim-Kwapong & Frimpong, 2004; Black et al., 2020; Cilas & Bastide, 2020; Gateau-Rey et al., 2018; Schroth et al., 2016). Nonetheless, the relative importance of these cocoa yield drivers remains unknown *{**Knowledge gap 1**}*. Strategies intended to improve yields and climate adaptation require an understanding of the relative contributions of cocoa yield drivers in order to prioritize interventions. In this thesis, the drivers of cocoa yield and their relative importance will be determined.

1.3. The cocoa yield gap

The need for sustainable intensification for cocoa requires an estimation of the scope for production increase on existing lands. Whilst cocoa yields remain low in West and Central Africa, relatively higher yields of over 3,000 kg/ha have been achieved on research stations in Ghana (Ahenkorah, Akrofi, & Adri, 1974; Appiah et al., 2000) and modelled potential yields in rainfed systems reach about 5000 kg/ha (Zuidema et al., 2005). By contrast, mean actual yields range from 300-600 kg/ha (Fig. 1.2). This means that the cocoa yield gap (i.e., the difference between potential and actual yields achieved by farmers) is as large as 80–95%. Quantifying the cocoa yield gap across farms would help determine how much additional cocoa can be produced on existing farmland, and what factors determine this potential for increased yield.

Yield gap analysis provides a means to assess the scope for yield increase and to identify factors that limit current yields (Lobell et al., 2009; van Ittersum et al., 2013). Few studies have conducted yield gap analyses for perennial crops, including coffee (Bhattarai et al., 2017; Wang et al., 2015), oil palm (Euler et al., 2016; Monzon et al., 2021; Rhebergen et al., 2018), banana (Wairegi et al., 2010) and cocoa (Abdulai et al., 2020; Aneani & Ofori-Frimpong, 2013). Estimating the cocoa yield gap requires robust estimates of the potential yield (Yp), which is the maximum yield a given crop variety can achieve when grown under favourable conditions with no limitation of water and nutrients nor reductions from pests and diseases (Lobell et al., 2009; van Ittersum et al., 2013). Under rain-fed cropping systems, which is the norm for cocoa farming in West Africa, potential yield is limited by the availability of water to plants, thus water-limited potential yield (Yw) is the relevant benchmark. The difference between the benchmark Yp (or Yw) and actual farmer yields achieved per unit area is the yield gap. Yield gaps can be determined either in absolute or relative terms. The absolute yield gap measures the scope for production increase in kg per ha whilst the relative yield gap is the absolute yield gap expressed as a percentage of the potential yield (i.e. normalization). Thus, the relative yield gap (expressed as a percentage) has the methodological advantage of allowing comparisons of yield gaps among different locations and different crops because it is normalized (Oort et al., 2017).

Three approaches are commonly used in estimating the potential yield as a reference in yield gap studies (Fig. 1.3). The standard approach to estimate potential yield under both irrigated (Yp) and rainfed (Yw) conditions is the use of crop simulation models. These models are developed based on current understanding of ecophysiological responses of crops to environmental and management factors (Monzon et al., 2021; Rahn et al., 2018; Zuidema et al., 2005). For cocoa, so far only one such model, Sucros-cocoa/Cacao Simulation Engine 2 (CASE2), has been developed and tested for simulating growth and yields of cocoa under irrigated and rain-fed conditions (Zuidema et al., 2005). The second approach for estimating potential yield is based on yield measurements from long-term field experiments, which aim to apply optimal crop management practices to eliminate all yield limiting factors (e.g., nutrient deficiencies, incidence of pests and diseases) (Lobell et al., 2009; van Ittersum et al., 2013). Under field conditions, it is generally impossible to exclude all yield limiting factors due to for instance, the large year-to-year climate variation in some locations which impact optimal management practices (Aggarwal et al., 2008; Lobell et al., 2009; van Ittersum et al., 2013). As such, attainable yields from experimental trials are often lower than model-based potential yields (Chapman et al., 2021; Hoffmann et al., 2020) and may not represent what can be theoretically obtained in optimally managed fields. Furthermore, for cocoa, such experimental trials are unavailable in most cocoa-growing areas in West and Central Africa. A few studies reported experimentally-based attainable yields for Ghana with values ranging between 1,890 and 3,500 kg/ha (Ahenkorah et al., 1987; 1974; Aneani & Ofori-Frimpong, 2013; Appiah et al., 2000). By contrast, attainable yields from research stations in Malaysia exceeded 6300 kg/ha (van Vliet & Giller, 2017)), very close to the values predicted by the CASE2 model (Zuidema et al., 2005). The third approach uses maximum farmer yields based on surveys and/or field observations. This approach is most suitable in intensively managed cropping systems where it is assumed that at least some farmers apply best management practices capable of approaching potential yield (Lobell et al., 2009). Two studies have reported maximum farmer yields between 477 and 2,125 kg/ha and explained cocoa yield gaps based on these benchmarks (Abdulai et al., 2020; Aneani & Ofori-Frimpong, 2013). In low-input systems, the use of maximum farmer attainable yields as benchmark may not represent the potential under rainfed conditions and thus may be lower than what is achievable with high input levels. Estimating yield gaps based on these three yield benchmarks (model-based, experimental and maximum farmer yield) approaches will give a comprehensive indication of the potential yield gains that could be achieved at the different levels of intensification, but this has not been done for cocoa yet *{* ***Knowledge gap 2****}*. In this thesis, I will quantify both absolute and relative yield gaps for cocoa, using all three methods.

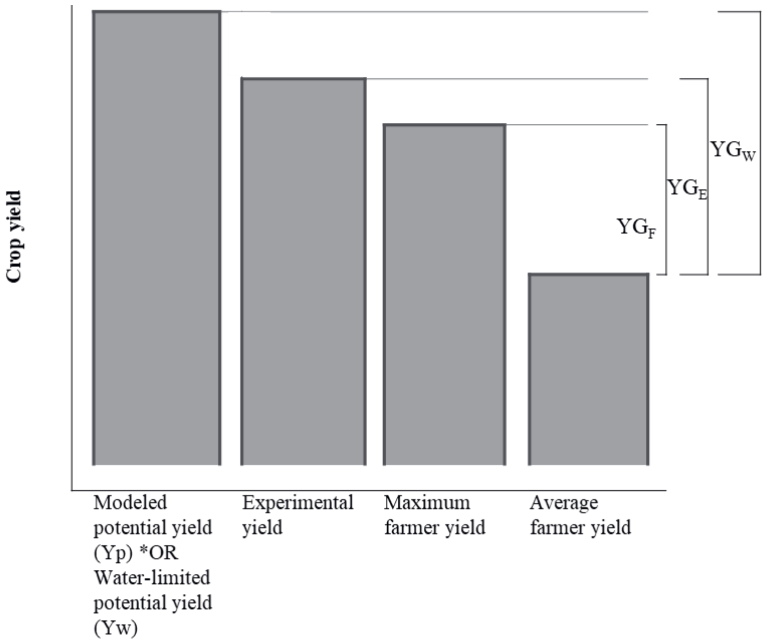

Fig. 1.3. Conceptual framework depicting the three measures of potential yield in comparison to average farmer yields and corresponding yield gap (YG) measures indicated on the right as follows, YG_F, maximum farmer based yield gap (yield potential estimated based on maximum farmer-based yield), YG_E, experimental-based yield gap (yield potential estimated from experimental trials), YG_W, model-based potential or water-limited potential yield gap (yield potential simulated with a crop model under irrigated or rainfed conditions). Adapted from Lobell et al. (2009).

1.4. Climate change and cocoa production

Climate change is likely to affect global food production (Parry et al., 2004; Porter et al., 2014) and West Africa is predicted to suffer large agricultural losses due to climate change (Mendelsohn et al., 2000; Trisos et al., 2022). West Africa is considered vulnerable to climate change due to the naturally high climate variability, heavy reliance on rainfed-agriculture and limited economic and institutional capacity to respond to climate change (Sultan & Gaetani, 2016). For perennial tree crops like cocoa, with a long economic life span of between 30 and 40 years (Wessel & Quist-Wessel, 2015), a tree planted today will experience climate change during its life. The long lifespan of perennial trees makes experiments expensive and time consuming and farmers with limited resources may not be able to compensate for erroneous decisions. Thus, quantitative knowledge on how climate change would impact cocoa productivity is urgently needed to inform policies that may counteract adverse effects on livelihoods and local and regional economies.

1.4.1. Projected changes in climate in cocoa growing areas

Increases in fossil fuel emissions and land-use change have caused a steady rise in greenhouse gas (CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; HFCs, hydrofluorocarbons; PFCs, perfluorocarbons; and SF6, sulfur hexafluoride) concentration levels in the atmosphere, which are driving increases in global average temperatures (+1.09 °C in 2011–2020 above pre-industrial times (1850–1900)) and changing precipitation patterns (IPCC, 2013; Pörtner et al., 2022). Carbon dioxide (CO_2) plays a major role in climate change and current levels are around 418 μmol mol^{-1} (NOAA-ESRL, 2022). With continued fossil fuel emissions and land-use change, climate models predicts that by 2100, atmospheric CO_2 levels could reach between 490 and 1370 μmol mol^{-1} depending on the particular socio-economic scenario applied, and global average temperatures are expected to have increased approximately 1.4 – 4.8 °C by the end of the 21st century (IPCC, 2013).

In West Africa, average surface temperature is expected to reach or surpass 1.5°C (above pre-industrial times) of warming by 2040 under the lower emission scenario and under mid- and high emission scenarios, increases of up to 2 to 3 °C respectively are expected with increased frequency and intensity of climate extremes (Trisos et al., 2022). At a 2°C warming, West Africa is projected to experience drier conditions and beyond 3°C warming increases in the frequency and intensity of drought events are projected (Trisos et al., 2022). Future predictions of changes in rainfall in Africa are not as robust as in other areas due to lack of reliable historical climate data and the inability of models to account for the factors that influence rainfall patterns on the continent such as land-use change (Girvetz et al., 2019). Global climate models (GCMs) project that many cocoa-growing regions in West and Central Africa will experience changes in precipitation patterns with some areas experiencing increases in rainfall and others experiencing decreases. For example, with medium confidence (assigned by IPCC based on robustness of available evidence and degree of agreement among scientists), West Africa, is projected to experience a decrease in rainfall in the west and increase in the east (Trisos et al., 2022).

1.4.2. Climate change effects on cocoa

As noted earlier in this chapter, the cocoa tree evolved in the Amazon rainforest, where environmental conditions are classified as tropical humid (warm and wet) and generally rather stable. This is why cocoa is considered sensitive to prolonged drought and high maximum dry season temperatures (Carr & Lockwood, 2011; Schroth et al., 2016). Temperature largely determines where cocoa plants can grow (Daymond & Hadley, 2004) and the mean minimum and maximum monthly temperatures in cocoa growing regions have been found to be between 18 to 21 °C and 30 to 32 °C, respectively, with an absolute minimum of 10 °C (Erneholm 1948 in Alvim, 1977). In West Africa, daily temperatures during the dry season can vary greatly, with temperatures reaching over 40 ºC (Denneth, 1984). Increasing temperature was found to enhance vegetative growth in cocoa (Daymond & Hadley, 2004; Lahive, Hadley, & Daymond, 2019). For instance, total extension growth in young cocoa plants was enhanced under 30 ºC compared to 23.3 or 26.7 ºC, and the loss of apical dominance at higher temperatures increased leaf flushing intensity, and leaf number and leaf area (Lahive et al., 2019). Nevertheless, at higher temperatures, cocoa pods were found to reach maturation earlier and pod losses to cherelle wilt increased (Daymond & Hadley, 2008). Climate-change-induced warming may increase potential evapotranspiration (ETP) and, combined with low or decreased rainfall, increase the risk of water stress (Carr & Lockwood, 2011; Schroth et al., 2016). Water limitation was found to reduce cocoa yields by about 10% in a rainfall exclusion experiment (ca. 78% rainfall exclusion over 13 months of about 3000 mm of rain in that period) (Schwendenmann et al., 2010) and using a physiology-based cocoa model, water limitation was reported to be responsible for 50% of yield losses (Zuidema et al., 2005). Under severe drought conditions, such as in El Niño-Southern Oscillation (ENSO) years, yields declined by about 62% to 89% with high tree mortality and increased infection rates of diseases, such as *Moniliophthora perniciosa* (Gateau-Rey et al., 2018; Keil et al., 2008). Thus, cocoa might be particularly vulnerable to climate change.

Climate change impact models have predicted that progressive climate change will affect the climate suitability of cocoa growing areas in West Africa (Fig. 1.4) (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). Impacts are predicted to vary across space with geographic shifts in climate suitability and a potential loss of about 50% of current climatically suitable areas for growing cocoa by 2050 (Schroth, Läderach, Martinez-Valle, et al., 2016). Nevertheless, it is unclear how changes in climatically suitable areas will affect cocoa production, since existing methods mainly used species distribution models (SDMs) driven by climate models outputs (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017) that do not consider the physiological processes underlying growth and production ***{Knowledge gap 3}***. Understanding the eco-physiological responses of cocoa trees to a changing climate is necessary to assess expected future yield and production. In this thesis, effects of climate change on cocoa growth and yield will be assessed using a crop modelling approach.

On the other hand, the key driver of climate change, the increase in atmospheric carbon dioxide concentration [CO_2], could potentially increase cocoa yield and offset the negative effects of warming on cocoa. Increases in [CO_2] levels may increase CO_2 substrate availability at the site of Rubisco and hence increase photosynthesis and reduce photorespiration (Farquhar et al. 1980; Cernusak et al., 2013). In addition, as CO_2 diffusion increases, stomatal conductance typically decreases, leading to improved water-use efficiency. Elevated [CO_2] is expected to improve photosynthesis efficiency of terrestrial C3 species, as the maximum velocity of the carboxylation by the enzyme Rubisco is achieved under roughly double the current atmospheric [CO_2] (Long et al., 2004; Walker et al., 2021). In cocoa, previous studies have shown that growing juvenile and mature pod-bearing trees under elevated CO_2 conditions (700 ppm) in a greenhouse experiment resulted in enhanced photosynthesis rates (Baligar et al., 2005; Lahive et al., 2019). In a modelling study, Black et al., (2020) showed that the positive effects of elevated [CO_2] on cocoa net primary productivity (NPP) mitigated the negative effects of expected warming and drought in the future (Black et al., 2020; Ríos-Bolívar et al., 2022). Yet, insights into how elevated [CO_2] might affect cocoa yields from these studies is limited as NPP is not equal to yield ***{Knowledge gap 4}***. In this thesis, I will evaluate potential cocoa productivity responses to warming and changes in precipitation by taking into account the role of elevated CO_2 on cocoa growth and yield.

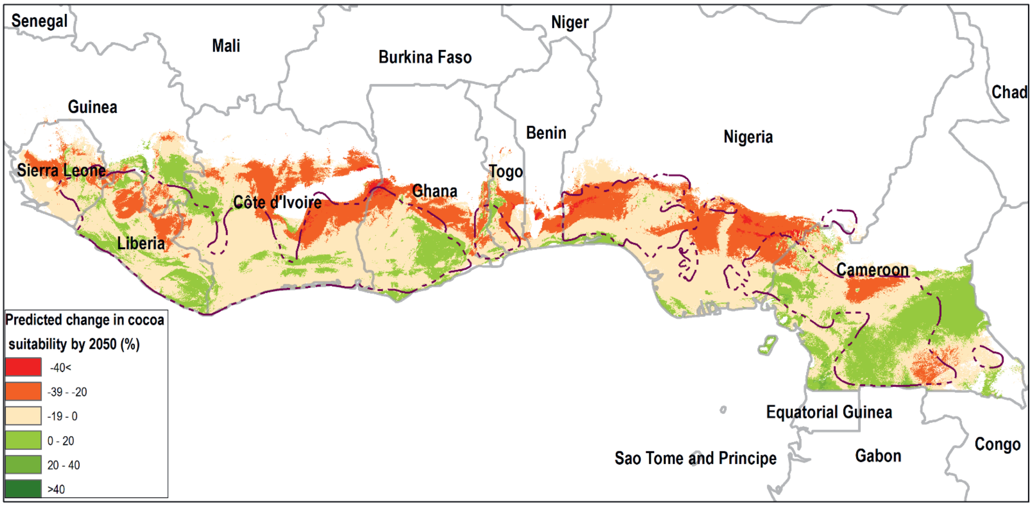

Fig. 1.4: Projected change in climate suitability of cocoa growing areas by 2050 in the West African cocoa belt (Schroth, Läderach, Martinez-Valle, et al., 2016). The purple dashed line shows cocoa production areas. Data was taken from Schroth, Läderach, Martinez-Valle Armando, & Bunn (2016).

1.5. Modelling climate change impacts on cocoa growth and yield

In modelling impacts of climate change on cocoa at regional level, most studies have utilized species distribution models (SDMs) driven by climate models (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). The SDMs are useful in data scarce environments such as most cocoa production areas, where data on yields, weather and soil conditions are often lacking (Rahn et al., 2018). A major limitation, however, is that SDMs lack the mechanistic processes to predict eco-physiological responses (Rahn et al., 2018) of cocoa to a changing climate. Also, they do not consider management practices such as shade management that might allow cocoa to adapt to future climate conditions (Blaser-Hart et al., 2021; Vaast et al., 2016; but see Abdulai et al., 2018). Mechanistic models are considered appropriate tools for explaining the relationship between climate, soil characteristics, management and yields (Rahn et al., 2018; Zuidema et al., 2005). They have the ability to mimic the relevant, physiological and bio-chemical processes that occur in the plant and describe how and why a particular response occurs. In the case of cocoa, SUCROS-Cocoa (CASE2; Zuidema et al. 2005), a crop model that calculates growth and yield of cocoa with or without water limitation has been developed. However, CASE2 lacks the ability to predict the impact of elevated [CO_2] on cocoa.

Thus, adapting this model to be able to simulate effects of warming and elevated [CO_2] on cocoa growth and yields could fill knowledge gaps on cocoa responses to climatic stress predicted by climate models and help design tailored adaptation strategies for cocoa under a changing climate. In this thesis, the CASE2 model will be adapted for cocoa tree growth and yield simulations under current and future climates.

1.6. Research objectives and questions

This thesis links, crop modelling, statistical and spatial analysis to identify and assess how current climate, soil and management factors affect current cocoa yields and the yield gap and assess the impacts of climate change on cocoa production. The following research questions were addressed:

RQ 1. How do current climate, soil and management factors affect current cocoa yields? ***{addressing Knowledge gap 1}***;

RQ 2. What are the current cocoa yield gaps on farms in Ghana and what factors explain these gaps? {***addressing Knowledge gap 2***}; and

RQ 3. How will projected changes in climate and underlying rise in [CO_2] affect future cocoa production in West and Central Africa? ***{addressing Knowledge gap 3 & 4}*** .

These research objectives and questions are addressed throughout the three core chapters of this thesis (Chapters 2–4), and brought together in the General Discussion (Chapter 5).

1.7. Study area

The study site for Chapter 2 and 3 in which RQ 1 and RQ 2 were addressed, respectively, was Ghana, the world's second largest cocoa-producing country, whilst Chapter 4 (addressing RQ 3) encompassed all the top-four cocoa producing countries in West and Central Africa: Côte d'Ivoire, Ghana, Nigeria and Cameroon (Fig.1.5). The main cocoa-growing regions in West and Central Africa are generally located in the (originally) forested coastal regions, where the climate is favourable for cocoa production. The extent of remaining forest cover differs substantially, being lowest in Ghana and Cote d'Ivoire and highest in Cameroon (Abu et al., 2021; Buchanan et al., 2021).

Cocoa growing areas in West and Central Africa typically have a humid equatorial or tropical rainforest climate characterized by decreasing rainfall along a South-North gradient with high temperatures (mean diurnal temperatures above 18 °C) throughout the year. Rainfall is highly variable (Fig. 1.5) with most areas having a bimodal rainfall regime (two wet and dry seasons). The length of the dry season (months with rainfall less than 100 mm) within the region is relatively longer than in other cocoa production regions like Malaysia (van Vliet & Giller, 2017). Cocoa is grown on a wide diversity of soils in West and Central Africa, but soils under cocoa farms are rather infertile (van Vliet & Giller, 2017). Major soil types within the growing areas include Acrisols, Lixisols, Ferralsols, Luvisols, Nitisols and Fluvisols (Snoeck et al., 2010).

Production of cocoa in our chosen region (West and Central Africa) is mainly carried out by about two million smallholder farmers who typically cultivate cocoa on small plots of land of about 3–4 hectares on average (Schroth et al., 2016; Wessel & Quist-Wessel, 2015). Cocoa farms are usually established by modifying the existing vegetation in humid forest landscapes (Sonwa et al., 2018). Recommended cocoa planting densities vary and depend on the area. For instance, in Cote d'Ivoire, a planting density of 1333 cocoa trees/ha is recommended, in Ghana 1730 cocoa/ha, and in Cameroon 1600 cocoa/ha, with a possibility of reaching 2000 or 2500 cocoa trees/ha for full-sun systems (Sonwa et al., 2018). Nevertheless, observed planting densities on farmer fields do not meet these recommendations (e.g. average planting density in Cameroon is 1168 cocoa trees/ha, and planting density in Ghana ranges from 1000 to 2500 trees/ha (Sonwa et al., 2018).

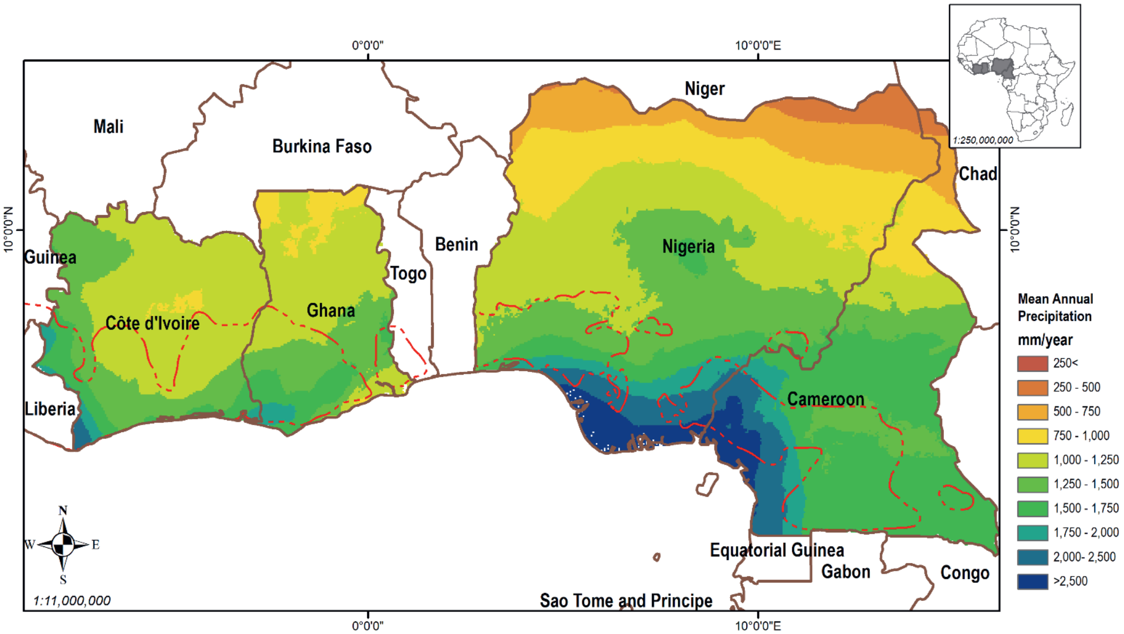

Fig. 1.5. Mean annual precipitation (mm) distribution across four major cocoa producing countries in West and Central Africa; Côte d'Ivoire, Ghana, Nigeria and Cameroon. Precipitation is based on Terraclimate data for the 2012–2019 period (Abatzoglou et al., 2018). The red dashed line shows cocoa production areas based on data from Schroth et al. (2016) and brown lines are national administrative boundaries.

1.8. Thesis outline

Chapter 1 (this chapter): The General Introduction aims to provide context to this thesis. The knowledge gaps are described. The relevance of assessing the drivers of cocoa yields and cocoa yield gaps and the impacts of climate change on cocoa production are presented. This chapter concludes with a description of the general research objectives and questions and provides a brief description of the study area and thesis outline.

Chapter 2: This chapter addresses RQ 1. In this chapter, the extent to which environmental (i.e., climate and soil) conditions drive cocoa yields, and how this differs for farms achieving on average low- and high mean production levels, was quantified based on an unprecedent dataset of 3,827 cocoa farms spanning the environmental gradients of the cocoa growing zone in Ghana using mixed-effects models. In addition, the relative role of management practices in determining yield variability was quantified based on yield data from 134 cocoa farms for which management information was available.

Chapter 3: This chapter addresses RQ 2. In this chapter, the cocoa yield gaps for Ghana and factors that contribute to narrowing these gaps were estimated. The cocoa yield gap was estimated as the difference between potential yield and actual farmer yield. Three potential yield benchmarks were estimated based on which yield gaps were estimated. These include: (1) simulated water-limited potential yield as upper limit that can be achieved on existing land in a rain-fed system quantified using the crop simulation model Sucros Cocoa/CASE2; (2) attainable yield in high-input systems based on average yields from experimental trials; and (3) maximum farmer yield based on average yield of the 10% best performing farmers. Both absolute and relative yield gaps were calculated. Each yield gap (absolute & relative) was then modelled as a function of environmental and management variables using mixed-effects models to determine the extent to which they explain variation in the yield gap. This was important for identifying potential causes of yield gaps and opportunities and entry points for sustainable intensification. Supplementary material for this chapter is included.

Chapter 4: This chapter addresses RQ 3 and 4. In this chapter, CASEJ, an extended version of the CASE2 model in which CO_2 effects can be simulated, was adapted and used to simulate effects of warming and changes in precipitation on simulated potential water-limited yields based on five plausible future climate scenarios projected by GCMs, with and without effects of elevated CO_2 on plant growth. The extent to which variation in current and projected future yields was associated with individual climate variables, was assessed using mixed-effects models. The total amount of cocoa that could be produced in the future on current planted area without expansion was quantified under low-input business-as-usual and high-input scenarios. Supplementary material for this chapter is included.

Chapter 5: In the General Discussion, the main findings of chapters 2-4 are synthesized. Broader implications for cocoa production in West Africa are considered, particularly in applying generated knowledge in support of decision making. Conclusions are drawn on the relative importance of climate, soil and agronomic management effects on cocoa yields and the yield gap and the potential impact of climate change on future cocoa production and recommendations for further research are provided

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Chapter 2

Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana

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Abstract

Cocoa (Theobroma cacao L.) is one of the world's most important agricultural commodity crops with the largest share of global production concentrated in West Africa. Current on-farm yields in this region are low and are expected to decrease in response to climate change, through warming and shifts in rainfall. Interventions intended to improve yields and climate adaptation require an understanding of the main drivers of yields across farms. In this regard, we quantified the extent to which environmental (i.e., climate and soil) conditions drive cocoa yields and how this differs for farms achieving on average low- and high mean production levels based on an unprecedented dataset of 3827 cocoa farms spanning the environmental gradients of Ghana. We further quantified the relative importance of management practices based on a subset of 134 farms for which management information was available. We modelled on-farm annual cocoa yield as a function of environmental variables for the large dataset and cocoa yield per tree as a function of environmental and management variables for the subset farms using mixed-effects models. Differences in effects on yield between farms with low and high mean production levels were evaluated using quantile mixed-effects models.

There was considerable variability in yields across farms, ranging from ~100 to >1000 kg ha^{-1} (mean = 554 kg ha^{-1}). Mixed-effects models showed that the fixed effects (i.e., environmental variables) only explained 7% of the variability in yields whilst fixed and random effects together explained 80%, suggesting that farm-to-farm variation played a large role. Explained variation in cocoa yields per tree of 134 farms in the subset increased from 10% to 25% when including management variables in addition to environ- mental variables. In both models, climate-related factors had a larger effect on yields than edaphic factors, with radiation of the main dry season and that of the previous year having the strongest effects on on-farm- and tree yields, respectively. The quantile regression analyses showed that productivity in high-yielding farms (90th percentile) was more strongly driven by environmental factors than in low-yielding farms (10th percentile). In conclusion, agronomic management is the dominant determinant of on-farm cocoa yields in Ghana, more so than environmental conditions. Furthermore, high-yielding cocoa farms are more sensitive to environmental conditions than low-yielding ones. Our findings suggests that good agricultural practices need to be in place before investing in additional climate adaptation practices.

Keywords: cocoa (Theobroma cacao L.), farm yield, cocoa yield per tree, solar radiation, cocoa planting density, shade tree density.

2.1 Introduction

Cocoa (*Theobroma cacao L.*) is one of the world's most important agricultural commodity crops with a great economic importance to producing countries and the confectionary industry. The crop is grown by nearly 6 million smallholder farmers on an estimated 10.2 million ha in over 60 countries in the humid tropics (Fairtrade Foundation, 2016; FAOSTAT, 2016). Globally, production is concentrated in West Africa, which supplies over 70% of global production with the main producing countries being Côte d'Ivoire and Ghana, and Nigeria and Cameroon becoming increasingly important (ICCO, 2018). Cocoa farming in this region is mainly low-input, with the majority of crops grown on farms with an average size of 3–4 ha (Aneani & Padi, 2016; Wessel & Quist-Wessel, 2015) .

Current average yields of cocoa are very low, about 300-600 kg ha^{-1} (Wessel & Quist-Wessel, 2015), compared to potential water-limited yields of about 5,000 kg ha^{-1} under rainfed conditions (Zuidema et al., 2005) and over 3,000 kg ha^{-1} achieved in experimental trials (Appiah, Ofori-Frimpong, & Afrifa, 2000). Thus, the cocoa yield gap (i.e., the difference between potential and actual yields) is as large as 80-95%. Numerous factors have been found to limit cocoa yields, such as high incidence of pests and diseases (Akrofi et al., 2015; Mpika et al., 2011; Opoku et al., 2000), aging farms and trees (Nalley et al., 2014), planting material with low yield potential (Adomako & Adu-Ampomah, 2000; Edwin & Masters, 2005), loss of soil fertility due to inadequate soil nutrient management (Appiah et al., 2000; Baah et al., 2011) and planting density issues (Sonwa et al., 2018; Souza et al., 2009). There is also growing concern on climate change impacts on cocoa growing areas in West Africa with the potential to further reduce yields and negatively affect cocoa dependent livelihoods (Anim-Kwapong & Frimpong, 2008; Gateau-Rey et al., 2018; Läderach et al 2013; Schroth et al., 2016). West Africa has been exposed to considerable droughts in the past (for instance in 1982/83 and recently in 2015/16) with concomitant cocoa yield reductions (Abdulai et al., 2018; Ruf et al., 2015).

Global climate models project further increases in temperature, shifts in rainfall with potential increase in the frequency and severity of climate extremes for this region (Niang et al., 2014; Serdeczny et al., 2017). Yet, limited knowledge exist (Black et al., 2020; Bunn et al., 2019; Läderach et al., 2013; Schroth et al., 2016) on the extent to which climate change will affect cocoa yield. Given the diverse agroecological conditions and production systems (e.g. ranging from intensive mono-specific plantations to fully integrated agroforestry systems) under which cocoa is grown, it is relevant to improve our understanding of the extent to which environmental conditions drive yields and the relative role of management practices (for instance planting density (Souza et al., 2009), shade levels and fertilizer use (Asare et al., 2017; Asare et al., 2019) on yield, in order to improve current cocoa systems' ability to adapt to the projected climate changes and to further close cocoa yield gap.

In general, the magnitude of crop yield responses to changes in climate has been found to be influenced by soil characteristics, as the water and nutrient holding capacity of soils enables crops to either sustain or reduce growth during periods of adverse conditions (Folberth et al., 2016; Mäkinen et al., 2017). In West Africa, soils under cocoa farms are rather infertile, (van Vliet & Giller, 2017), exacerbated by continued nutrient mining after forest clearing (Hartemink, 2005). On nutrient limited soils, yields are not only low on average, but have also been reported to be relatively constant from year to year, thus insensitive to changes in climate (Descheemaeker et al., 2020; Masikati et al., 2019). Increasing nutrient inputs through soil fertility management technologies could increase average yields (Ahenkorah et al., 1987; Schroth & Krauss, 2006; Vanlauwe et al., 2010), but year-to-year variability might also increase as yield becomes less limited by nutrients and more by seasonal climate variation (Descheemaeker et al., 2020; Keating et al., 2010). Therefore, identifying the extent to which climate drives yields on farms with different overall mean production levels is needed to provide context-specific information on the challenges of different farmer groups. Such knowledge is relevant for developing tailormade strategies and provides background knowledge for sustainable intensification.

In this study, we analyse effects of environmental (i.e., climate and soil) conditions on yields for 3,827 cocoa farms in Ghana and assess how these effects differ between farms achieving on average low and high yields. We also explore the role of management practices, i.e., cocoa- and shade-tree density, fertilizer-use and farm age on yield using a subset of 134 cocoa farms for which information on management was available. Such knowledge is quintessential for developing long-term planning of cocoa adaptation strategies to climate change and for reducing cocoa yield gaps. We address the following questions (1) What environmental conditions drive cocoa yields and what is their relative importance? (2) Are effects of environmental conditions stronger for farms that achieve on average relatively high compared to low yields? (3) To what extent do management practices influence cocoa yields?

We expect environmental variables to drive cocoa yield with positive effects of water availability and radiation and negative effects of stressful climatic conditions such as high climatic water deficit (CWD). Furthermore, we expect that climate effects will be stronger for farms with high yields as they are less limited by other factors such as soil nutrients. Finally, we expect positive effects of cocoa planting density and fertilizer use and negative effects of high shade tree density.

2.2. Materials and Methods

2.2.1. Study Area

The study was conducted in Ghana, the world's second largest cocoa-producing country after Côte d'Ivoire located in West Africa (Latitude: 7.9528 Longitude: -1.0307). In Ghana, climate is highly variable and follows a pronounced gradient with arid conditions in the north and humid conditions in the south (MOFA, 2016). Cocoa is grown in the southern part of the country. In this study, we focus on a dry-to-wet gradient based on rainfall (Fig. 2.1 and Table 1) from 2012 to 2019 for which period cocoa yield data was available.

The annual cocoa production cycle in Ghana follows a distinct seasonal pattern of rainfall (Asomanin et al., 1971). Peaks of leaf flushing, flower production and pod setting occur during the major wet season (Adjaloo et al., 2012; Asomanin et al., 1971). There are two harvest seasons; the 'main crop', which is harvested during the minor wet season through to the main dry season (i.e. September to January with peaks in November or December) and the 'light-crop' with relatively lower yields harvested during the main wet season with peaks in April or May (Ali, 1969; Asomanin et al., 1971).

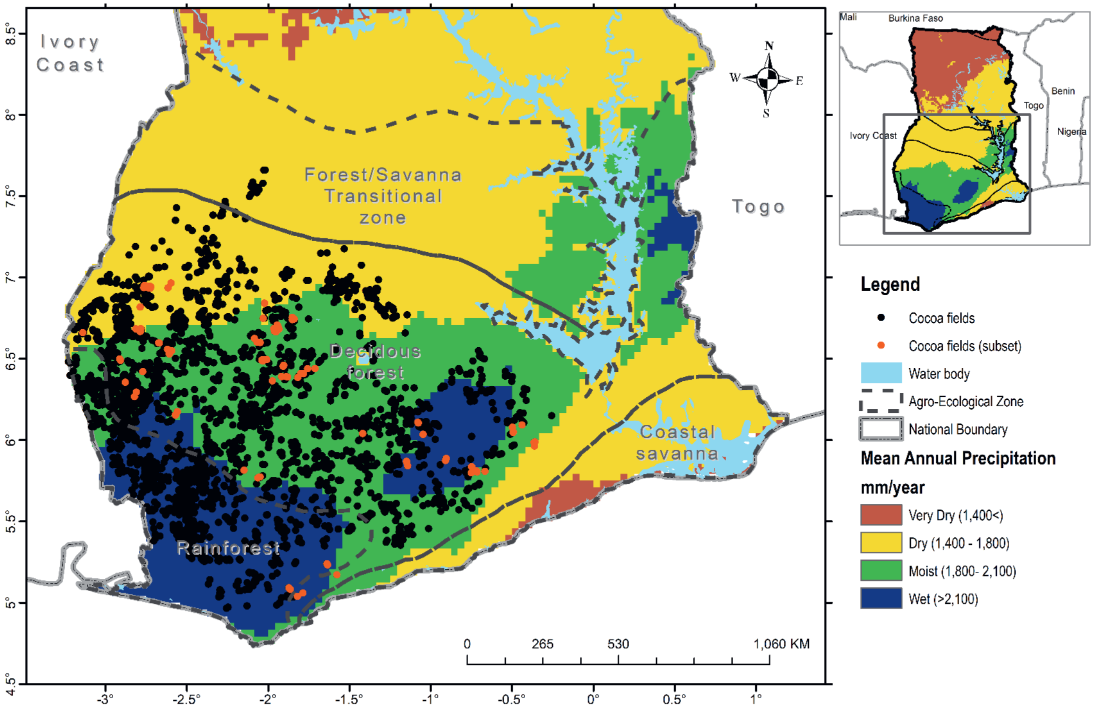

Fig. 2.1. Mean annual precipitation (mm) distribution across southern Ghana, based on Terraclimate data (Abatzoglou et al., 2018). Rainfall values are calculated means of 2012-2019 on a 4-km resolution. Black circles indicate the locations of the included cocoa farms and red circles indicate a subset of cocoa farms for which more detailed data on management were available.

Table 2.1. Characteristics of the dry, moist, and wet zones in Ghana where cocoa is grown.

	Dry	**Moist**	**Wet**
Wet season (months)	MJ=April to July, MN=September to October	MJ=March to July, MN=September to November	MJ=March to July, MN=September to November
Dry season (months)	MJ= November to March MN=August	MJ=December to February MN=August	MJ=December to February MN=August
Mean annual temperature (°C)	27-30 ˚C	25.5-30 °C	27-30 ˚C
Agroecological zone	forest/savanna transition	deciduous forest	rain forest
Dominant vegetation type	dry semi-deciduous	moist & dry semi-deciduous	moist & wet evergreen
Dominant soil types	acrisol, alfisol	acrisol, alfisol, oxisol	acrisol, alfisol, oxisol

MJ=Major season MN=Minor season. Sources: (Abdulai et al., 2020; Asare-Nuamah & Botchway, 2019; FAO, 2005; Stanturf et al., 2011; MOFA, 2016).

2.2.2. Cocoa yield data

Cocoa yield data across Ghana for the period 2012/2013 to 2018/2019 seasons (excluding for 2014/2015) was obtained from farmers, cocoa companies AgroEcom Ghana Ltd and Mondelez International 'Mapping Cocoa Productivity' project data (Daymond et al., 2017), and published data (Blaser et al., 2018). A total of 3,827 farms (i.e., 4015 yield data points) for which the location was known was obtained. The data set includes: 758 records in the dry zone, 2,011 records in the moist zone and 1,246 records in the wet zone. With this large sample size our study covered the full range of environmental conditions in the cocoa growing region of Ghana (Fig. 2.1). For a subset of 134 farms (i.e., 267 data points) data on management (cocoa and shade trees per hectare, fertilizer use and farm age) and average annual cocoa yield per tree was available (Fig. 2.1). We defined cocoa yield as the quantity of dried beans (i.e., assuming, 28 pods give 1 kg of dried beans and 1 bag is 64 kg) harvested per year (annual cocoa cropping season; March of a given year – February of the next year, e.g., the yield for 2017/2018 refers to March 2017 – Feb 2018), per unit cocoa plantation area (ha). We verified datasets for outliers and excluded those extreme values that were considered impossible e.g., extremely high (>7000 kg ha), or low or negative values.

Different approaches were used for collecting cocoa production records and measuring field size to estimate yield. For cocoa production, 93% of records were collected through farmer reports with verification from sale books usually referred to as cocoa passbooks (Asare et al., 2018) and 7% using pod counts. Most (86%) of the field size information was obtained using GPS measurements and 14% through farmer estimates.

2.2.3. Climate and soil data

Monthly climate data for the period 2011-2019 with a spatial resolution of 4 km covering the study area was obtained from the Terraclimate database (Abatzoglou et al., 2018). We included minimum and maximum temperature (°C), average precipitation (mm), downward surface shortwave radiation (W/m^2), actual and reference evapotranspiration (ET_0; mm), vapor pressure and vapor pressure deficit (kPa) as well as climatic water deficit (CWD; mm). CWD is defined as the absolute difference between reference and actual evapotranspiration, and more positive values indicate drier conditions. CWD was included as it better represents climatic stress than temperature and precipitation alone. For all climate variables, we analyse annual totals starting from March of a given year to February of the next year, based on the cocoa cropping season in Ghana.

Soil properties were obtained from the ISRIC/SoilGrids database (Hengl et al., 2017), at a depth of 0-30 cm with a spatial resolution of 250 m. We included, sand (g 100 g^{-1}), clay (g 100 g^{-1}) and silt (g 100 g^{-1}) content.

2.2.4. Statistical analyses

We assessed how, and to what extent, environmental conditions influenced cocoa yields by modelling annual cocoa yield (kg ha^{-1}) as a function of climatic and soil variables using linear mixed-effects models (MEMs) (Zuur et al., 2009). For climate, we considered all four seasons in this study defined as, main wet season (March-June), minor dry season (July-August), minor wet season (September-November), main dry season (December-February). To account for possible lag effects of climatic variables on cocoa yields, we considered both the seasons of the previous and the current year. To identify for each climate variable in which season it most strongly influenced yield, we first performed for each climatic variable linear regression between annual cocoa yield and the climatic variable for each of the seasons separately. We selected for each climate variable the season that was included in the best model (i.e., lowest Akaike Information Criterion; AIC).

We included all selected environmental variables in the model as fixed effects (Table 2). All continuous explanatory variables were standardized by subtracting the mean value of the variable and dividing it by the standard deviation. This allowed for direct comparison of the relative importance of explanatory variables (Maldonado, 2012). A larger standardized coefficient means that the variable is more important. We included a random intercept for each farm to account for non-independence of data points from the same farm. We evaluated collinearity of explanatory variables using the variance inflation factor (VIF). We excluded variables with the highest VIF until none of the included variables had a variance inflation factor >3. Based on this procedure, actual and reference evapotranspiration, maximum temperature, vapour pressure, climate water deficit and sand content were excluded from the final model. Conditional and marginal R^2 were calculated to evaluate variation explained by fixed effects alone and fixed effects and random effects together, respectively (Nakagawa & Schielzeth, 2010).

We used a quantile mixed-effects model to analyse how effects of environmental conditions differed between farms with low and high yields. In the quantile mixed-effects model, we included the same climate and soil variables as fixed effects as in the final mixed-effects model described above, and we also included a random intercept per farm.

Finally, to assess the relative importance of management practices in explaining variability in cocoa yields, we performed a separate analysis for a subset of 134 farms for the period 2012-

2017 (excluding 2014/2015) for which data on management was available. We compared a mixed-effects model with climate and soil variables only, with a model that also included management practices. The management variables included the number of cocoa and shade trees per hectare, fertilizer (use vs. no use) and farm age. Because yield per ha is estimated by multiplying average yield per tree with the number of cocoa trees per hectare, we used cocoa yield per tree instead of per hectare as response variable and included planting density as explanatory variable. However, to evaluate the effects of number of cocoa trees on yield at the hectare-level we also performed a log-log simple regression (log(cocoa yield per tree) ~ -1*log(cocoa planting density), i.e., a log transformation of cocoa yield per tree ~ 1/cocoa planting density, to test whether yield per hectare is independent of cocoa planting density). If the slope of cocoa planting density is larger (less negative) than -1, it indicates that hectare-yield would increase with cocoa planting density, the opposite holding if the slope is smaller than -1. Following the model selection procedure for the full data set, we selected the seasons of the climate variables based on a comparison of regression models between yield per tree and climate variables for the different seasons using AIC. Again, we excluded variables with the highest VIF, and excluded, precipitation, actual and reference evapotranspiration, vapour pressure and vapour pressure deficit, and sand content.

All analyses were performed using R statistical software (R Core Team, 2018). Mixed-effects models were performed with the “lmer” function of the lme4 package (Bates et al., 2015). The “lqmm” function of the lqmm package in R was used to perform the quantile mixed-effects model (Geraci & Bottai, 2014).

Table 2.2. Selected predictors for the mixed-effects model based on AIC and collinearity tests for the full dataset based on 3,874 farms and for the subset of 134 farms.

Predictors	Unit	Min	Max	Range	Mean±SD
Full data predictors					
Precipitation (minor dry season)	mm	36.5	167	130.5	90.4±29.5
Downward surface shortwave radiation (main dry season)	W m^2	194	239	45	216±10
Minimum temperature (minor wet season of previous year)	°C	19.5	23.9	4.4	22.6±0.7
Vapour pressure deficit (main dry season)	kPa	0.6	2.4	1.8	1.5±0.3
Silt content	g 100 g^{-1} (%)	7.7	32.7	25	20±4.5
Clay content	g 100 g^{-1} (%)	14	35.7	21.7	26.8±2.9
Subset data predictors					
Downward surface shortwave radiation (main dry season of previous year)	W m^2	203	228	25	217±8.4
Minimum temperature (main dry season)	°C	20.1	23.7	3.6	21.7±0.5
Maximum temperature (main dry season of previous year)	°C	30.7	33.7	3	32.6±0.6
Climate water deficit (minor wet season)	mm	0	11.7	11.7	2.7±4.1
Silt content	g 100 g^{-1} (%)	12	32	20	24±4.4
Clay content	g 100 g^{-1} (%)	18	32	14	26±2.5
Cocoa planting density	trees ha	276	3626	3350	1211±440
Shade tree density	trees ha	0	178	178	15.9±26.5
Farm age	years	8	58	50	22.4±9.4
Fertilizer use	yes/no	-	-	-	-

2.3. Results

2.3.1. Variability of farm level cocoa yields across the rainfall gradient

Over the six-year timespan included in our dataset (2012-2019), strong inter-annual variability in cocoa yields across the rainfall gradient and individual farms was observed (Fig. 2.2). Annual mean yields per rainfall zone and year varied from ~300 to 700 kg ha^{-1} whilst that of individual farms ranged from ~100 kg ha^{-1} to >1000 kg ha^{-1}. Annual mean yields were highest in 2012-2016 for all rainfall zones and lower in later years. For instance, from 2015/2016 to 2018/2019 mean yields declined from ~650 to ~400 kg ha^{-1} in the dry zone, and from ~700 to ~300kg ha^{-1} in the moist and wet zones, respectively.

Relatively small differences in yields were observed between rainfall zones, with highest mean yields in the wet zone, 568 kg ha^{-1}, followed by the moist zone, 559 kg ha^{-1} and the dry zone with a lower mean yield of 522 kg ha^{-1}. Within rainfall zones, strong variation in cocoa yields was observed particularly in the moist and wet zones.

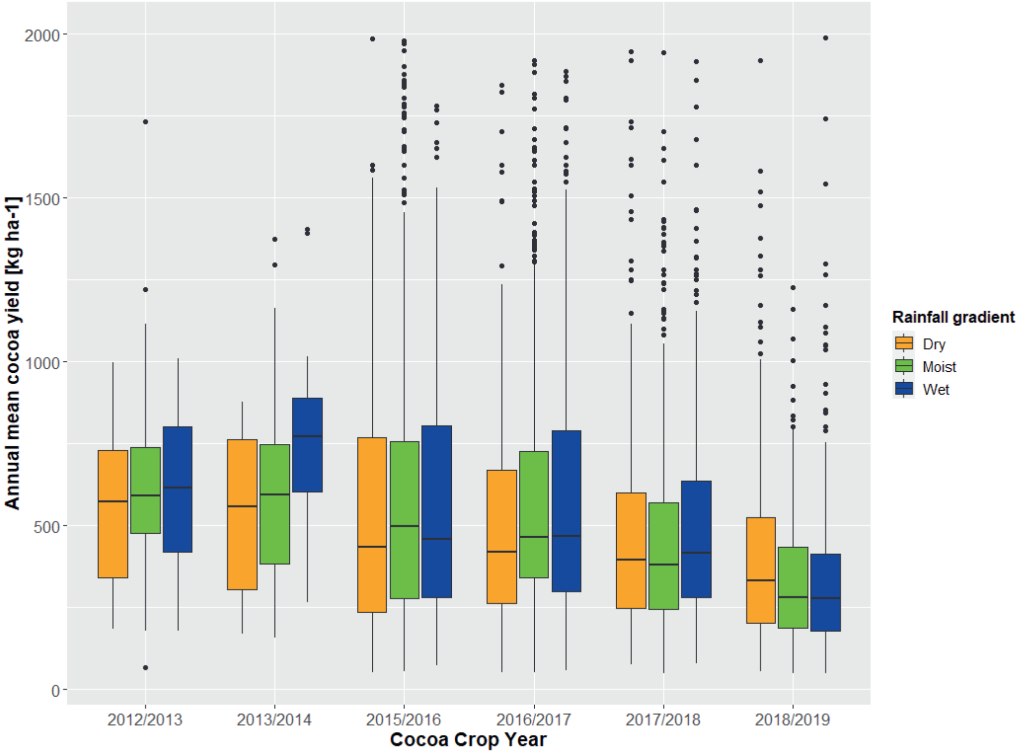

Fig. 2.2. Variation in on-farm cocoa yields in Ghana across a rainfall gradient. Cocoa crop year: March of a given year – February of the next year.

2.3.2. Effects of environmental conditions on on-farm cocoa yield

Effects of environmental conditions on annual cocoa yields were found to be generally weak. The climatic and soil variables (i.e., fixed effects), together explained only 7% (marginal R^2 of 0.07) of the variation in annual mean cocoa yields in Ghana. Whilst the variance explained by the fixed and random (i.e., farm-to-farm variation) effects together was 80% (conditional R^2 of 0.80). Thus, variation in cocoa yield was largely driven by farm-to-farm variation in other variables than those tested as fixed effects, suggesting that effects of management related factors predominated.

Effects of climatic variables were stronger than soil effects (Fig. 2.3A). The main dry season solar radiation had the strongest effect, with a significant, positive effect on annual mean cocoa yield. Minimum temperature of the previous year minor wet season was the next most influential with a significant, positive effect on yield, whilst minor wet-season precipitation, had a significant negative effect. Vapour pressure deficit of the main dry season was included in the final model, but it had no significant effect on yield.

For soil variables, we observed significant, negative effect of clay content on yield whilst the effect of silt content was not significant.

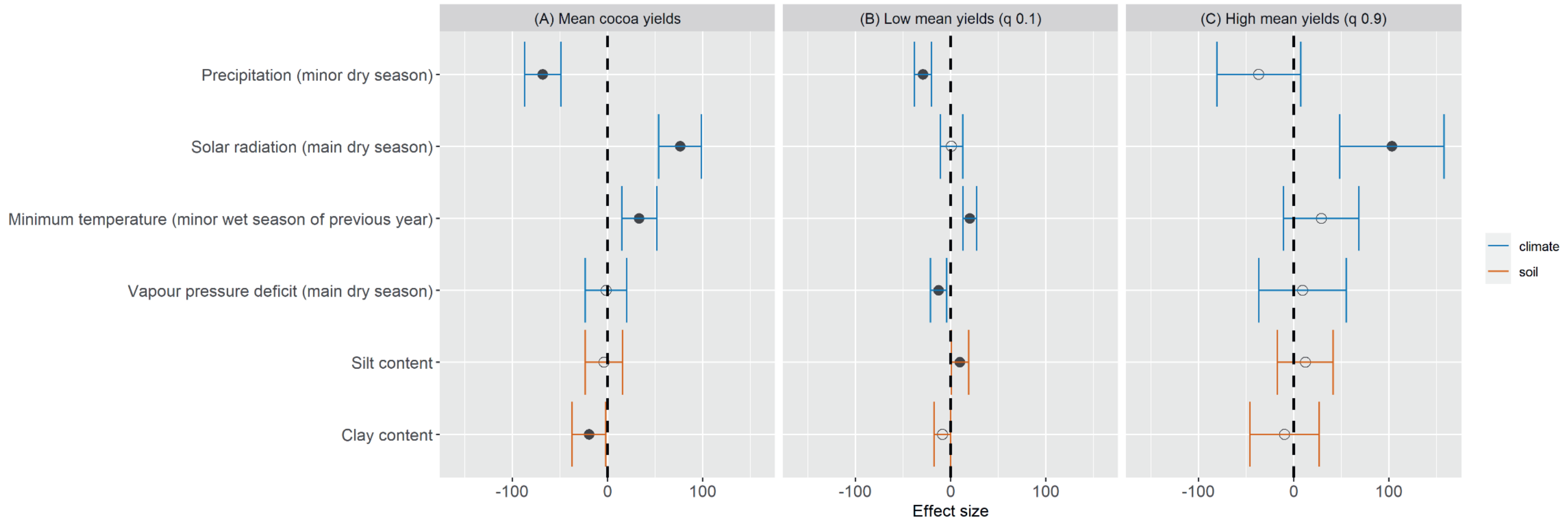

Fig. 2.3. Mixed-effects model results of annual yield as a function of environmental conditions (A) and quantile mixed effect model results of the 0.1 and 0.9 annual yield quantile as a function of environmental variables (B and C). Filled circles indicate significant effects, while open circles indicate non-significant effects. Standardized coefficients with 95% confidence intervals are included.

2.3.3. Effects of environmental conditions on farms with different production levels

The role of environmental conditions in determining cocoa yields varied among farms with different overall mean yields. In most cases, effects of the environmental variables including radiation, minimum temperature, vapour pressure deficit and silt content were stronger for high-yielding (i.e., at the 0.9 yield quantile) farms than for low-yielding (i.e., at the 0.1 yield quantile) farms (Fig. 2.3B, C). This indicates that high-yielding farms could be more sensitive to changes in environmental conditions, particularly climatic ones.

Amongst environmental variables, the effect of dry-season solar radiation was strong, with significant, positive, effect on high yielding farms. However, the effect of all other environmental variables were not significant. On the other hand, for the low-yielding farms, minimum temperature of the minor wet season of the previous year and silt content had significant positive effects on yield, while precipitation of the minor dry season and vapour pressure deficit of main dry-season had significant negative effects.

2.3.4. Effects of management on cocoa yield

The effect of management practices on cocoa yield per tree was stronger than that of environmental conditions based on a subset of 134 (for 2012-2017 crop seasons, 2014/2015 not inclusive) cocoa farms across Ghana for which data on management practices were available. When only environmental variables (Fig. 2.4A) were used as fixed effects for the subset of 134 farms, 10% (marginal R^2 of 0.10) of the variability in cocoa tree yields was explained by environmental conditions and fixed and random effects together explained 55%. By including management (Fig. 2.4B), the fixed effects (i.e., environment and management variables), explained 25% (marginal R^2 of 0.25) of the variation in cocoa yield, and similarly the fixed and random effects together explained 55%. Thus, here a relatively large share of the total explained variance is due to the fixed effects.

In this model, management variables had the strongest effects on yield, followed by climate and then soil (Fig. 2.4). Amongst the management variables, cocoa planting density (Fig. 2.5a) had the strongest influence, with a significant negative effect on cocoa yield per tree. However, when yields per tree were plotted against plant density after log-transforming both variables and using simple regression, the slope was -0.36 and significantly larger than -1, which indicates that cocoa yield per hectare increase with cocoa planting density. Shade tree density (Fig. 2.5b) was the next most influential variable in the mixed-effect model with a significant, but weak, negative effect on yield. For shade tree density, excluding farms with >100 shade trees per hectare resulted in a non-significant effect on yield, though there was still a negative trend.

Amongst environmental variables, solar radiation of the previous dry season (Fig. 2.5c) was the most influential variable with significant positive effects on cocoa yield per tree. Effects of climate water deficit of the minor wet season, minimum temperature of the main dry season, maximum temperature of the previous year main dry season, silt content, clay content, fertilizer use, and farm age were not significant.

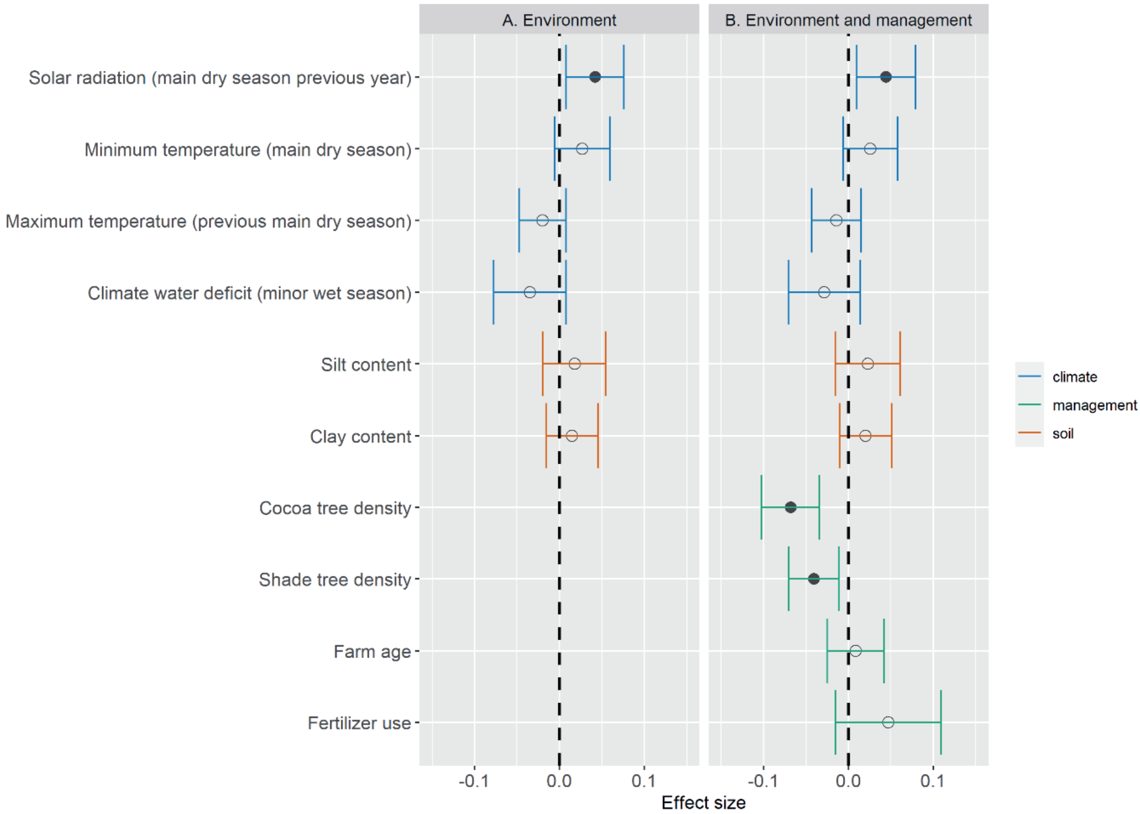

Fig. 2.4. Mixed-effects model results of annual cocoa tree yield as a function of environmental and management conditions. The size of the fertilizer use coefficient is not comparable since it is a categorical variable. Filled circles indicate that the variable is significant, whilst open circles indicate that the variable is not significant. Standardized coefficients with 95% confidence intervals are included.

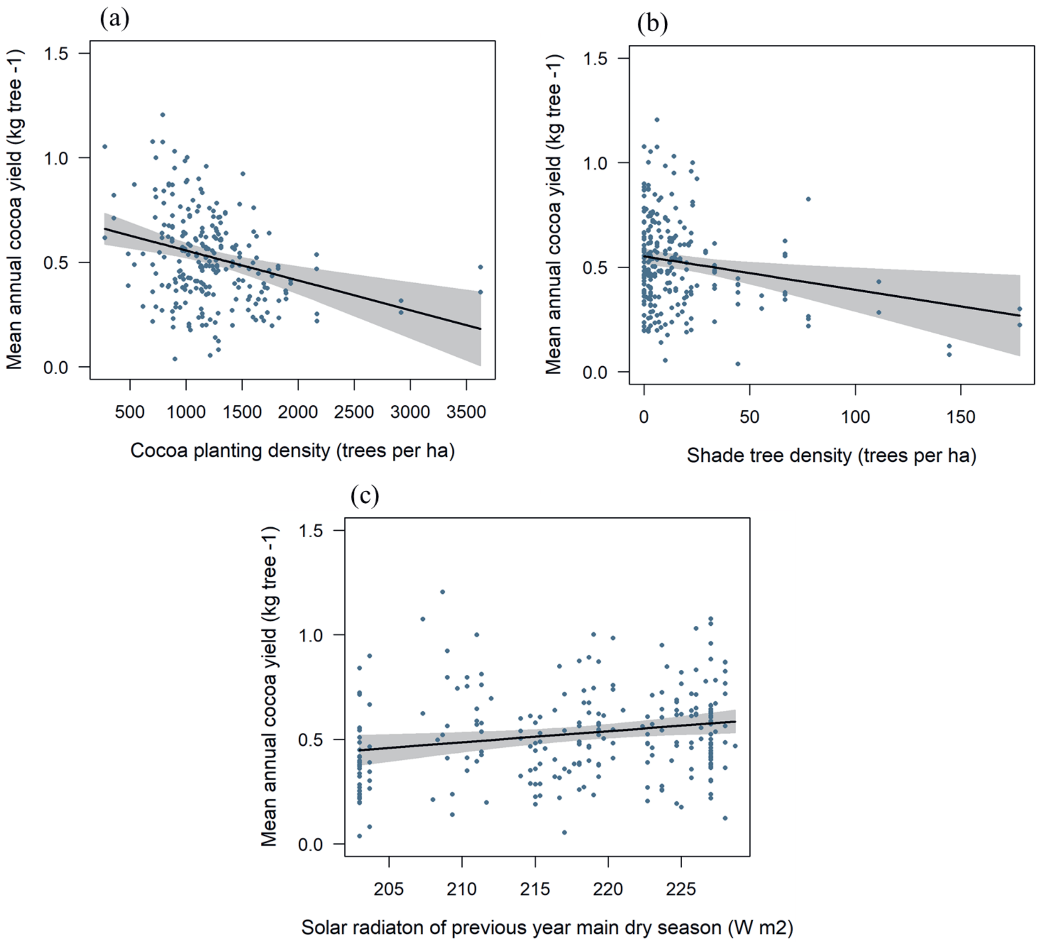

Fig. 2.5. Relationship between annual cocoa yield per tree and (a) cocoa and (b) shade tree density and (c) Solar radiation (previous main dry season), based on subset of 134 farms from 2012-2017. Predictions include the use of fertilizer (use vs. no use), other predictors were kept constant at the mean.

2.4. Discussion

2.4.1. Climate effects on cocoa yields were stronger than soil effects, but variability in management was high.

Generally, our results supported the hypothesis that environmental conditions drive cocoa yields but, surprisingly, the degree to which they influenced yields in Ghana was lower than expected. Environmental variables only explained 7% (Fig. 2.3A) of the variation in yields of the full dataset and 10% (Fig. 2.4A) of the variation in yields of the subset of 134 farms in Ghana, which is a very small portion of the total variance explained when both environment and farm-to-farm variation is considered (i.e.,80% and 55% of the variation in yields for the full dataset and subset of 134 farms respectively). This suggests that management-related factors strongly drive on-farm yields. A huge variability in management has been observed across cocoa growing areas (Daymond et al., 2017; van Vliet & Giller, 2017). The weak effect of environment on cocoa yields found here may explain the relatively small differences in annual mean cocoa yields observed between rainfall zones. On the other hand, the strong yield variation within the rainfall zones may also be due to the huge variability in management. This points to a significant opportunity for many farmers to increase yields through improved management independent of environmental conditions.

The magnitude of climate effects on cocoa yields was larger than soil effects, suggesting that yields are more sensitive to changes in climatic conditions. Radiation in the main dry season of the current and previous year were the most prominent environmental variables that significantly increased yields at the hectare and tree level, respectively. Radiation affects yields mainly through photosynthesis (Baligar et al., 2008; Jaimez et al., 2018; Zuidema et al., 2005). , and previous studies have reported significant increases in photosynthesis rates under high light conditions (i.e., beyond the cocoa light saturation point of ~ 400 μmol m^{-2} s^{-1} to ~ 1000 μmol m^{-2} s^{-1}) when soil water and nutrients are not limiting (Balasimha et al., 1991; Baligar et al., 2008; Jaimez et al., 2018). On the one hand, increases in yields under high light conditions, such as experienced during the dry season, may be due to the increased carbohydrate production resulting from higher assimilation rates (Owusu, 1980). On the other hand, the positive effect of high radiation of the main dry season on yield could also be a consequence of lower humidity levels which reduces incidence of diseases such as black pod (Akrofi et al., 2015; Mpika et al., 2011). More data on pest and disease incidence in relation to spatial and temporal weather variation is thus needed to quantify effects on yields. With a crop growth model it was shown that solar radiation and precipitation together explained 70% of the variation in simulated water-limited potential cocoa yield (Zuidema et al., 2005). The strong positive relationship between cocoa yield and minimum temperature of the minor wet season of previous year at the field level is not fully understood. One possible explanation could be that temperature has significant effects on pod development and final pod size (Daymond & Hadley, 2008). The observed negative relationship between precipitation of the minor dry season and yield may be related to high humidity levels favouring diseases during pod development. The effects of precipitation on pods may be to some extent dependent on the developmental pod stage. Precipitation has been reported to be beneficial at initial stages of pod development possibly because of its effect on assimilation rates, but becomes less positive with maturity, as damp conditions can lead to an increase in disease incidence (Ali, 1969; Bridgland, 1953) which may reduce yields. The observed positive effect of radiation on cocoa yields supports our hypothesis. However, our data do not indicate that precipitation has a positive effect on cocoa yields as we hypothesized. Negative effects of stressful climatic conditions such as high climatic water deficit (CWD) on yield were also not significant. Amongst soil variables, a negative relationship was found between clay content and yields. Clayey soils have a large moisture holding capacity, and contain more nutrients than sandy soils (Feller & Beare, 1997). However, water and nutrient release to plants was found to be slower, and water and nutrients were therefore not readily available for plant use (Wessel, 1971; Wood, 1985). Zuidema et al. (2005) suggested that loamy soils will give best yields especially under sub-optimal rainfall conditions.

2.4.2. Cocoa farms with high yields are more sensitive to changes in environmental conditions than farms with low yields

We found that farms with high yields were more sensitive to environmental conditions than farms with low yields (Fig. 2.3B,C), which suggests low-yielding farms are more nutrient limited (i.e., no or insufficient fertilizer management) and hence less affected by changes in climate (Descheemaeker et al., 2020; Masikati et al., 2019). This illustrates that climate effects become more important when other limiting factors are removed, in this regard, supporting our hypothesis. The dependence of climate effects on overall production levels suggests that there is a need for a diversified climate adaptive strategy that is tailored to the management level of the crop. For instance, on low-yielding farms good agricultural management practices needs to be put in place before investing in additional climate adaptation practices whilst on high-yielding farms, management practices that can facilitate better adaptation of cocoa to the local climatic conditions may be needed.

Amongst the evaluated variables, the strong positive effect of radiation on yields highlights the importance of light availability for increasing yields.. On low-yielding farms, yields were more sensitive to precipitation, minimum temperature, vapour pressure deficit, and silt content. To the best of our knowledge, this is the first study to report such differential effects of environmental conditions on cocoa yields for low- vs high-yielding farms.

2.4.3. Management effects were stronger than climate and soil effects

Based on yield data for a subset of 134 farms over a four-year period, we assessed the relative importance of environmental conditions and management practices (cocoa- and shade-tree density, fertilizer-use, and farm age) on cocoa yield per tree. Without considering management factors, the general results were consistent with the results of the full (3,827 farms) dataset. However, by including the management factors a large part (25%) of the variability in cocoa yield per tree was explained (Fig. 2.4). This indicates the importance of improved management practices to increase yields.

Management practices influenced yield; average tree-level yield decreased with increasing cocoa planting density, however, at the hectare-level yield increased with increasing cocoa planting density. Cocoa planting density has consistently been identified as a significant yield determining factor, and at the plot level increases in cocoa yields with increasing planting densities have been reported (Abdulai et al., 2020; Daymond et al., 2017; Somarriba et al., 2018; Sonwa et al., 2018; Souza et al., 2009). A decreasing average yield per tree with increasing planting densities is likely explained by plant intra-specific competition similar to results reported for coffee (Paulo & Furlani Jr., 2010), or increased disease incidence (Sonwa et al., 2018).

Cocoa yields are significantly reduced with increasing shade tree density supporting our hypothesis, but when farms with more than 100 shade trees per hectare were removed from the analysis, the effect on yield became non-significant. This indicates that the effect of shade tree density is not strong, and that the relationship might be non-linear. A curvilinear relationship is usually found between cocoa yield and shade tree canopy cover (Blaser et al., 2018), however, here we only use shade tree density and therefore cannot make a direct comparison between yield and shade-level. Moreover, the number of shade trees can lead to very different competition effects depending on the shade tree species composition. Shade cover or basal area are better predictors of shading. Our results support the hypothesis that plot level yield increases with cocoa planting density, however, tree level yield decreases.

We found no significant effects of fertilizer use and farm age on cocoa yields, which is agrees with findings reported by Aneani & Ofori-Frimpong (2013). The lack of significant fertilizer effects in our analyses might be due to poor information about quantity and timing of fertilizer application, which is important for determining the effects of fertilizer on yield.. In addition to the management practices we included, other factors such as pest and disease control, and planting material, amongst others, could also have important yield implications. Unfortunately, data on such factors were not available.

2.5. Conclusion

Our results clearly illustrate the enormous yield variability that exists between farms within rainfall zones in Ghana and suggest that there is a significant opportunity for farmers to increase yields through improved agronomic management. The effects of agronomic management, particularly cocoa planting density, on on-farm cocoa yields, are considerably stronger than effects of environmental conditions. Nevertheless, our results also showed that the effects of environmental conditions on on-farm yield became more prominent with increasing yields suggesting that the less cocoa yield is limited by management the more sensitive it is to environmental conditions. Hence, effects of future climate change on cocoa yields may depend on the level of management, which means that sustainable intensification plays a key role in climate adaptive strategies.

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Chapter 3

The cocoa yield gap in Ghana: A quantification and an analysis of factors that could narrow the gap

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Abstract

Global cocoa production is largely concentrated in West Africa where over 70% of cocoa is produced. Here, cocoa farming is largely a rain-fed, low-input system with low average yields, which are expected to decline with climate change. With increasing demand, there is a need to evaluate opportunities to increase production whilst avoiding deforestation and expansion to croplands. Thus, it is important to know how much additional cocoa can be produced on existing farmland, and what factors determine this potential for increased yield. The objective was to quantify the cocoa yield gap in Ghana and identify the factors that can contribute to narrowing the gap. We calculated the cocoa yield gap as the difference between potential yield (i. water-limited potential (Yw) quantified using a crop model, ii. attainable yield in high-input systems(Y_E), iii. attainable yield in low-input systems(Y_F)) and actual farmer yield. Both absolute and relative yield gaps were calculated. We then related each yield gap (absolute & relative) as a function of environment and management variables using mixed-effects models.

There were considerable yield gaps on all cocoa farms. Maximum water-limited yield gaps (YG_W) were very large with a mean absolute gap of 4,577 kg/ha representing 86% of Yw. Attainable yield gap in high-input (YG_E) was lower with mean absolute gap of 1,930 kg/ha representing 73% of Y_E. The yield gap in low-input (YG_F) was even lower with mean absolute gap of 469 kg/ha representing 42% of Y_F. Mixed-effects models showed that, absolute YG_W were larger at sites with higher precipitation in the minor wet and minimum temperature in the minor dry season explaining 22% of the variability in YG_W. These same factors and cocoa planting density explained 28% of variability in absolute YG_E. Regardless of climate, absolute YG_F and relative YG_W, YG_E and YG_F were reduced by increasing cocoa planting density and application of fungicide against black pod. The models explained 25% of the variability in absolute YG_F, and 33%, 33% and 25% in relative YG_W, YG_E and YG_F respectively. In conclusion, climate determined absolute YG_W in Ghana whilst absolute YG_E were determined by both climate and management. In contrast, absolute YG_F and relative YG_W, YG_E and YG_F can be reduced by agronomic management practices. Our study is one of the first to quantify cocoa yield gaps in West Africa and shows that these can be closed by improved agronomic practices.

Keywords: cocoa (Theobroma cacao L.), crop model, water-limited yield, yield gap, cocoa planting density, black pod control.

3.1. Introduction

Global cocoa production is largely concentrated in West Africa where 77.4% (of the total 5,175,000 tons) of cocoa beans are produced on an estimated six million ha of land by nearly two million smallholder farmers (ICCO, 2021; Wessel & Quist-Wessel, 2015). Ghana is the second largest producer after Côte d'Ivoire and globally these two countries supply about 64% of cocoa beans. While these countries lead in total cocoa production, their yield per hectare in smallholder farms – typically 300-600 kg/ha -- is among the lowest in the world (*Chapter 2*, Wessel & Quist-Wessel, 2015). In addition, climate suitability is expected to decrease in response to climate change with potential negative effects on yields (Anim-Kwapong & Frimpong, 2004; Gateau-Rey et al., 2018; Läderach et al., 2013; Schroth et al., 2016). Over the past three decades, increases in production have been driven by a sharp increase in plantation area with only marginal increases in yield (van Vliet & Giller, 2017; Wessel & Quist-Wessel, 2015). Expansion of the land area under cocoa cultivation is driving deforestation as cocoa is grown mainly in regions that used to be covered with highly diverse moist tropical forests (Abu et al., 2021; Ruf et al., 2015). Another challenge is that cocoa is also replacing food croplands, threatening food security in the cocoa growing belt, as exemplified for Ghana (Ajagun et al., 2021). In the coming decades, increased demand for cocoa (growing at approximately 3% per year (Beg et al., 2017)), and the projected potential loss of about 50% of the current cocoa growing area due to decreasing climatic suitability (Läderach et al., 2013; Schroth et al., 2016) could drive producers to new areas, resulting in additional deforestation (Ruf et al., 2015) and food insecurity (Ajagun et al., 2021). To avoid further deforestation and expansion of cocoa fields into other sensitive areas, there is a need to evaluate opportunities to increase yields per unit area on existing lands to meet the growing demand for cocoa. Whilst increasing productivity may not necessarily lead to a reduction in deforestation without supporting governmental policies that contribute to forest protection (e.g., The Cocoa Forest REDD+, The Cocoa & Forests Initiative) and a social safety net that ensures strong farmer livelihood through improved negotiation skills, it can be a necessary step to reduce pressure on areas designated for forests and other land uses.

Yield gap analysis provides a means for evaluating the scope to increase production on existing lands as it can provide information on the factors that limit current yields (van Ittersum et al., 2013). Evaluating available room to increase yield requires robust estimates of potential yield, which is the maximum yield a crop can achieve in a specific environment with no limitation of water and nutrients nor reductions from pests and diseases (van Ittersum et al., 2013). Under rain-fed cropping systems, which is the norm for cocoa farming in West Africa, potential yield is limited by plant available water and therefore, water-limited potential yield (Yw) is a more relevant benchmark.

Dynamic simulation models are commonly used to estimate potential yield, which are developed on the basis of current understanding of ecophysiological crop processes in response to environmental and management factors (Monzon et al., 2021; Rahn et al., 2018; Zuidema et al., 2005). For cocoa, only one such model, namely Sucros-cocoa/Cacao Simulation Engine 2 (CASE2), has been developed and tested for simulating cocoa growth and yield under irrigated and rain-fed conditions (Zuidema et al., 2005).

Another means to estimate potential yield is based on direct measurements from long-term field experiments which utilize crop management practices designed to eliminate all yield-reducing factors (e.g., nutrient deficiencies, incidence of pests and diseases) (Lobell et al., 2009; van Ittersum et al., 2013). Attained yields from experimental trials are expected to come close to model-based potential values, however, it is generally impossible to exclude all yield limiting and reducing factors under field conditions (Aggarwal et al., 2008; Lobell et al., 2009; van Ittersum et al., 2013). Location-specific yield limiting and reducing factors such as year-to-year climate variation can be large for some locations, which means required optimal management practices can vary substantially from one year to another (Aggarwal et al., 2008; Daymond et al., 2020; Lobell et al., 2009). These location-specific yield-reducing factors can lower the experimental yields by up to two-thirds of model-based potential yields (Chapman et al., 2021; Hoffmann et al., 2020). In West Africa, experimental trials are unavailable for most cocoa growing areas. Thus, even though model-based potential yields may probably be an overestimation of what can be achieved in experimental trials, it does provide a reference of what can be obtained theoretically in optimally managed fields (best agronomic practices in place) with no nutrient limitation (fertilized fields) and no incidence of pests and diseases. In Ghana, a few studies have reported experimentally-based potential yields including 1,891.3 kg/ha (Ofori-Frimpong et al., 2006 in Aneani & Ofori-Frimpong, 2013), 3,500 kg/ha (Ahenkorah et al. 1974), 2000 kg/ha (Ahenkorah et al. 1987) and 3,245.97 kg/ha (Appiah et al. 2000), but the estimated national-level experimental-based cocoa yield gap was obtained using only one experimental yield (1,891.3 kg/ha) benchmark obtained from one location (Aneani & Ofori-Frimpong, 2013).

The use of maximum farmer yields based on surveys represents another way to estimate potential yield. This is most suitable in intensively managed cropping systems where it is reasonable to assume that at least some farmers apply management practices capable of approaching the potential yield (Lobell et al., 2009). In Ghana, two studies have quantified and explained yield gaps for cocoa using maximum farmer yields as benchmark (Abdulai et al., 2020; Aneani & Ofori-Frimpong, 2013). However, considering that cocoa cropping systems in West Africa are largely low-input, it is likely that even maximum farmer yields are well below the potential under rainfed conditions and using them as benchmark would not allow to assess the potential yield gain that could be achieved under high input.. Also, from a previous study it appears that actual cocoa yields in Ghana are not very sensitive to climate as they are strongly limited by low level of agronomic management, yet strong climatic influence is expected with good agronomic management (*Chapter 2*). Hence, we believe that using both model-based and maximum farmer yield-based benchmarks will give a comprehensive indication of the potential yield gains that could be achieved at the different levels of intensification. To our knowledge this has not previously be done for cocoa.

The difference between the benchmark (i.e., either model-simulated, experimental attained or based on farmer maximum) and actual farmer yields (Ya), which is the yield achieved in a farmer's field is the absolute yield gap, a measure which provides relevant information on the scope for production increase in kg per ha (Lobell et al., 2009; van Ittersum et al., 2013). Defining this in relative terms (relative yield gap), which expresses the absolute yield gap as a percent of the potential yield calculated as; $Yg_{rel} = \frac{benchmark - actual}{benchmark} * 100\%$, has the methodological advantage of allowing comparison of the absolute yield gaps between different locations and with different crops (Oort et al., 2017). Also, in the case of the model-simulated benchmark normalization of the absolute yield gap reduces the dominant effect of Yw on yield gap when this is mainly driven by variation in Yw.

The objective of this study was to quantify the cocoa yield gap for Ghana and to identify the factors that contribute to narrowing the gap. We provide three different yield gap estimates: (1) a yield gap estimate where we obtain Yw as upper limit that can be achieved on existing land in a rain-fed system using the crop simulation model Sucros Cocoa/CASE2 (Zuidema et al., 2005) and field-level Ya data obtained on farmer fields (maximum water-limited yield gap; YG_W), (2) a yield gap estimate based on attainable yield from experimental trials and Ya (attainable yield gap in high-input systems; YG_E) and (3) a yield gap estimate based on maximum farmer yield and Ya (attainable yield gap in low-input systems; YG_F). YG_W, YG_E and YG_F were calculated in both absolute and relative terms for 93 (84 in the case of YG_F) cocoa farms spanning the cocoa growing belt of Ghana. We then analysed the association of yield gaps (absolute and relative) with variation in a set of environmental conditions (climate, soil) and agronomic management factors. This is important for identifying potential causes of yield gaps and opportunities and entry points for sustainable intensification. We addressed the following questions: (1) What are the current cocoa yield gaps on farms across cocoa growing areas of Ghana? (2) To what extent and how do environmental and management factors explain these yield gaps?

We expect that variation in absolute yield gaps will be mostly driven by climatic factors as potential yields tend to be very sensitive to climate (Zuidema et al., 2005). Absolute yield gaps are expected to become smaller in drier areas as Yw and attainable yields will be lower due to negative impacts of low water availability and high temperature. The climate effect on absolute yield gaps will be smaller for YG_F than for the others because low-input attainable yield is expected to be less climate-sensitive than high-input attainable yield and Yw yields. On the other hand, relative yields gaps are expected to be driven more by management factors as effects of variation in potential/attainable yields on yield gaps is normalized and variation in actual farm-based yields in Ghana was shown to be driven more by management than by climate or soil factors (*Chapter 2*). We expect agronomic management practices like pest and disease control, cocoa planting density, and fertilizer use to reduce relative yield gaps whilst high shade levels, tree age and farm size are expected to increase relative yield gaps.

3.2. Materials & Method

3.2.1. Study Area

The study was conducted at 93 different cocoa farm locations spanning the cocoa growing areas of Ghana, to represent the range of environmental conditions and production systems in the cocoa belt (Fig. 3.1). Cocoa is grown in southern Ghana within three agroecological zones; i.e., evergreen rainforest, deciduous forest and forest/savanna transition zones. The pattern of rainfall distribution within this region is bimodal, with two wet (main wet season from April to June/July, and minor wet season from September to November) and two dry seasons (main dry season from December to February/March and a short dry period from July/August during which relative humidity is still high). Mean rainfall is highest in the south-west and decreases gradually towards the North (Fig. 3.1). Temperature is less variable across the cocoa belt with mean monthly values of about 25°C and a diurnal range of 5–9 °C. The dominant soil types within the region are the strongly weathered Acrisols (Ochrosols - Ghana Great Soils Group) found in the deciduous forest and parts of the forest/savanna transition agro-ecological zones and the highly leached, strongly weathered Ferrasols (Oxysols - Ghana Great Soils Group) with low soil pH (strong acidity) occurring in areas with high rainfall such as in the south west (Adjei–Gyapong & Asiamah, 2002; Appiah et al., 1997). The high acidity, and low amounts of nutrients make Ferralsols unfavourable for cocoa growth (Appiah et al., 1997).

3.2.2. Quantifying the water-limited potential cocoa yield

Simulation of water-limited potential cocoa yield was done using the CASE2 model (Zuidema et al., 2005). This is a dynamic crop simulation model for cocoa that simulates all major processes of crop growth and production, including light interception, photosynthesis, maintenance respiration, evapotranspiration, biomass production and associated growth respiration and biomass allocation. Resulting bean yield of cocoa trees can be simulated for conditions with or without shade from associated trees and with or without water-limitation. CASE2 is originally implemented in FORTRAN using the Fortran Simulation Environment (FSE) (van Kraalingen & Kraalingen, 1995) which makes it difficult to automate simulations for different inputs. To address this, RCASE2, a wrapper around CASE2 has been developed by Wageningen University and Research, which allows CASE2 to be run with R statistical software (R Core Team, 2018).

CASE2 has been parameterised based on existing information of cocoa physiology and morphology with values obtained from literature (Zuidema et al., 2003). It uses information on weather, soil and cropping system as inputs for growth and yield simulations at a daily time step. For weather, the CASE2 model requires input data on daily minimum and maximum temperature, precipitation, solar radiation, and early morning vapour pressure for at least an eight year period (Zuidema et al., 2005). Assumed climatic limitations for growth and yield in CASE2 include: average temperature between 10 to 40 °C and an annual precipitation of at least 1250 mm. Soil data required in CASE2 includes information on thickness; number and depth of soil layers, the sum of which should add up to 1.5 m, and soil physical characteristics including, the water content at saturation, field capacity, wilting point and for air-dried soil with standard values defined based on the Driessen soil types (Driessen, 1986).With regard to data on cropping systems, CASE2 requires information on cocoa tree age, planting density and shade levels. Simulations can be carried out for cocoa trees (assuming planting material is uniform) between the age of 3 to 40 years (i.e., 18.5 – 70 kg dry weight per plant; CASE2 does not include the juvenile phase), with planting density ranging from 700-2500 trees/ha. Horizontally homogeneous shading is assumed and the shade level is calculated as a function of shade tree leaf area index (SLAI) and light extinction coefficient (k) which varies between 0.4 to 0.8 (Zuidema et al., 2005). Simulations can be carried out for shade levels between 0 to 3 SLAI (i.e., with 0 representing no shading to 3 representing heavy shading). Here, we calculated the relative light intensity reaching the cocoa canopy using the modified Lambert-Beer equation (Monsi & Saeki, 2005); $PARb/PARi = e^{\wedge}(-k * SLAI)$, where $PARb$ refers to the Photosynthetically Active Radiation below the shade tree canopy (but above the cocoa tree canopy), and $PARi$ the incident Photosynthetically Active Radiation above the shade tree canopy (i.e., unobstructed day light) and k is the light extinction coefficient. $PARb$ values were measured with hemispherical photographs in cocoa farms from which yield data was obtained (Daymond et al., 2017). The value of k was taken as 0.6, the standard setting in CASE2 (Zuidema et al., 2005). Although validating the CASE2 model is difficult due to limited availability of yield data that approach potential or water-limited yield, a validation study comparing model output with available cocoa plantation outputs from locations where empirical data (regularly reported values) was available, showed that the model produces realistic outputs for bean yield, standing biomass, leaf area and size-age relations (Zuidema et al., 2005). Yield estimates from the model were not far off estimates of experimental yields in some countries and the represented processes represent our current understanding of cocoa growth and yield formation (Zuidema et al., 2005).

In simulations of Yw, the model assumes non-limited nutrient supply while yield losses caused by pests and diseases are considered absent. Most climate variation (e.g. temperature, radiation and precipitation) is considered with the exception of flooding. Simulations of Yw were carried out for a period of 8 years (from 2007 to 2014), using weather, soil and cropping system information observed at 93 cocoa farm locations within the cocoa growing areas of Ghana. Simulations were carried out for cocoa trees with initial average tree age of 14 years (based on the average, observed cocoa tree age), a planting density of 1246 trees per hectare (based on the average observed across the cocoa farms) and under a shade tree canopy of 10% (based on average SLAI calculated for the cocoa farms). Fixing these factors in our calculation of Yw allows us to compare how yield gap affecting factors vary across farms.

3.2.3. Weather and soil data

Daily minimum and maximum temperature (ºC), precipitation (mm), and solar radiation (MJ m^{-2} d^{-1}) at a spatial resolution of 0.1° (approximately 11 km) for the period of 2007 to 2014 were obtained from the Copernicus AgERA5 database (Boogaard & Grijn, 2020). Early morning vapour pressure was estimated following the calculation procedure by FAO (Allen et al., 1998). In the FAO procedure, actual vapour pressure per day was estimated from relative humidity and air temperature using the following equation, $e_a = \frac{RH_{mean}}{100}[\frac{e^0(T_{max})+e^0(T_{min})}{2}]$ where ea is the actual vapour pressure [kPa], and RHmean is the mean relative humidity, whilst e°(Tmin) and e°(Tmax) is the saturation vapour pressure at daily minimum temperature [kPa] and at daily maximum temperature [kPa], respectively. This saturation vapour pressure at minimum and maximum air temperature is calculated as, $e^0(T) = 0.6108exp[\frac{17.27\,T}{T+237.3}]$ where T is the minimum or maximum temperature (ºC), respectively. We included the saturated vapor pressure derived from minimum temperature e°(Tmin) as early morning vapour pressure values, as the lowest temperature is registered in the early morning and e°(Tmin) is often lower than actual vapour pressure (e_a) but when relative humidity is below ~70%, e_a is lower than e°(Tmin).

Soil texture data, classified based on the USDA system at six standard depths (0-5, 5-15, 15-30, 30-60, 60-100 & 100-200 cm) at a spatial resolution of 250m were obtained from the ISRIC database (Hengl et al., 2017). Since the sum of the depth of all soil layers (thickness) should not exceed 1.5 m, we took the mean of the 100-200cm standard depth layer in addition to the first five layers of the soil data from ISRIC. For information on physical characteristics (i.e., standard values of soil water content at saturation, field capacity, wilting point and for air-dried soil), we compared the soil texture classification of the soil classes of the USDA system to the soil texture properties of the Driessen soil types, to be able to include the soil type in the simulations with CASE2 (Table 3.S1, Driessen, 1986; Zuidema et al., 2003).

3.2.4. Actual cocoa yield

Actual cocoa yield data from farmer fields with information on management (cocoa planting density, cocoa tree age, radiation interception by shade trees, fungicide application against black pod (*Phytophthora palmivora and megakarya*), insecticide application against capsid (*Sahlbergella singularis and Distanfiella theobroma*) and fertilizer use) and soil (field measured pH, carbon (%), nitrogen (%), available phosphorus (µg/g), potassium (meq/100g), and magnesium (meq/100g)) for 93 farms with georeferenced locations across the cocoa belt of Ghana were obtained from Mondelez International 'Mapping Cocoa Productivity' project data (Daymond et al., 2017). Yield data was available for a period of two years (2012/2013 and 2013/2014 cocoa cropping season). We defined cocoa yield as the amount of dried beans (pod to kilogram conversion based on field measured mean pod value of 24.2 (±3.6) to 1 kg) harvested per year (cocoa crop year is defined as March of a given year – February of the next year), per unit of cocoa plantation area (ha). Production data was collected using pod counts and field size determined using GPS measurements.

3.2.5 Yield gap definition and statistical analysis

With reference to Table 3.1, we defined the absolute yield gap for YG_W, YG_E, YG_F as the difference between Yw (YG_W) or attainable yield in high-input (YG_E) or attainable yield in low-input systems (YG_F) and actual farmers' yield (Ya). Hence the absolute yield gap is given as:

$$YG_{abs} = Ybench - Ya \qquad (1)$$

where Y_{bench} is the benchmark yield: the water-limited potential yield (Yw), the high-input attainable yield (Y_E) or the low-input attainable yield (Y_F) in the cases of YG_W, YG_E and YG_F, respectively. The relative yield gap (for YG_W, YG_E, YG_F) was calculated as a percentage of the benchmark yield using the following equation

$$YG_{rel} = \frac{Ybench - Ya}{Ybench} * 100\% \qquad (2)$$

These yield gaps (eq. 1 and 2) were calculated for every farm in our sample. The attainable yield in high-input systems was defined as 50% of Yw based on the average of the maximum experimental potential yields (2500 kg/ha) from four experimental trial studies in Ghana

(Ahenkorah, et al., 1987; Ahenkorah et al., 1974; Aneani & Ofori-Frimpong, 2013; Appiah, Ofori-Frimpong, & Afrifa, 2000). On the other hand, attainable yield in low-input systems was defined as the average yield from the 10% best performing farmers across the 93 cocoa farms. Thus, the YG_F was calculated for only the 90% lowest performing farmers (84 cocoa farms).

We examined the drivers of the absolute and relative yield gaps for YG_W, YG_E, and YG_F by modelling the absolute (or relative) yield gap as a function of climate, soil and management variables using mixed-effects models (MEMs) (Zuur et al., 2009). For management, we considered farm size, fertilizer use, application of fungicide against black pod, application of insecticide against capsid, cocoa planting density, tree age and radiation interception by shade trees. As soil variables, we considered measured soil properties including soil pH, carbon, nitrogen, available phosphorus, potassium and magnesium. For climate, we considered seasonal variables (i.e. all four seasons; the main wet season (March–June), the minor dry season (July–August), the minor wet season (September–November), and the main dry season (December–February)). Thus, daily weather data was aggregated to seasonal climate variables. We performed MEM between the absolute (or relative) yield gap and the seasons of each climate variable separately. This was done to select the season for which the climate variables most strongly influenced the yield gap. We included for each climate variable the season that was included in the best model (i.e., lowest Bayesian Information Criterion; BIC) (Table 3.2). We excluded solar radiation as an explanatory variable for YG_F as MEM between the seasons (of solar radiation) and YG_F did not converge.

To obtain the most parsimonious MEM that explains most of the variation in the absolute or relative yield gap, we used a two-step approach; correlation analyses and stepwise regression. We first conducted correlation analyses for all explanatory variables (which included all selected climate, soil and management variables) to identify and remove one variable out of variable pairs that were strongly correlated (i.e., having $r > 0.7$) in order to avoid collinearity. Based on this procedure, none of the variables was excluded from the list of explanatory variables for the absolute yield gap and for the relative yield gap of YG_W, YG_E and YG_F as we found no case of explanatory variables having $r > 0.7$ (Fig. 3.S3, S4 and S5). Next, we included all explanatory variables after the correlation analyses (Table 3.2) in the MEM as fixed effects and farm ID as random intercept to account for non-independence of data points (more than one year yield data) from the same farm. We tested including year as random intercept but this did not improve the model, hence only farm ID was used as random intercept. To allow comparison of the relative importance of explanatory variables, we standardized all continuous variables by subtracting the mean value of the variable and dividing it by the standard deviation (Maldonado, 2012). A backward stepwise elimination of MEM models was conducted using the "buildglmmTMB" function from R package "buildmer" to identify the most parsimonious model. The final model was selected based on BIC. Conditional and marginal R^2 for the models were estimated to evaluate variation explained by only the fixed effects (i.e. the explanatory variables) and both the fixed effects and random effects, respectively (Nakagawa & Schielzeth, 2010). All analyses were performed in R (R Core Team, 2018).

Table 3.1. Definitions and descriptive statistics for yield gap estimates

Abbreviation	**Variable**	**Unit**	**Definition**	**Mean (std. dev.)**
Ya	Actual yield	kg/ha	Yield achieved in a farmer's field	717 (343.7)
Yw	Simulated water-limited potential yield	kg/ha	Theoretical maximum yield limited by water, temperature and light as simulated with a crop model	5,294 (553.7)
Y_E	Attainable yield in high-input systems	kg/ha	50% of Yw, determined based on reported average yields from experimental trials in Ghana	2,647 (276.8)
Y_F	Attainable yield in low-input systems	kg/ha	Average yield from the 10% best performing farmers across the 93 cocoa farms	1,109
Absolute YG_W	Absolute maximum water-limited yield gap	kg/ha	Difference between Yw and Ya expressed in kg/ha	4, 577 (641.7)
Relative YG_W	Relative maximum water-limited yield gap	%	The maximum water-limited absolute yield gap as a percentage of Yw	86(6.8)
Absolute YG_E	Absolute attainable yield gap in high-input systems	kg/ha	Difference between attainable yield in high-input systems and Ya expressed in kg/ha	1,930 (433.9)

Relative YG_E	Relative attainable yield gap in high-input systems	%	The Ya as a percentage of attainable yield in high-input systems.	73 (13.5)
Absolute YG_F	Absolute attainable yield gap in low-input systems*	kg/ha	Difference between attainable yield in low-input systems and Ya expressed in kg/ha	469 (248.9)
Relative YG_F	Relative attainable yield gaps in low-input systems*	%	The Ya as a percentage of attainable yield in low-input	42 (22.4)

* Yield gap was calculated for only the 90% lowest performing farmers (84 cocoa farms)

Table 3.2. Descriptive statistics of selected climate, soil and management (explanatory) variables based on model selection using the Bayesian Information Criterion and correlation analyses for each of the dependent variables in the first step of the analysis.

Explanatory variables	Unit	min	max	mean	std.dev	Dependent variables
Climate variables						
Precipitation (minor wet season)	mm	189	476	287	71	All yield gaps
Solar radiation (minor dry season)	MJ	12,756	14,899	13,481	509.8	All yield gaps
Maximum temperature (main wet season)	◦C	28.5	30.6	29.8	0.4	Absolute YG_W
Maximum temperature (minor wet season)	◦C	28.0	29.6	28.8	0.3	Relative YG_W, Absolute YG_E, & Relative YG_E
Maximum temperature (minor dry season)	◦C	26.8	28.4	27.6	0.3	Absolute YG_F, & Relative YG_F

Minimum temperature (minor dry season)	◦C	20.8	22.1	21.6	0.2	All yield gaps
Management variables						
Cocoa planting density	trees ha	276	3626	1221	531	All yield gaps
Radiation interception by shade trees	%	0	0.31	0.07	0.08	All yield gaps)
Tree age	years	6	57	22.2	11.0	All yield gaps
Farm size	hectares	0.26	7.7	1.7	1.4	All yield gaps
Application of insecticides against capsid	yes/no					All yield gaps
Application of fungicides against Black pod	yes/no					All yield gaps
Fertilizer use	yes/no					All yield gaps
Soil variables						
soil pH	-	4.3	7.5	5.8	0.7	All yield gaps
Soil carbon content (C)	%	0.7	2.8	1.5	0.4	All yield gaps
Soil nitrogen (N)	%	0.07	0.28	0.1	0.0	All yield gaps
Available Phosphorus in soil (P)	µg/g	3.7	58.6	17.6	12.1	All yield gaps
Soil potassium content (K)	meq/100g	0.2	0.8	0.4	0.1	All yield gaps
Soil magnesium content (Mg)	meq/100g	0.01	5.8	1.5	1.1	All yield gaps

The selected variables were subsequently included in the mixed-effects models for relative (or absolute) YG_W, YG_E, YG_F (dependent variables) in the second step of the analysis, to select the final best model.

3.3. Results

3.3.1. Magnitude of actual yield (Ya), water-limited yield (Yw), and the yield gap for cocoa farms in Ghana

The Ya across the 93 cocoa farms of the 2012/2013 and 2013/2014 cropping seasons was generally low with a mean of 717 kg/ha. Ya for some farms was as low as 78 kg/ha whilst other farms achieved yields as high as 2,331 kg/ha depending on the year. Relatively small differences in Ya were observed between wet and dry areas within the study area (Fig. 3.1(b)). Yw values, on the other hand, were generally high with a mean of 5,294 kg/ha. Average maximum Yw yields of 6,567 kg/ha and average minimum of 4,178 kg/ha were observed across farms and cropping seasons. Lowest Yw were observed in dry areas and highest Yw in wet areas (Fig. 3.1(a)). Across all cocoa farms, Ya was lower than Yw (Fig. 3.1).

The resulting estimated YG_W was accordingly very large with a mean absolute yield gap of 4,577 kg/ha, representing a relative yield gap of 86% (Fig. 3.2.). Across farms, absolute YG_W ranged between 2,223 kg/ha and 6,072 kg/ha which represents a range of 49-98% for relative YG_W over the two-year period. Absolute YG_W was largely driven by Yw. The spatial pattern of the distribution of absolute YG_W across the study area was similar to Yw, with larger absolute YG_W observed in wet areas and low absolute YG_W in dry areas (Fig. 3.S1(a)). Yet, relatively small differences in relative YG_W were observed across dry and wet areas (Fig. 3.S1(b)).

The YG_E, was obviously lower than YG_W with mean absolute YG_E of 1,930 kg/ha (representing 73% of the relative yield gap). For some farms, YG_E was negative, -53.9kg/ha (i.e. relative yield gap of -2%) , thus achieved yields were beyond the reference attainable yield, whilst others had YG_E as high as 2,873 kg/ha (i.e., relative yield gap of 97%) (Fig. 3.2). The YG_F was generally lower with mean absolute YG_F of 469 kg/ha which represents 42% of the relative yield gap. Across farms, YG_F ranged from 4kg/ha (relative yield gap of 0.3%) to 1,031 kg/ha (relative yield gap of 93%) (Fig. 3. 2). Similarly to actual yields, relatively small differences in both absolute and relative YG_F were observed between wet and dry areas within the study area (Fig. 3.S2).

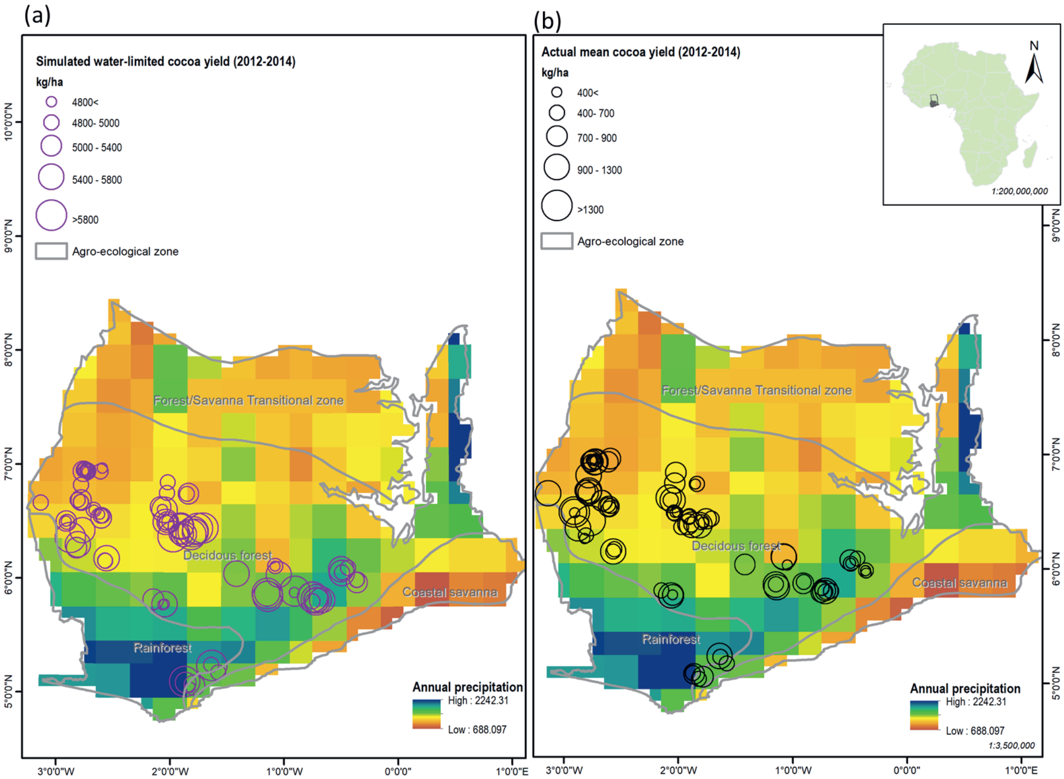

Fig. 3.1. (a)Simulated cocoa water-limited yields (Yw, circles) and b) actual mean cocoa yield (Ya, circles) for 93 farm locations and annual precipitation (background colour) in southern Ghana. Rainfall and cocoa yields are averages of the 2012/2013 and 2013/2014 cocoa crop years on a 11-km resolution. The size of the circle is proportional to the average Yw and Ya for that location.

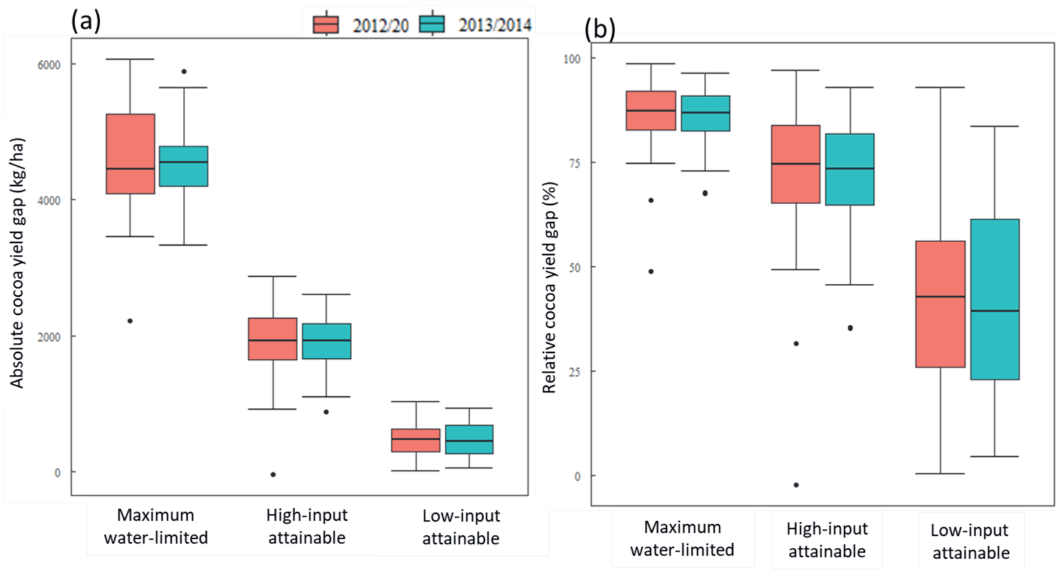

Fig. 3.2. Variation in (a) the absolute yield gap (difference between potential and actual yield) for maximum water-limited (YG_W), high-input attainable (YG_E) and low-input attainable (YG_F) yield, and (b) the relative values for YG_W, YG_E and YG_F, across 93 (84 in the case of YG_F) cocoa farms in Ghana for the 2012/2013 and 2013/2014 cocoa crop years. Yield refers to dry bean yield and cocoa crop year is March of a given year to February of the next year of 2012/2013 and 2013/2014, respectively.

3.3.2. Determining factors of the absolute cocoa yield gap

Results of initial correlation analyses between the absolute YG_W, YG_E and YG_F and explanatory variables showed that absolute YG_W was significantly and positively correlated with precipitation of the minor wet season, solar radiation of the minor dry season, minimum temperature of the minor dry season and radiation interception by shade trees (Fig. 3.S3). Significant negative correlations with absolute YG_W were found for soil magnesium content (Mg), soil pH and available phosphorus (P) (Table 3.2, Fig. 3.S3). Absolute YG_E was also significantly and positively correlated with precipitation of the minor wet season and minimum temperature of the minor dry season (Fig. 3.S4). Significant negative correlations with absolute YG_E were found for cocoa planting density, soil pH, P, and Mg. On the other hand, correlations between absolute YG_F and explanatory variables differed from YG_W and YG_E.. In this case only cocoa planting density showed a significant negative correlation with absolute YG_F (Spearman's rank correlation (*r)* of 0.47) (Fig. 3.S5).

The mixed-effects models indicated that the absolute YG_W was driven by only climatic factors, with precipitation of the minor wet season (Fig. 3.3a) having the strongest influence followed by minimum temperature of the minor dry season (Fig. 3.3b). Precipitation of the minor wet season and minimum temperature of the minor dry season showed a relatively strong positive correlation (r of 0.44 and 0.34 respectively) with absolute YG_W (Fig. 3.S3), and significantly increased this gap (Table 3.3(i)). These two factors (fixed effects) explained 22% (marginal R^2 of 0.22) of the variation in the absolute YG_W and 70% when random effects (farm-to-farm variation) were included (conditional $R^2 = 0.70$). Thus, variation in the absolute YG_W was largely driven by other variables than those tested as fixed effects. Absolute YG_E on the other hand, was driven by both climatic and management variables. Amongst climatic factors, precipitation of the minor wet season (Fig. 3.S7a) and minimum temperature of the minor dry season Fig. 3.S7b) significantly increased this gap (Table 3.3(iii). Amongst management factors, only cocoa planting density (Fig. 3.S7c) was influential and significantly reduced the absolute YG_E. The fixed effects of the final model for YG_E explained 28% (marginal R^2 of 0.28) of the variation whilst 66% of the variation in absolute YG_E is explained when including random effects (conditional $R^2 = 0.66$) (Table 3.3(iii)).

The final mixed-effects model for absolute YG_F revealed that only management variables explained absolute YG_F. Cocoa planting density (Fig. 3.S8a), which showed a significant correlation with absolute YG_F, and application of fungicides for controlling black pod disease (Fig. 3.S8b) were the most important variables (Table 3.3(v)). These two factors (fixed effects) explained 25% (marginal R^2 of 0.25) of the variation in absolute YG_F whilst 61% (conditional R^2 of 0.61) of the variation was explained by fixed and random effects together.

Table 3.3. Results of the mixed-effects models for the YG_W, YG_E, YG_F absolute yield gap and relative yield gaps as a function of environmental and management factors. Only variables retained in the final model are shown. Significance levels are indicated (* $p<0.05$ ** $p<0.01$ *** $p<0.001$).

	Estimates	***std. Error***	***Confidence Interval***	***Marginal R2 / Conditional R2***
(i) Absolute YG_W predictors				*0.22 / 0.70*
Precipitation (minor wet season)	219.81 ***	48.26	124.49– 315.14	
Minimum temperature (minor dry season)	168.95 ***	46.68	76.75 – 261.14	
(ii) Relative YG_W predictors				0.33 / 0.65
Cocoa planting density	-2.89 ***	0.48	-3.84 – -1.94	
Application of fungicide against black pod (yes)	-3.38 **	1.16	-5.67 – -1.10	
(iii) Absolute YG_E predictors				*0.28 / 0.66*
Precipitation (minor wet season)	119.47 ***	31.07	58.10 – 180.84	
Minimum temperature (minor dry season)	93.05 **	30.24	33.32 – 152.77	
Cocoa planting density	-126.45 ***	33.74	-193.10– -59.81	
(iv) Relative YG_E predictors				*0.33 / 0.65*
Cocoa planting density	-5.79 ***	0.96	-7.69 – -3.88	
Application of fungicide against black pod (yes)	-6.76 **	2.31	-11.33 – -2.19	
(v) Absolute YG_F predictors				*0.25 / 0.61*
Cocoa planting density	-94.95 ***	22.24	-138.91– -50.98	
Application of fungicide against black pod (yes)	-160.19 **	52.09	-263.18– -57.21	

				0.25 / 0.61
(vi) Relative YG_F predictors				
Cocoa planting density	-8.56 ***	2	-12.52 – -4.60	
Application of fungicide against black pod (yes)	-14.44 **	4.7	-23.72 – -5.16	

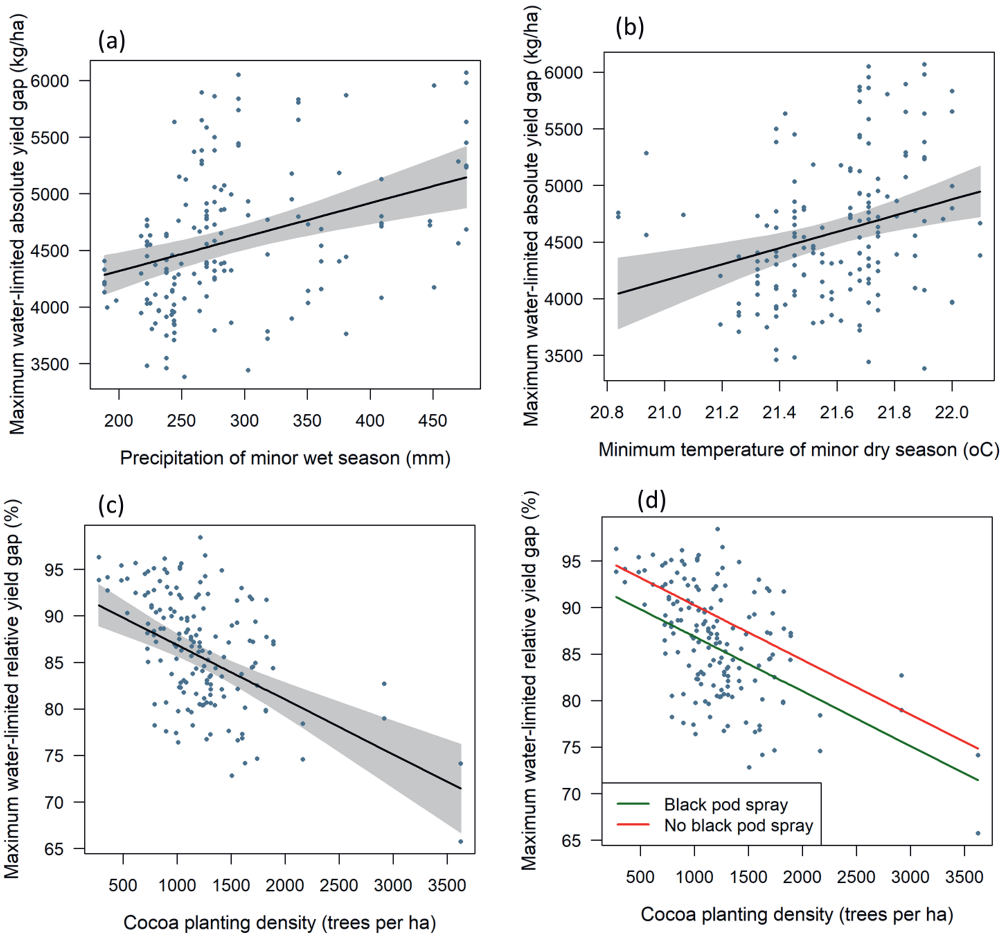

Fig.3.3. Relationship between absolute YG_W and (a) precipitation of minor wet season and (b) minimum temperature of minor dry season and between YG_W relative yield gap and (c) cocoa planting density and (d) application of fungicide against black pod (use *vs.* no use) based on 93 cocoa farms from 2012 to 2014. Lines are predicted relations from the mixed-effects model, other predictors were kept constant at mean values.

3.3.3. Determining factors of the relative cocoa yield gap

The drivers of the relative YG_W and YG_E differed from the drivers of the absolute YG_W and YG_E but drivers of absolute and relative YG_F were the same. Results of initial correlation analysis between relative YG_W, YG_E and YG_F and explanatory variables showed that only cocoa planting density had a significant negative correlation (i.e., *r* of 0.54, 0.54, 0.47 for relative YG_W, YG_E and YG_F respectively) with relative YG_W, YG_E and YG_F (Fig. 3.S3, Fig. 3.S4, Fig. 3.S5).

The final mixed-effects model for relative YG_W, YG_E and YG_F all revealed that management variables primarily drove relative YG_W, YG_E and YG_F. Cocoa planting density (Fig. 3.3c, Fig. 3.S7d, Fig. 3.S8c), which was strongly correlated with the relative YG_W, YG_E and YG_F and application of fungicides for controlling black pod disease (Fig. 3.3d, Fig. 3.S7e, S8d) were the most important variables which significantly reduced the relative YG_W , YG_E and YG_F (Table 3.3(ii, iv, vi)). These two factors (fixed effects) explained 33% (marginal R^2 of 0.33) of the variation in relative YG_W whilst 65% (conditional R^2 of 0.65) of the variation was explained by fixed and random effects together. Similarly, the two factors explained 33% (marginal R^2 of 0.33) of the variation in relative YG_E and 65% (conditional R^2 of 0.65) when including random effects. For relative YG_F 25% (marginal R^2 of 0.25) of the variation was explained by the two factors and 61% (conditional R^2 of 0.61) when including random effects.

3.4. Discussion

3.4.1. Magnitude of the cocoa yield gap in Ghana

The YG_W of the 93 farms in Ghana was very large. Actual cocoa yields per annum ranged between 78 to 2,331 kg/ha (mean=717 kg/ha) and were considerably lower than simulated water-limited yields (range between 4,178 to 6,567 kg/ha with mean = 5,294 kg/ha) at all locations over the two-year period (2012-2014). The absolute YG_W ranged from 2,223 to 6,071 kg/ha (mean=4,577 kg/ha) representing a relative yield gap of 49 to 98% (mean= 86%). These yield gap values are amongst the highest documented globally for perennial tree crops grown under rainfed conditions by smallholder farmers. For instance, YG_W for oil palm was 63% on average in smallholder farms in Indonesia (Monzon et al., 2021). Euler et al. (2016) also found average oil palm yield gaps ranging from 43% to 55% for smallholder oil palm producers in

Jambi (Sumatra, Indonesia) under irrigated conditions. Besides these studies, other yield gap studies for tropical tree crops including cocoa (Aneani & Ofori-Frimpong, 2013), coffee (Bhattarai et al., 2017; Wang et al., 2015), banana (Wairegi et al., 2010) and oil palm (Rhebergen et al., 2018) used empirical approaches. Thus, to the best of our knowledge, our study is the first to quantify yield gaps at field level for cocoa using a crop modelling approach. The YG_W of cocoa we found is slightly comparable but still higher than yield gaps reported for some annual crops (e.g. rainfed maize =80%, rainfed rice =81.8%, millet =75% etc.) produced by smallholder farmers in Ghana (Global Yield Gap Atlas, 2022). This shows that cocoa farmers are producing far below what is theoretically achievable under ideal management in a rain-fed system (i.e., where only water availability limits yields), and that this at least to some extent is comparable to large yield gaps in other crops. This large gap also reveals an enormous potential for yield improvement as means to increase cocoa production without the need to further expand the area planted.

The cocoa yield gap calculated as the difference between attainable yield in high-input systems (estimated as 50% of Yw) where improved or recommended management practices are applied and actual yields were relatively larger but comparable to other experiment based yield gap estimates for cocoa in Ghana (Aneani & Ofori-Frimpong, 2013). The mean absolute YG_E we found was 1,930 kg/ha (relative yield gap of 73%) which is slightly larger than the national experimental yield gap estimate of 1,553.4 kg/ha (relative yield gap of 82.1%) for cocoa in Ghana (Aneani & Ofori-Frimpong, 2013). In relative terms however, our YG_E value 73% was lower than the national experimental-based relative yield gap of 82.1% indicating that relying only on a relative yield gap can lead to low or high prioritization of impact if not compared with the absolute yield gap (Oort et al., 2017). The attainable, relative yield gap values for cocoa are again amongst the highest documented globally for perennial tree crops. In oil-palm, a mean attainable yield gap of 47% was found for small-holder farmers in Indonesia when attainable yield was defined as 70% of simulated water-limited yields (Monzon et al., 2021). With a relatively lower attainable yield benchmark (50% of simulated water-limited yields) for cocoa, our YG_E of 73% still remains higher than the yield gap estimate for oil palm in that study. Euler et al, (2016) also found attainable oil palm yield gaps of between 46% to 50% for smallholder oil palm producers in Jambi (Sumatra, Indonesia), where attainable yield was defined as 85% of the potential yield (irrigated crops). These large attainable cocoa yield gaps results suggest large opportunities for further increases in cocoa yields beyond current levels.

Yield gap estimates based on maximum farmer yields in Ghana (YG_F) where cocoa farming is dominated by low-input systems were consistent with findings of other yield gap studies for cocoa in Ghana (Abdulai et al., 2020; Aneani & Ofori-Frimpong, 2013). Across the dry, mid and wet cocoa growing areas in Ghana, Abdulai et al., (2020) reported absolute YG_F of 434 kg/ha, 697 kg/ha, and 1126 kg/ha which represent a relative yield gap of 67%, 59% and 53%, respectively. Thus, in their study absolute yield gaps increased significantly along a rainfall gradient but relative yield gaps between dry and mid zones were not significantly different, although the wet zone was significantly different from the dry zone. While we found similarly low YG_F values (i.e. from 4 to 1,031 kg/ha with a mean of 469 kg/ha representing a relative yield gap range of 0.3 to 93% and mean of 42%) for the 84 cocoa farms in our study, we did not observe this spatial pattern of absolute YG_F increasing along a rainfall gradient (Fig. 3.S2). Instead, the spatial pattern of absolute and relative YG_F differed less across the rainfall gradient, indicating that YG_F was relatively insensitive to climate variation (*Chapter 2*). Also, our study differs from the study of Abdulai et al (2020), as we do not analyse data separately for the different climatic zones but for the entire cocoa growing region. We did this because the analysis of a huge (~3800 cocoa farms) dataset on cocoa yields in Ghana found climate did not show strong effects on actual yields, as yield variability was mainly driven by management (*Chapter 2*). At the national level, Aneani & Ofori-Frimpong (2013) found YG_F of 1,537.2 kg/ha (relative yield gap of 82%) which is somewhat larger than our value and the value obtained by Abdulai et al., (2020).

3.4.2. Climate drives absolute maximum water-limited and attainable yield gaps in high-input systems, but not in low-input systems

Climate factors were identified as the main determinants of absolute YG_W and YG_E but not absolute YG_F, which supports our hypothesis. Climate variables explained 22% of the variation in absolute YG_W but when both climate and farm-to-farm variation are considered 70% of the variation is explained. This suggests that, other factors, including other climate, soil and management factors not tested as fixed effects, drive the absolute YG_W. The strong effect of climate on absolute YG_W was mainly due to strong effects of climate on simulated water-limited yields (Fig. 3.S6) (Zuidema et al., 2005). Water-limited yields are more climate sensitive than the actual yields because all non-climatic factors, other than crop traits, are, by definition, assumed to be non-limiting (*Chapter 2*; Zuidema et al., 2005). For YG_E, climate together with agronomic management drove the absolute yield gap and explained 28% of the variation and 65% when farm-to-farm variation is considered thus also suggesting that factors not tested played a large role.

Absolute YG_W and YG_E were significantly and positively related to precipitation of the minor wet season and minimum temperature of the minor dry season, (Table 3.3(i, iii)). The positive effects of precipitation of the minor wet season on the absolute YG_W and YG_E may relate to positive effects of water availability on simulated water-limited cocoa yields (Fig. 3.S6a) (Zuidema et al., 2005). In CASE2, bean yield is determined largely by water-availability to cocoa trees and water limitation reduces yields (Gateau-Rey et al., 2018; Zuidema et al., 2005). The minor wet season (i.e. September to November) coincides with the period when the major cocoa harvest starts in Ghana (Fig. 3.4), hence, when cocoa trees have many maturing pods. Assimilate demand for pod growth in this period is therefore high. Water-limitation induced reductions in photosynthesis at this time will thus have a relatively large negative effect on pod yield, whilst increasing precipitation has positive effects on pod yield hence on the absolute YG_W and YG_E. These results support our hypothesis.

The positive effect of minimum temperature of the minor dry season (July/August) on absolute YG_W and YG_E may be related to the temperature effects on pod development. In CASE2, minimum temperature affects photosynthesis, respiration and pod development. Minimum temperature values observed within the minor dry season in Ghana range from 20.8 to 22.1°C (Table 3.2) and are expected to drive average temperature (23.9 to 25.1°C) within this period as relative humidity is still high with overcast weather conditions (Anim-Kwapong & Frimpong, 2004). For photosynthesis, average daytime temperature of 30 to 32.1°C are considered optimal for obtaining maximum photosynthesis rates (Balasimha, Daniel, & Bhat, 1991; Zuidema et al., 2003). Higher temperatures beyond 34°C and temperatures below 24 °C result in a rapid decline in photosynthesis (Balasimha et al., 1991). Increasing minimum temperature is expected to increase respiration (increases exponentially with increasing temperature) and pod development (increases linearly from 20°C to 28°C) (Zuidema et al., 2003). Higher respiration suppresses net assimilation rates and tends to result in lower yields. More rapid pod development on the other hand tends to allow pods to pass more quickly to maturing developmental stages with higher sink strength, which would thus positively affect yields. The minor dry season in Ghana coincides with the early/mid stage of pod development as the bulk of pods initiate development in the main wet season (April to June) and pods take approximately 5-6 months after pollination to reach maturity (Fig. 3.4) (Gerritsma, 1995; Toxopeus, 1985; Wessel, 1971). The net positive effect of temperature on yield suggests that temperature-driven stimulation of pod development had a stronger effect than the negative effects of higher temperature on net assimilation. Thus, in our simulations increasing minimum temperature increased simulated yields and thereby the absolute yield gap.

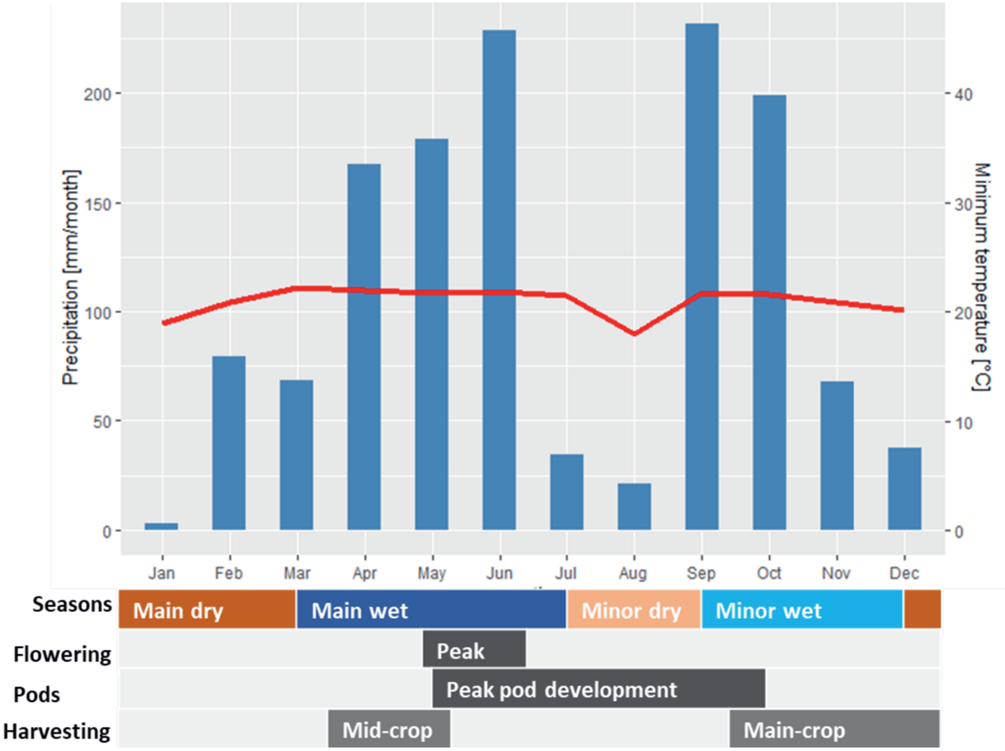

Fig. 3. 4. Monthly data of precipitation (bars) and minimum temperature (red line) of Ghana (Tafo) and annual cocoa cropping cycle. Adapted from van Vliet & Giller, 2017.

3.4.3. Cocoa planting density and application of fungicide against black pod reduces cocoa yield gaps in Ghana

Agronomic management factors reduced both absolute YG_F and YG_E and the relative yield gaps (YG_W, YG_E and YG_F) highlighting the importance of improved management practices for closing the cocoa yield gap and confirms our hypothesis. Absolute yield gap for $YG_{F,}$ was determined by only agronomic management factors and explained 25% of the variation and 61% when farm-to-farm variation was considered. Whilst absolute $YG_{E,}$ was driven by agronomic management in addition to climate factors. In Ghana, strong climatic influence for farms with best agronomic management have been found but farms with average yields were less sensitive to climate (*Chapter 2*).

On the other hand, quantifying not only the absolute, but also the relative yield gap, helps to quantify the relative importance of specific controllable measures for closing the yield gap, as the climatic effects that drive the water-limited yield predominate as drivers of the absolute YG_W. Agronomic management factors were identified as the main determinants of relative YG_W, which explained a large part (33%) of the variation in relative YG_W. Similar to relative $YG_{W,}$ agronomic management factors were the main determinants of relative YG_E and relative YG_F, also explaining a large part, namely 33% in the case of relative YG_E and 25% of the variation in relative $YG_{F.}$

Increasing cocoa planting density significantly reduced the absolute YG_E and YG_F and relative values of YG_W, YG_E and YG_F. Planting density has consistently been identified as an important yield-limiting factor for cocoa (Abdulai et al., 2020; Daymond et al., 2017; Efron et al., 2005; Sonwa et al., 2018; Souza et al., 2009; *Chapter 2*), as well as for other crops (Duvick & Cassman, 1999) including tree crops like coffee (Bhattarai et al., 2017; Wang et al., 2015). The simulations of water-limited yield with CASE2 were based on a standardized planting density of 1246 trees per hectare. This was based on the assumption that density can be controlled and changed by the farmer to reduce the yield gap. However, increasing densities also tend to increase disease incidence (e.g. due to microclimate effects and greater ease of transmission) but also greater competition between trees especially in mature stands (Sonwa et al., 2018; Souza et al., 2009). The latter can be controlled by thinning (Lachenaud & Oliver, 1998) and pruning (Tosto et al., 2022). Breeding for high yielding cocoa genotypes, that are smaller but also have a higher allocation to pods, as a means to suppress competition and stimulate the positive effect of planting density on yields is recommended (Lockwood & Pang, 1996).

Application of fungicides against black pod reduces absolute YG_F and relative values of YG_W, YG_E and YG_F. Black pod disease which occurs in all cocoa growing areas is considered as one of the most destructive diseases that prevents pod development and ripening and reduces yields (Akrofi et al., 2015; Anim-Kwapong & Frimpong, 2004; Daymond et al., 2017; Opoku et al., 2000). This disease has been found to be more prevalent under damp conditions (wet and humid conditions and shaded systems), particularly in the minor dry season (Anim-Kwapong & Frimpong, 2004) and can cause mean annual pod losses of about 40% and higher (Idachaba & Olayide, 1976 in Aneani & Ofori-Frimpong, 2013; Opoku et al., 2000; Wessel & Quist-Wessel, 2015). Cocoa farmers who do not apply fungicide against black pod suffer yield losses whilst application increases yields (Akrofi, Appiah, & Opoku, 2003) and therefore reduces the yield gap. Adequate knowledge of techniques of fungicide application, the use of more black pod disease resistant genotypes and management practices that improves air circulation and reduce humidity (e.g. pruning, regular harvesting of infected pods, removal of pod husk heaps) have been recommended for controlling black pod disease (Adejumo, 2005; Akrofi et al., 2003; Cilas et al., 2018; Opoku et al., 2000). The reduction in relative yield gaps for YG_W, YG_E, and YG_F due to cocoa planting density and application of fungicides against black pod supports our hypothesis. However, application of insecticides against capsid, fertilizer use, shade level, tree age and farm size had no effects, contrary to our expectations.

3.4.4. Limitations and future steps

This study had several limitations. First, it should be noted that there are still important knowledge gaps regarding to how cocoa responds to water limitation and hence modelled Yw estimates based on a physiological model such as CASE2 need to be treated with some care. The extent to which seasonal fluctuations in water supply affect growth and productivity under field conditions, is not well understood and probably not fully captured by CASE2. For instance, how the dynamics in leaf flushing and cherelle wilt are mediated by seasonal fluctuation in assimilate supply is not well understood. There are also insufficient field data of these dynamics to validate model simulations. Second, we only analysed data for two years, and may have failed to capture the negative effects of extreme climatic conditions on yields (Abdulai et al., 2018; Gateau-Rey et al., 2018). There was no case of extreme climatic conditions during the period for which data was available; hence, we could not evaluate this. Furthermore, regarding the effect of planting density, it is important to note that there is a huge variability in planting densities across cocoa farms. Even though we have planting density as a co-variate in the regression analysis, it is difficult to assess how much of the climate sensitivity is actually captured in the regression as compared to a data set with more homogeneous planting densities (effects could be stronger in this case) along a climate gradient. Finally, even if planting density is similar, farms can differ in the number of unproductive trees (Jagoret et al., 2017; Wibaux et al., 2018), which we did not have any information on.

What are the options to close the yield gap? We recommend considering variability in the absolute yield gap for cocoa across Ghana. Areas with large absolute yield gaps such as the wetter areas indicate potential for larger yield gains, whilst farmers in areas with low absolute yield gaps maybe more vulnerable due to climate change. Progressive climate change may alter simulated water-limited yields (upper limit of yields in rain-fed system) through direct changes in temperature and water availability (Bunn et al., 2019; Läderach et al., 2013; Schroth et al., 2016). Thus, it is important for climate change impact studies to carefully evaluate projected changes in climate and potential responses of cocoa growth and yield. Even though yield gaps are lower in the dry area, there is still a significant potential for yield increase following best management practices. Furthermore, using irrigation (Carr & Lockwood, 2011), mulching (Acheampong et al., 2021), shading (but with careful consideration of compatible shade tree species selection) (Abdulai et al., 2018) and planting drought-resistant cocoa varieties (Dzandu et al., 2021) are often specific recommended practices to increase yields under dry conditions. Based on the relative yield gap, management aspects like increasing planting density and application of fungicide against black pod are highlighted to be important for closing the yield gap regardless of climatic conditions. However, after achieving optimal density, other management practices that would help increase yields need to be evaluated. For instance, high density may increase the need for adequate pruning (Tosto et al., 2022). A stepwise management approach has been recommended, which targets yield limiting practices step-by-step. Only after implementing good agricultural practices (e.g. planting improved material, weeding, pruning, pest and disease control) nutrient management is considered (Wessel & Quist-Wessel, 2015) to ensure that nutrient addition actually results in increased yields. Also, monitoring and better surveys (improved data quality and additional management variables) are needed to evaluate the effect of management factors on the yield gap.

3.5. Conclusion

We quantified three cocoa yield gap estimates based on model-based maximum water-limited yield, and attainable yield in high- and low-input systems both in absolute and relative terms. A considerable model-based, mean absolute yield gap of 4,577 kg/ha representing a relative yield gap of 86%, was found for the cocoa growing areas in Ghana. The attainable yield gap in high-input systems where improved or recommended management practices are applied was relatively lower (mean absolute yield gap of 1,930 kg/ha representing a relative yield gap of 73%) than the maximum water-limited estimate but larger than yield gap estimates in low-input systems (where the mean absolute yield gap was 469 kg/ha, representing a relative yield gap of 42%). These yield gaps suggest large opportunities for increasing cocoa yield beyond current levels. Climate factors including precipitation and minimum temperature were found to primarily drive absolute maximum water-limited and attainable yield gaps in high-input systems. . The absolute and relative attainable yield gap in low-input systems and the relative yield gaps based on maximum water-limited yield and attainable yield in high-input systems were reduced by increased cocoa planting density and control of black pod disease. This suggests that irrespective of current climate conditions, investments in good management practices, such as cocoa planting density and improved access to pest and disease control by smallholder farmers, offer opportunities to substantially increase production in present-day cocoa farms.

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APPENDIX A

Supplementary Materials for Chapter 3

The cocoa yield gap in Ghana: A quantification and an analysis of factors that could narrow the gap

Table 3.S1. Conversion of ISRIC soil texture data in USDA system (Hengl et al., 2017) to texture classes in the Driessen soil types (Driessen, 1986; Zuidema et al., 2003).

Soil textures classes of USDA (with corresponding class number)	**Soil texture classes of Driessen 1986 (with corresponding class number)**
Clay (1)	Heavy clay (19)
Sandy clay (3)	Light clay (17)
Clay loam (4)	Clay loam (16)
Sandy clay loam (6)	Sandy clay loam (14)
Loam (7)	Loam (13)
Sandy loam (9)	Sandy loam (9)

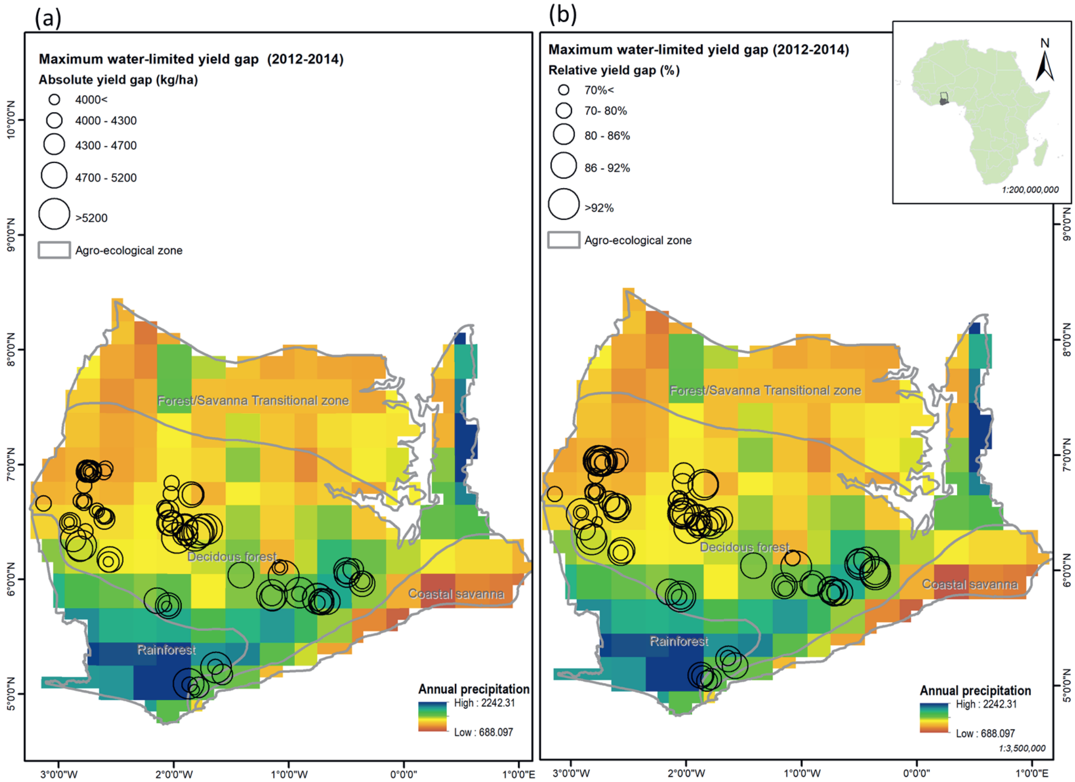

Fig. 3.S1: (a) Absolute YGw (circles) (left) and (b) Relative YGw (circles) for 93 farm locations and annual precipitation (background colour) in southern Ghana. Rainfall and cocoa yields are averages of the 2012/2013 and 2013/2014 cocoa crop years on a 11-km resolution. The size of the circle is proportional to the average YGw for that location.

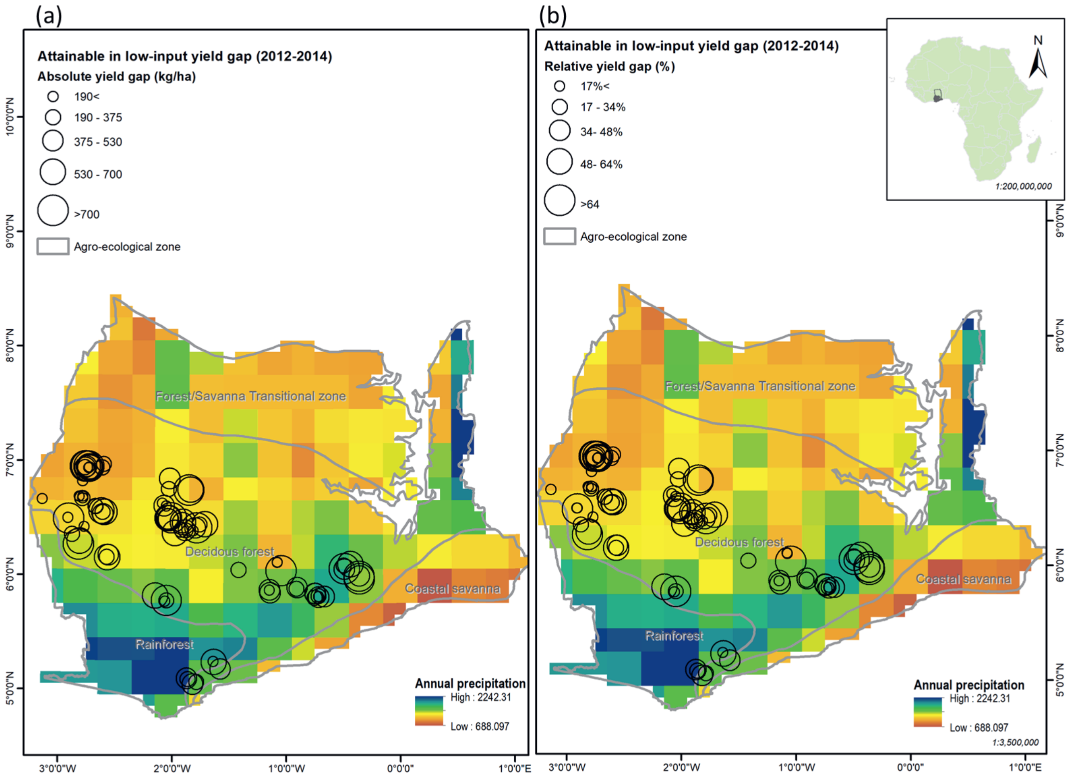

Fig. 3.S2: (a) Absolute YG_F (circles) and (b) Relative YG_F (circles) for 84 cocoa farm locations and annual precipitation (background colour) in southern Ghana. Rainfall and cocoa yields are averages of the 2012/2013 and 2013/2014 cocoa crop years on a 11-km resolution. The size of the circle is proportional to the average YG_F for that location.

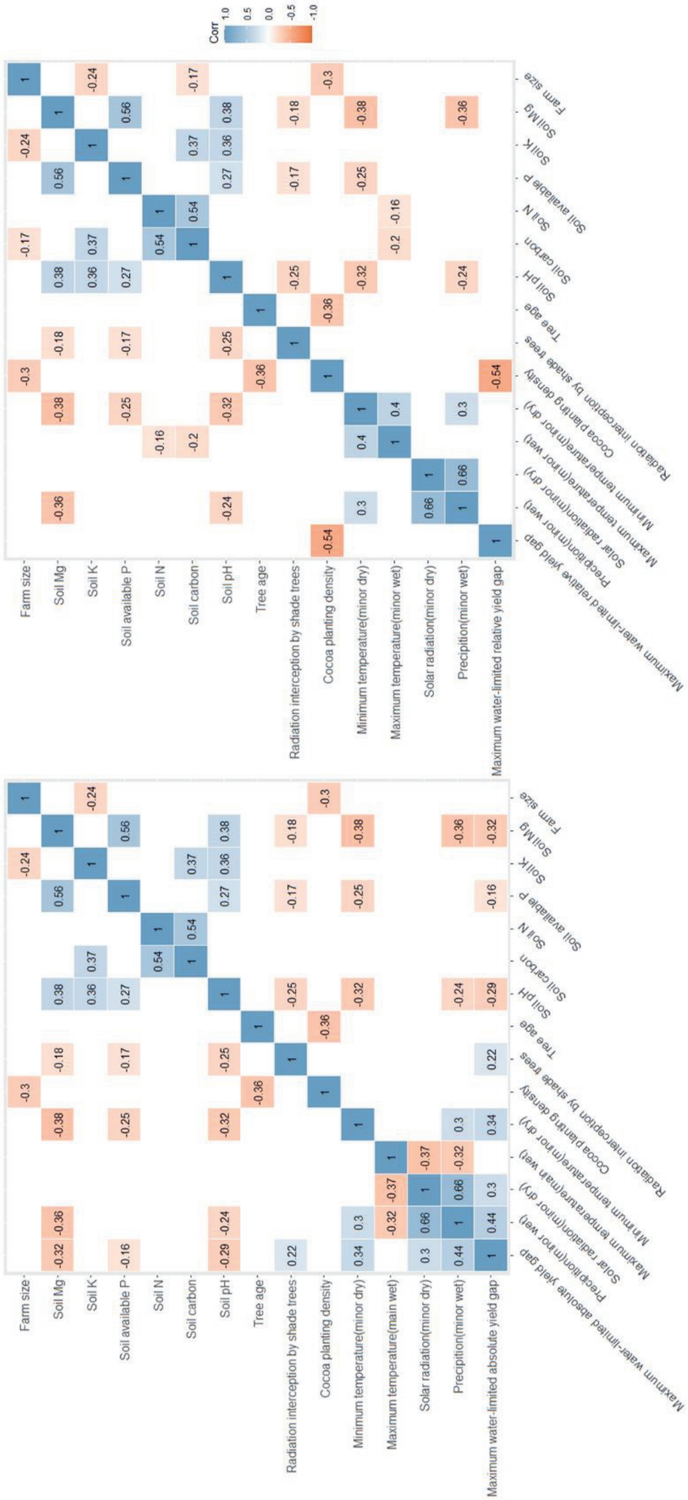

Fig. 3.S3: Correlation between absolute YG$_W$ (left) and relative YG$_W$ (right) and explanatory variables. Only significant correlations are shown.

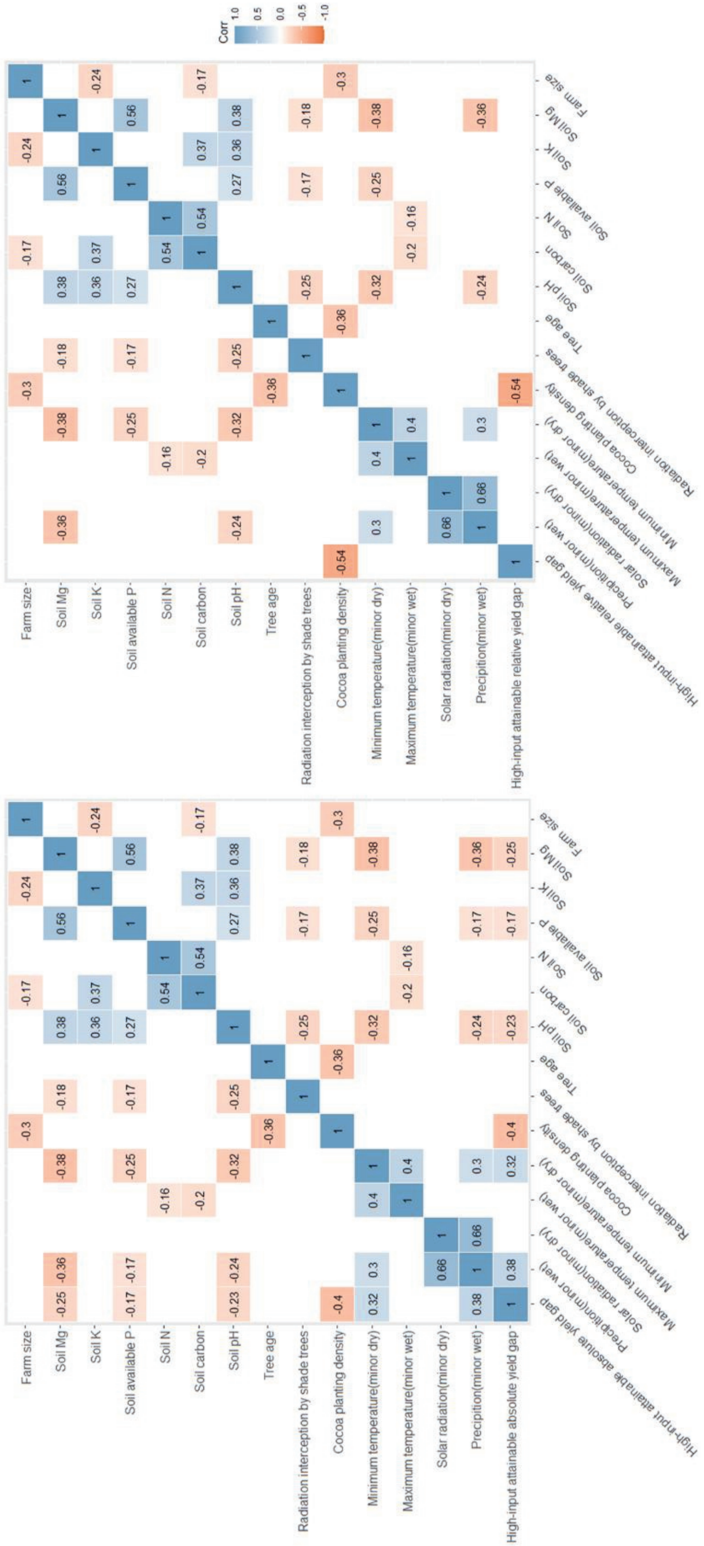

Fig. 3.S4: Correlation between absolute YG_E (left) and relative YG_E and explanatory variables. Only significant correlations are shown.

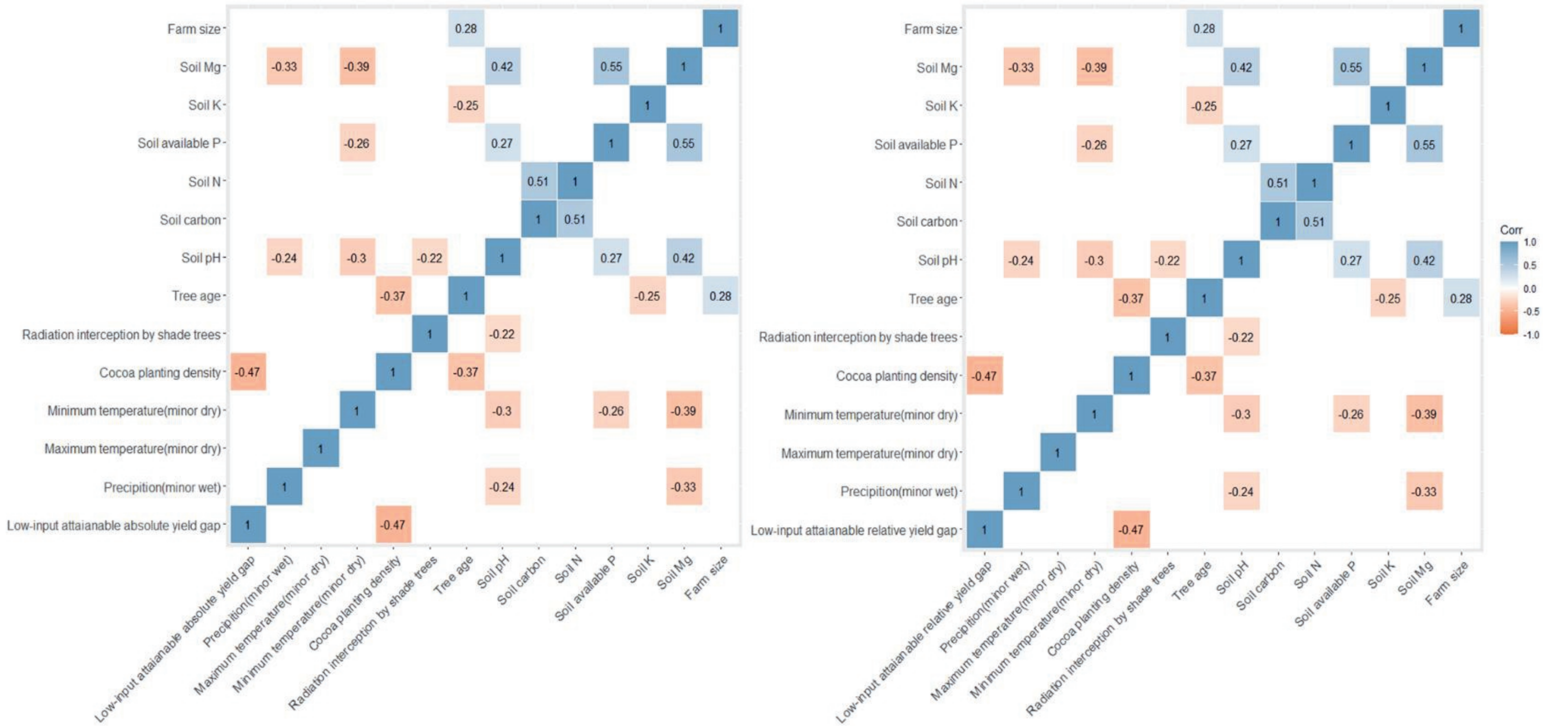

Fig. 3.S5: Correlation between YG_F absolute (left) and relative (right) yield gap and explanatory variables. Only significant correlations are shown.

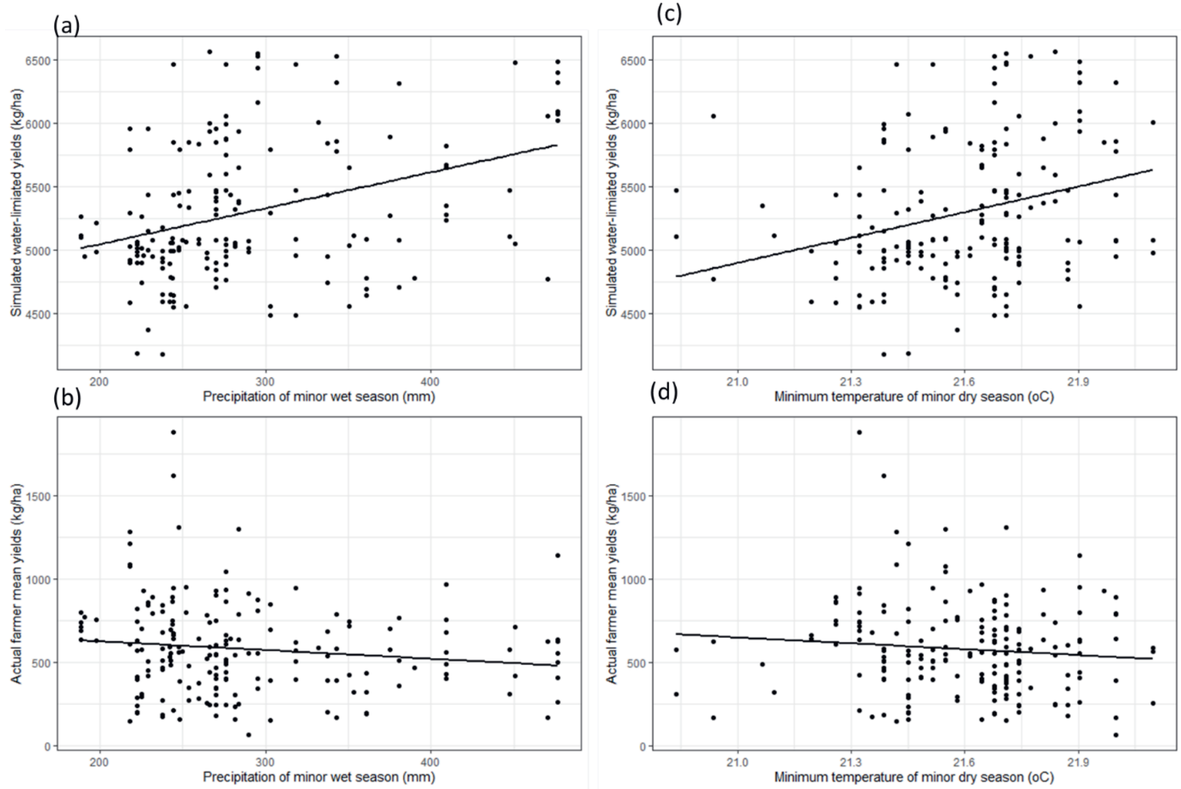

Fig. 3.S6. Relationship between precipitation of the minor wet season and a) simulated water-limited yields and b) actual farmer yields and between minimum temperature of the minor dry season and c) simulated water-limited yields and d) actual farmer yields of cocoa based on 93 cocoa farms in Ghana from 2012 to 2014.

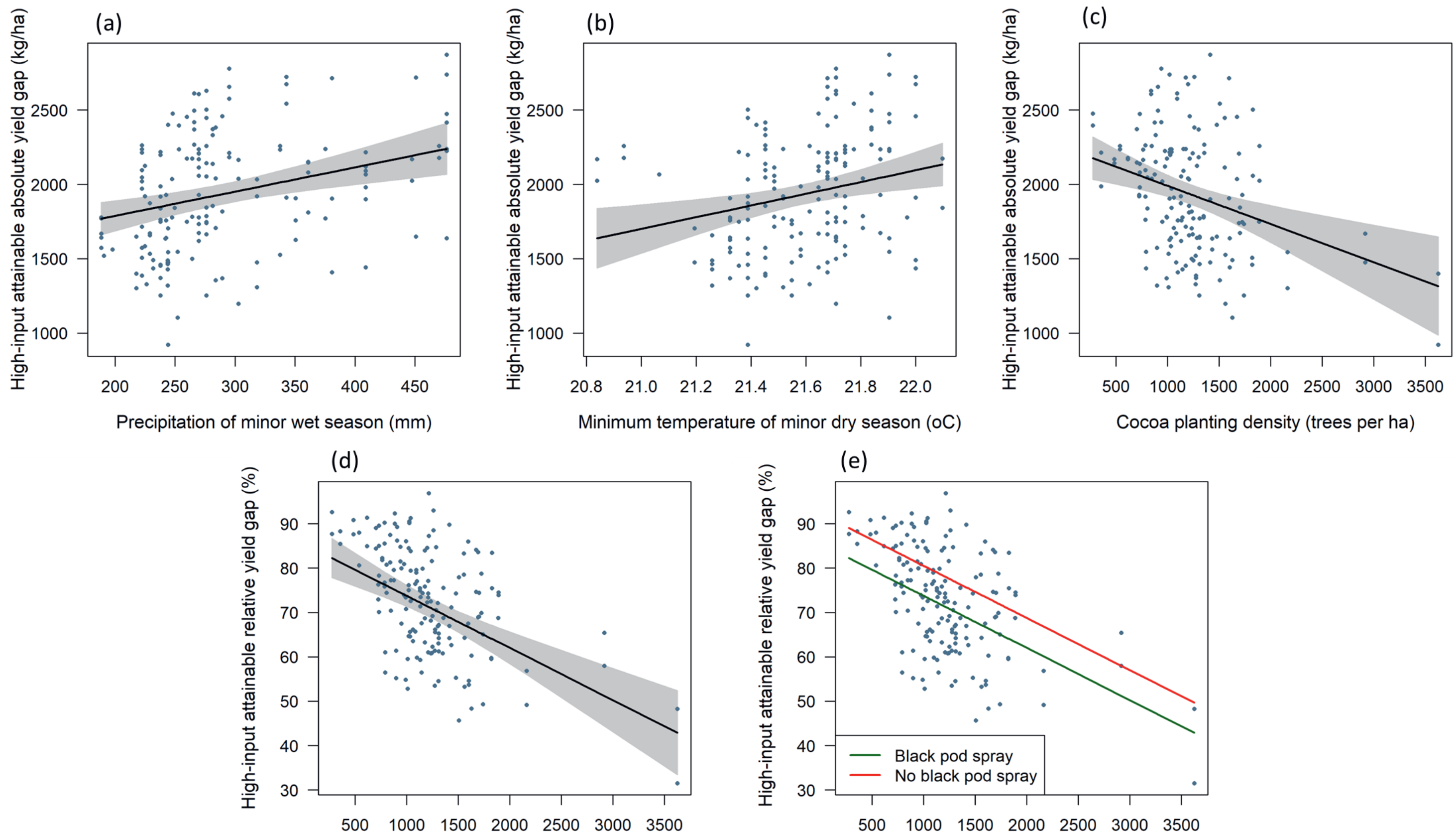

Fig. 3.S7. Relationship between absolute YG_E and (a) precipitation of minor wet season and (b) minimum temperature of minor dry season (c) cocoa planting density and between YG_E and (d) cocoa planting density and (e) application of fungicide against black pod (use vs. no use) based on 93 cocoa farms from 2012 to 2014. Lines are predicted relations from the mixed effects model, other predictors were kept constant at the mean.

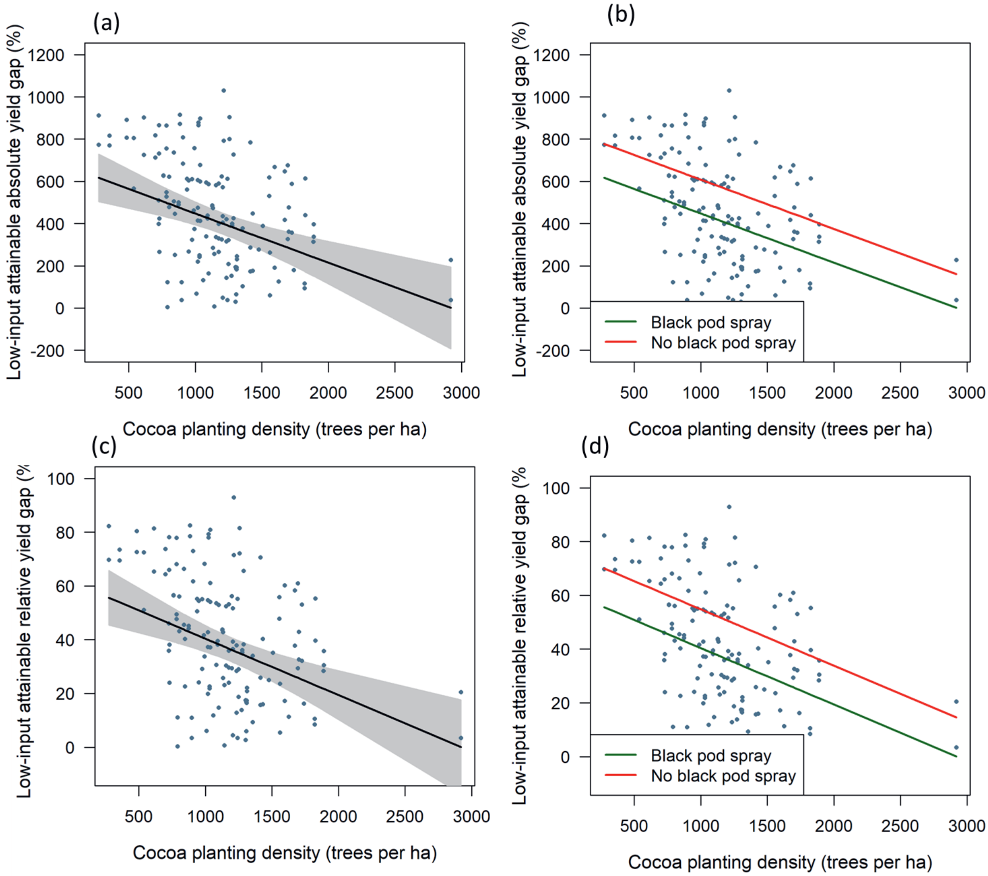

Fig. 3.S8. Relationship between absolute YG_F and (a) cocoa planting density (b)) application of fungicide against black pod (use *vs.* no use) and between relative YG_F and (c) cocoa planting density and (d) application of fungicide against black pod (use *vs.* no use) based on 93 cocoa farms from 2012 to 2014. Lines are predicted relations from the mixed effects model, other predictors were kept constant at the mean.

Chapter 4

Climate change impacts on cocoa production in the major producing countries of West and Central Africa by mid-century

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This chapter has been submitted

Abstract

Climate change is expected to negatively impact cocoa production in West and Central Africa, where over 70% of cocoa is grown. However, the effects of temperature, rainfall and atmospheric carbon dioxide concentration [CO_2] on cocoa tree physiology and productivity are poorly understood. Consequently, possible implications of climate change for cocoa productivity and adaptations have not yet been adequately considered. Our objective was to improve understanding of potential cocoa productivity responses to climate change projected by general circulation models (GCMs) in the major cocoa producing countries of West and Central Africa up to mid-century using a crop modelling approach. We simulated potential water-limited yields (Yw) using a physiology-based crop model to evaluate effects of warming and changes in precipitation based on five plausible future climate scenarios projected by bias corrected and downscaled GCMs, with and without elevated CO_2 effects. We examined the extent to which variation in current and projected future yields was associated with variation in individual climate variables using mixed-effects models. We then quantified how much cocoa could be produced in the future without expanding the current cocoa plantation area under low-input business-as-usual and high-input scenarios.

With some notable exceptions, the overall tendency was that under future climate (2030-2060), increases in Yw and gains in suitable area for cocoa production are expected, particularly when assuming full effects of elevated [CO_2] and in the wetter climate-change scenarios. There was a clear (south) east - west gradient with projected yield increases being most positive in Cameroon and Nigeria (~39-60%) followed by Ghana and Côte d'Ivoire (~30-45%). On the other hand, larger yield reductions were expected in Côte d'Ivoire and Ghana (~12%) followed by Nigeria (~10%) and Cameroon (~2%). Furthermore, the largest increases in land area suitable for cocoa were expected in Nigeria (~17-20 Mha), followed by Cameroon (~11-12 Mha) and Ghana (~2 Mha) while reductions (~6-11 Mha) in suitable area were expected for Côte d'Ivoire by 2060. In areas with increasing yields, inter-annual yield variability was expected to decrease, but increased variability was predicted in areas with low yields, especially in north-west Côte d'Ivoire. Overall, our simulations based on one climate change scenario with average predicted changes in temperature and precipitation, predict current country-level production to be maintained within current cocoa growing areas of Côte d'Ivoire and Ghana by mid-century. Predicted increases in Yw were mostly associated with projected increases in dry season precipitation whilst projected shortening of the dry season reduced yield variability.

These modelling results indicate that, despite the increases in temperature and changes in rainfall distribution as projected by the selected GCMs, many areas where cocoa is currently grown will either maintain or increase in productivity, particularly if full effects of elevated [CO_2] are assumed.

Keywords: climate change, cocoa yield, cocoa yield variability, CO_2 effects, dry season precipitation

4.1. Introduction

Amongst the crop producing regions of the world, West Africa is considered to be relatively vulnerable to climate change due to naturally high climate variability, high reliance on rain-fed agriculture, and limited economic and institutional capacity to respond to climate variability and change (Sultan & Gaetani, 2016). Since the mid-1970s, increases in annual average and seasonal surface temperatures of about 1-3 ºC have been observed over this region (Cook et al., 2020; Dosio, 2017; Lelieveld et al., 2016) whilst increases in annual precipitation have been observed since the mid-1990s following the devastating droughts in the 1970s and 1980s (Barry et al., 2018; Maidment et al., 2015; Trisos et al., 2022). Observed climate trajectories are expected to continue with warming predicted to reach or surpass 1.5 °C (above pre-industrial times 1850–1900) by 2040 and, under mid- and high-emission scenarios, increases in temperatures of up to 2 °C and 3 °C, respectively, are expected along with more frequent and intense climate extremes (Sheffield & Wood, 2008; Trisos et al., 2022). At a 2 °C warming, West Africa is projected to experience drier conditions and at a warming beyond 3 °C it may experience increases in the frequency and intensity of drought events (Trisos et al., 2022). Currently, much revenue in West African countries is generated through perennial crops like cocoa that have a long economic life span of between 30 and 40 years (Wessel & Quist-Wessel, 2015), thus a tree planted today will experience the effects of climate change up to mid-century and beyond. Thus, more quantitative knowledge of how projected climate change and variability could impact productivity of such crops is urgently needed to inform policies that may counteract the adverse effects on livelihoods and local and regional economies.

Progressive climate change is expected to negatively impact cocoa production in West and Central Africa, where over 70% of cocoa is produced (Anim-Kwapong & Frimpong, 2004; Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). Previous studies have indicated that climate change will affect the climate suitability of cocoa growing areas, particularly in West Africa with potential to significantly reduce the extent of the current cocoa growing area (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). Impacts are predicted to vary regionally with geographic shifts in climate suitability of production areas and a potential loss of about 50% of current climatically suitable areas for growing cocoa by 2050. This could drive producers to new areas which may further accelerate deforestation as cocoa is grown mainly in regions that used to be covered with highly diverse moist tropical forests and cocoa production generally replaces forests (Abu et al., 2021; Kroeger et al., 2017).

Nevertheless, it is unclear how predicted changes in climatic suitability of different areas will translate into changes in cocoa production since existing methods mainly used species distribution models (SDMs) driven by general circulation models which are unable to predict cocoa yield responses to climate change (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). SDMs do not consider the physiological processes underlying growth and yield nor do they consider the effects of elevated atmospheric carbon dioxide concentration [CO_2] on cocoa productivity. Elevated atmospheric [CO_2] has a direct effect on the rate of photosynthesis in terrestrial C_3 plants (like cocoa), as the maximum velocity of the carboxylation reaction by the enzyme Rubisco is achieved under roughly double the current atmospheric [CO_2] (Long et al., 2004; Walker et al., 2021). Therefore, elevated atmospheric [CO_2] could potentially increase cocoa yields by increasing photosynthetic rates (Black et al., 2020), while stomatal conductance typically decreases, leading to higher water-use efficiency (Lambers et al. 1998; Lahive et al. 2017;2018). Photorespiration is also expected to decrease under elevated [CO_2], since CO_2 competes with O_2 for Rubisco and elevated [CO_2] would compete more (Cernusak et al., 2013; Long et al., 2004). Together, these CO_2 effects may mitigate negative warming and drought effects on photosynthesis. A recent modelling study by Black et al., (2020) provided a comprehensive process-based assessment of the impact of climate change on cocoa net primary productivity (NPP) under current and elevated [CO_2]. Yet, insights on cocoa yield changes based on this study are limited, as NPP is not equivalent to yield, hence, the yield response to climate change and [CO_2] rise remains poorly understood. Therefore, improving our understanding on how projected climate change and variations in climate would impact cocoa tree physiology and productivity, taking into account potential effects of elevated atmospheric [CO_2], is relevant for assessing possible implications of climate change impacts on future cocoa production.

The objective of this study is to advance our understanding of potential cocoa responses to climatic change projected by general circulation models and its implications for production (mean yield per hectare, interannual yield variability and total production in tons) across the major cocoa-producing countries in West and Central Africa up to mid-century. We do so by utilizing a mechanistic cocoa crop model which simulates the relevant physical and biochemical processes that occur in the plant, and we describe how and why a particular response to climatic conditions occurs. To this end, we use the CASEJ (based on CASE2; Zuidema et al. 2005) crop model that simulates growth and production of cocoa with or without water limitation and adapted the crop model to be able to simulate effects of warming and elevated atmospheric

[CO_2] on cocoa yield. We address the following questions: 1) how will projected changes in climate (i.e., temperature, precipitation) and the underlying rise in [CO_2] affect cocoa production in the four major cocoa producing countries (Côte d'Ivoire, Ghana, Nigeria and Cameroon) in West and Central Africa?; 2) how will variations in projected changes in climate affect interannual cocoa yield variability?; and 3) how much cocoa could potentially be produced under future climatic conditions without expansion of the land area under cocoa cultivation?

To address these questions, we simulated both the average and variation in yield over a 30-year timespan in the past (1980-2010) and in the future (2030-2060). We expect that the rise in atmospheric [CO_2] will partially offset the negative effects of increases in temperature and drought intensity/frequency on cocoa yields and will reduce interannual cocoa yield variability in the four major cocoa producing countries in West and Central Africa.

4.2. Materials & Methods

4.2.1. Study Area

The study was conducted for the four main cocoa producing countries in West and Central Africa; Côte d'Ivoire, Ghana, Nigeria and Cameroon (Fig. 4.1). The cocoa growing areas are mainly in the Southern part of these countries (except Cameroon), from the coast of the Gulf of Guinea several hundred km land inwards. Cocoa farming in the region is mainly low-input with a large share (~ 90%) of the crop grown by about two million smallholders (average cocoa farm size of 3 - 4 ha) on an estimated six million ha of land (Schroth et al., 2016; Wessel & Quist-Wessel, 2015). Côte d'Ivoire and Ghana are the largest producers followed by Nigeria and Cameroon. Average yields are generally low, typically 300-600 kg/ha (Chapter 2; Wessel & Quist-Wessel, 2015). Precipitation within these countries is characterized by decreasing rainfall along a South-North gradient (Fig. 4.1) with generally high temperatures (mean temperature above 18 °C) throughout the year.

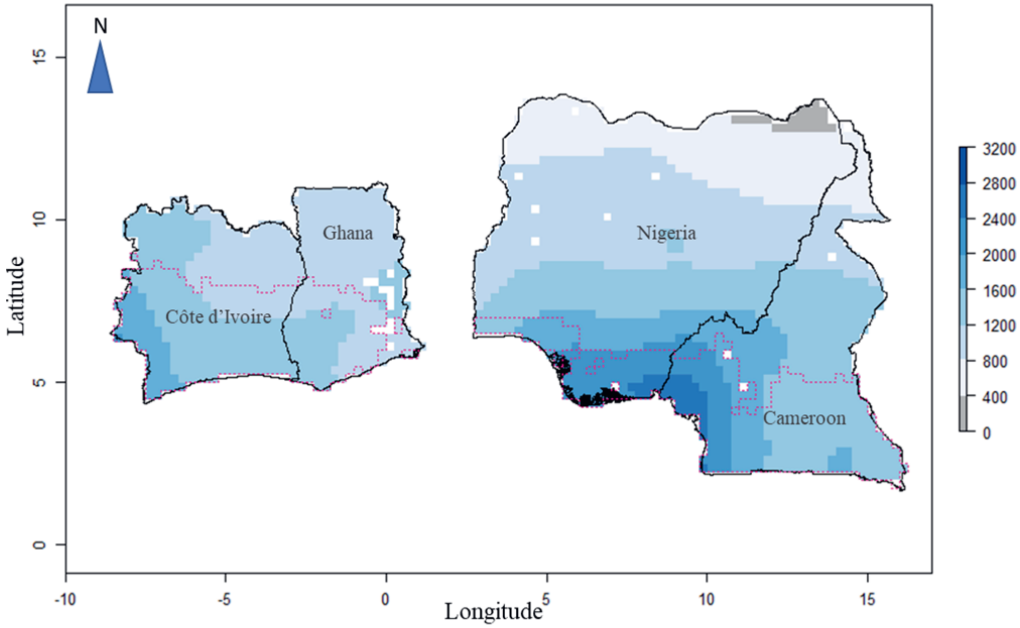

Fig. 4.1. Mean annual precipitation (in mm) distribution across West Africa; Côte d'Ivoire, Ghana, Nigeria and Cameroon, based on the Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling (Sheffield et al., 2006). Rainfall values are calculated means of 1980–2010 on a 25-km resolution. The simulated current cocoa area extent (indicated by the red line) indicates where based on model simulations cocoa was able to grow in the period from 1980-2010.

4.2.2. CASEJ model description and update

CASEJ is based on the CASE2 physiological model that simulates growth and yield of cocoa trees for different weather and soil conditions, and cropping systems (Zuidema et al., 2005), with the modification that photosynthesis is calculated following the Farquhar–von Caemmerer–Berry (FvCB) biochemical model (Farquhar et al., 1980). CASE2 was originally implemented in FORTRAN using the Fortran Simulation Environment (FSE), and it simulates major processes of cocoa crop growth and yield including: light interception, photosynthesis, maintenance respiration, evapotranspiration, biomass production and associated growth respiration and biomass allocation (Zuidema et al., 2005). The model allows simulating bean yield of cocoa trees as a function of varying degrees of overhead shade from a homogeneous canopy of associated trees and with varying degrees of water limitation. The model has been parameterized based on information on cocoa physiology and morphology, with values obtained from the literature. A validation study comparing model outputs to available empirical data obtained from cocoa plantations showed that the model predicts realistic output for bean yield, standing biomass, leaf area and tree size-age relations (Zuidema et al., 2005).

A major limitation of CASE2 for climate change impact studies, is that the calculation of photosynthesis was based on light response curves (Tosto et al., 2023; Zuidema et al., 2005), which does not allow to assess the effect of changes in atmospheric [CO_2] and its interaction with temperature and water use on photosynthesis, and thus makes it poorly suitable for modelling the effects of climate change. In the CASEJ model version, a simplified version of the FvCB model has therefore been incorporated. This version computes photosynthesis as limited by electron transport and Rubisco kinetics (i.e., no form of acclimation to elevated [CO_2] is included) and assuming no mesophyll resistance and a fixed ratio between intercellular and air [CO_2] of 0.7. These last two assumptions allow simplifying the calculations of CO_2 diffusion and hence match the original model (CASE2) as much as possible (i.e., light-response curves are still used, but with the effect of [CO_2] mechanistically included). The effect of temperature on light-saturated photosynthesis was modelled the same way as in CASE2. Simulation outputs obtained with CASEJ were similar to those of the original CASE2 when compared for current climatic conditions. In addition, as CASE2 was written in FORTRAN using FSE, automation of simulation from different inputs is difficult. To address this, CASEJ was implemented in the Julia programming language (Bezanson et al., 2017) plus an interface that allows CASEJ to be run from within the R programming language (R Core Team, 2018).

CASEJ requires information on atmospheric [CO_2] in addition to the original input information required by CASE2, which includes information on weather (daily minimum and maximum temperature, precipitation, solar radiation, and early morning vapor pressure), soil texture (thickness; number and depth of soil layers) and cropping systems (cocoa tree age, planting density and shade levels) for growth and yield simulations (Zuidema et al., 2003). Simulations can be carried out for mature cocoa trees (assuming uniform planting material) with an age between 3 and 40 years (i.e., 18.5–70 kg dry weight per tree) planted at a density between 700 and 2500 trees/ha. For simulations with shade from associated trees, the model assumes horizontal homogenous shading with a maximum shade tree leaf area index (SLAI) of 3 (i.e., heavy shading) and a light extinction coefficient (k) varying between 0.4 and 0.8. Climatic and soil limitations assumed for growth and yield in the model included an average day temperature between 10 and 40 °C, annual precipitation of at least 1250 mm, and maximum soil depth of 1.5 m with soil physical characteristics (water content at saturation, field capacity, wilting point) defined based on Driessen soil types.

In this study, simulations were carried out for cocoa trees with an initial tree age of 10 years over a 30-year period, both for the historical (1980-2010) and future (2030-2060) time periods. We assume equal management practices (planting density of 1000 trees/ha, 20% shade) for both time periods. A full description of model parameter values is included in Table S1.

4.2.3. Historical & future weather, atmospheric [CO_2] and soil data

Historical daily minimum and maximum temperature, precipitation, and solar radiation at a spatial resolution of 0.25° (approximately 25 km) for the period of 1980 to 2010 were obtained from the Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling, available from the Terrestrial Hydrology Research Group at Princeton University (Sheffield et al., 2006). Saturated vapor pressure (e^0, kPa) was derived from minimum temperature and calculated as $0.6108exp[\frac{17.27\,Tmin}{Tmin+237.3}]$, where *Tmin* is the minimum temperature (°C).

Future weather data from the high-spatial resolution, downscaled and bias-corrected climate change projections from the National Aeronautics Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset were obtained for the period of 2030-2060 (Thrasher et al., 2012, 2021, 2022). This dataset consists of climate scenarios, derived from the General Circulation Model (GCM), runs under the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016) across two of the four greenhouse gas emissions scenarios (SSP2-4.5 and SSP5-8.5) available at a spatial resolution of 0.25°. We included GCMs from one Shared Socioeconomic Pathway; SSP5-8.5 (high greenhouse gas emissions scenario). Daily minimum and maximum near-surface temperature, precipitation, and solar radiation were obtained.

Global monthly records of atmospheric [CO_2] from 1980 to 2010 were obtained from the Mauna Loa Observatory database (Thoning et al., 1989). For the future period, atmospheric [CO_2] for CMIP6 under SSP585 was obtained from Cheng et al. (2022). To ensure consistency, historical and future [CO_2] records from one location (19.5° N, 155.6° W) were used. Monthly data were converted to daily inputs (each day of a given month had the same monthly data value) for CASEJ.

Soil texture data classified based on the USDA system were obtained from the ISRIC database at six standard depths (0-5, 5-15, 15-30, 30-60, 60-100 and 100-200 cm) (Hengl et al., 2017). Data were available at a spatial resolution of 250 m. We converted the soil texture classes based on the USDA system into the Driessen system, following the approach in Chapter 3, to be able to retrieve the standard values of soil water content at saturation, field capacity, wilting point, which are defined in CASEJ based on the soil texture classes in the Driessen system (Driessen, 1986).

4.2.4. GCM model selection

A total of 31 GCMs with complete information on required climate input variables including temperature, precipitation and solar radiation were available in the NEX-GDDP-CMIP6 database. To select representative GCMs that realistically reflect potential future changes, we included only GCMs with low to mid climate sensitivity, thus having equilibrium climate sensitivity (ECS) values below 5 °C, excluding those with values above 5 °C (hot models). GCMs with high sensitivity have been reported to poorly reproduce historical temperature over time (Hausfather et al., 2022). Next, we manually examined the GCMs for any unrealistic projections (i.e., consistently falling outside the range predicted by all GCMs) and excluded such GCMs. In the end, a total of 19 GCMs were considered for further analysis.

Five representative GCMs were selected by grouping GCMs into five different classes (climate-change quadrants) based on the projected average change in precipitation and temperature between the historical (1980-2010) and future (2030-2060) periods for four different locations, one in each of the included countries (Fig. 4. S1) (Ruane & McDermid, 2017). To do this, we first characterized each GCM's location-specific projected temperature and precipitation change in terms of its deviation from the ensemble median (i.e., projected changes by all 19 GCMs). Thus, each GCM was categorized as relatively warm or hot and relatively wet or dry. We then used this climate information to group GCMs into four climate change quadrants namely, warm/wet, warm/dry, hot/wet, hot/dry (Fig. 4. S1). We included a mid-class, which included GCMs within -0.4 °C to 0.4 °C and within 5% of the ensemble median average temperature and precipitation change, respectively, to represent the nexus of the four climate-change quadrants. For each class, we selected a GCM that consistently fell within the same quadrant for all the four countries (Fig. 4. S1, Table S2).

4.2.5. Estimating climate change effects on mean cocoa yields

To understand how projected changes in climate and elevated [CO_2] levels influence cocoa yields, we first simulated water-limited potential cocoa yield (Yw) with CASEJ based on historical climate and [CO_2] values. To determine to what extent atmospheric [CO_2] levels could affect cocoa production in the future, we simulated Yw based on future climatic conditions for two scenarios: i) simulated Yw with effects of atmospheric [CO_2] (based on future [CO_2], assuming no acclimation to elevated [CO_2]); and ii) simulated Yw without atmospheric [CO_2] effects (setting the [CO_2] at 363 ppm, corresponding to the average concentration of the historical period 1980-2010). These simulations were performed for each of the five selected GCMs (warm/wet, warm/dry, hot/wet, hot/dry and mid). For simulations with effects of atmospheric [CO_2], we allowed both projected future atmospheric [CO_2] levels and climate variables (temperature, precipitation) to change during the simulations. For the simulation without atmospheric [CO_2] effects, we kept the atmospheric [CO_2] level constant at 363 ppm, while climate variables changed according to the GCM projections. We calculated the mean annual historical Yw (1980-2010) and future mean annual Yw (2030-2060) for the five representative GCMs with and without CO_2 effects and calculated the relative change (in percentage) between the historical (Yw_H) and the future (Yw_F) values of Yw, that is $\left(\frac{Yw_F}{Yw_H} - 1\right) \times 100$.

We assessed to what extent climate influenced annual Yw in the past and future by modelling Yw_H and Yw_F as a function of climatic variables using linear mixed-effects models (MEMs) (Zuur et al., 2009). We included both annual and seasonal (March-July; main wet and December-February; main dry) climate variables (precipitation, and minimum, maximum and average temperature) as fixed effects to better explain yield responses in this study. We also included the number of consecutive months with precipitation below 100 mm (consecutive dry months) as a measure of the length of the dry season. Cocoa as a perennial crop is sensitive to seasonal cycles in rainfall; areas with more than three consecutive months with precipitation below 100 mm were found to be less suitable for growing cocoa (Läderach et al., 2013). In order to compare the relative importance of the effects of climate variables on Yw, we standardized all climate variables by subtracting the mean and dividing by the standard deviation (Maldonado, 2012). We included grid ID as a random intercept. To ensure independence of explanatory variables, we evaluated collinearity using the variance inflation factor (VIF) and included only those variables with VIF < 3 in the final models. Conditional and marginal R^2 were calculated to evaluate the variation explained by fixed effects only, and the variation explained when including both fixed and random effects, respectively (Nakagawa & Schielzeth, 2010). All analyses were conducted with the R programming language (R Core Team, 2018).

4.2.6. Calculating change in cocoa yield variability

To estimate inter-annual cocoa yield variability, we detrended Yw_H and Yw_F using the cubic smoothing spline method (where the frequency response was 0.50 at a wavelength of 0.67) within the detrend function in the dplR library in R (Bunn et al., 2022). We calculated the standard deviation (SD) of the detrended Yw_H and Yw_F as a measure of interannual yield variability for both the historical and future (for each of the selected GCMs under the two [CO_2] scenarios) periods respectively. The relative change (in percentage) in yield variability between the historical (Ywv_H) period and the future (Ywv_F) period was then calculated as $\left(\frac{YWv_F}{YWv_H} - 1\right) \times 100$.

Next, we examined to what extent historical and future variability in climate influenced Ywv_H and Ywv_F using MEM. Following the inter-annual yield variability calculation procedure, we detrended climate variables (annual and seasonal precipitation, and minimum, maximum and average temperature and consecutive dry months) and calculated the SD of the detrended climate data. We included SD of the climate variables as fixed effects and grid ID as a random intercept. Following the same MEM procedure as for the annual Yw, we standardized all fixed variables. We included only those variables with VIF < 3 in the final models and calculated the conditional and marginal R^2 for each model.

4.2.7. Estimating future cocoa production at country level without expansion in the area planted

We estimated how much cocoa can be produced in the current cocoa growing area in the future, assuming that there will be no expansion in the current cocoa planted area. To do this, we calculated current and future cocoa production (i.e., cocoa area × yield) for Côte d'Ivoire and Ghana with and without [CO_2] effects, based on the mid GCM only. The total cocoa plantation area per 0.25° grid cell (Fig. 4. S2) was estimated using a map of cocoa growing areas based on remote-sensing imagery (Abu et al., 2021). No spatial data on current cocoa cultivation areas were available for Nigeria and Cameroon. Therefore, this analysis was only conducted for Côte d'Ivoire and Ghana, which together supply about 60% of global cocoa beans (ICCO, 2021). We estimated total cocoa production based on two yield gap scenarios: a business-as-usual (BAU) scenario, where the (relative) cocoa yield gap is assumed to stay the same as current (a yield gap of 86% of Yw) (Chapter 3) and a high-input scenario where the yield gap is assumed to reduce from 86% to 73% of Yw to represent nearly a 100% increase in yield in high-input systems which is a realistic yield target for farmers.

4.3. Results

4.3.1. Projected changes in climate in West and Central Africa

Relative to the historical period (1980-2010), a change in precipitation pattern over space and time and an increase in temperature was projected for the four major cocoa producing countries in West (Côte d'Ivoire, Ghana, Nigeria) and Central (Cameroon) Africa by 2060 under the high emission scenario (SSP585) (Fig. 4.S3-S5). Precipitation projections by GCMs ranged from increases to decreases (Fig. 4. S4, Fig. 4. 2A-C). The wetter GCMs (warm/wet, hot/wet) predicted relatively larger increases in annual (maximum average increase of ~800 mm per year ; Fig. 4.2A) and wet season (maximum increase of ~250 mm; Fig. 4.2B) precipitation with small reductions (50 mm) over a few areas in the region, whilst the mid and dry GCMs (warm/dry, hot/dry) predicted smaller increases in annual (maximum increase of ~200 mm) and wet season (~50 mm) precipitation and larger reductions (maximum ~ 400 mm and ~250 mm annually and in the wet season, respectively) over most areas. Main precipitation changes in the dry GCMs were in the wet season. In contrast to the uncertainty about annual and wet season precipitation changes projected by the GCMs, there was agreement regarding changes in dry season precipitation, as all GCMs projected increases (maximum increase of ~200 mm) along the coastal areas (Fig. 4. 2C) where cocoa is grown, and reductions up to 100 mm towards the northern parts of the countries mostly beyond the cocoa belt. Also, all GCMs predicted a reduction in the number of consecutive months with precipitation less than 100 mm (up to 2 months, i.e. the length of the dry season becomes shorter) over most parts of the region (Fig. 4.2D). The relative uncertainty in precipitation projections has been reported by several authors (e.g. Kent, Chadwick, & Rowell, 2015).

For temperature, there was general consensus among the five GCMs with future annual and seasonal minimum, maximum and average temperature (Fig. 4.S5) projected to increase in the four cocoa producing countries by 2060, relative to the historical period (Fig. 4.S3e-S3m). Projected increases in annual and seasonal minimum temperature were stronger (annual: 1-5 ^{o}C, dry season: 1-7 ^{o}C, wet season: 1-5 ^{o}C) than the projected increases in annual and seasonal maximum temperature (annual: 1-3 ^{o}C, dry season: 1-5 ^{o}C, wet season: 1-3 ^{o}C) across the four countries (Fig. 4. S6).

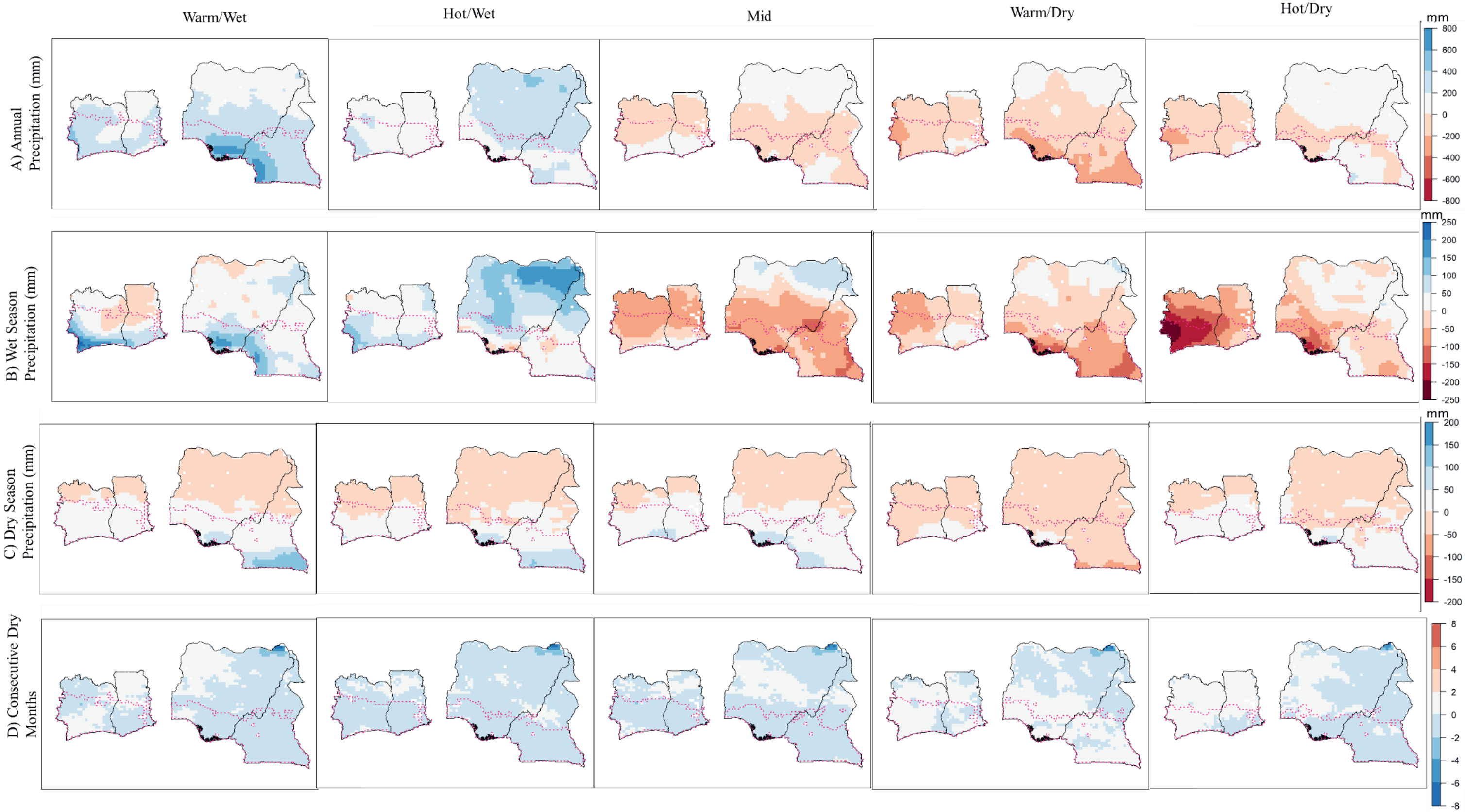

Fig. 4.2. Projected change between future (2030-2060) and historical (1980-2010) annual and seasonal precipitation across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). Shown are projected changes in annual (first row), wet season (second row), dry season (third row) precipitation (mm) and the number of consecutive months with precipitation less than 100mm (consecutive dry months) (fourth row). The red line indicates the border of the current suitable cocoa production area (i.e. where simulated water-limited yield >0), based on yield simulations.

4.3.2. Climate change effects on mean cocoa yields and suitability with and without CO_2 effects

Generally, simulated water-limited potential yields for the future period (Yw_F; 2030-2060) were higher than predicted yields for the historical period (Yw_H; 1980-2010) for both with and without CO_2 effects for all five GCMs (Fig. 4. S7). Predicted changes in Yw (future − historical) under the scenario assuming no acclimation to CO_2 (full elevated CO_2 effects) were consistently more positive than predictions under the scenario without CO_2 effects for all GCMs (Fig. 4.3). Across GCMs, predictions based on the wetter GCMs (warm/wet, hot/wet) were much more positive than those based on the mid and dry (warm/dry, hot/dry) models. Among the four countries, the most positive changes in Yw were projected in Cameroon and Nigeria where larger increases in Yw of up to ~60% and ~39% were expected with and without CO_2 effects, respectively (Fig. 4.3-4, Fig. 4.S8). Yet, without CO_2 effects, reductions in Yw (up to ~2% in Cameroon and ~10% in Nigeria) were expected for a few areas depending on the selected climate scenario. In Côte d'Ivoire and Ghana, however, relatively smaller increases in Yw (up to ~45% and ~30% with and without CO_2 effects, respectively) were expected. Under the scenario without CO_2 effects, higher reductions in Yw up to ~12% were expected for several areas in Côte d'Ivoire and Ghana particularly in the northern parts (Fig. 4.3). Predicted reductions in Yw based on the drier GCMs were higher than those based on wetter models. Notably, almost no negative changes were predicted for Cameroon under the hot/dry GCM (without CO_2 effects), while Côte d'Ivoire under this scenario exhibited more areas with predicted negative change than areas with positive change (Fig. 4.4).

Besides predicted changes in Yw, there were also changes in areas suitable for cocoa (i.e., areas based on model simulations where cocoa can grow and produce) (Fig. 4.3-4). Relatively larger gains and smaller reductions in suitable areas for cocoa were predicted with CO_2 effects than without CO_2 effects for all the four countries. Amongst GCMs, the hot/dry model predicted larger reductions in areas suitable for cocoa under both CO_2 scenarios than predictions based on the other GCMs. Almost no gains in suitable area were expected for Côte d'Ivoire in the future, rather considerable losses of up to ~11 Mha (i.e., ~50% of the predicted suitable cocoa area in the country) without CO_2 effects and up to ~6 Mha were predicted with CO_2 effects (Fig. 4.4). The largest gains in suitability, i.e., up to ~20 Mha (with CO_2 effects) and ~17 Mha (without CO_2 effects) with only small (~2 Mha without CO_2) to no reduction in suitable area, were expected in Nigeria and Cameroon (~12 Mha and ~11 Mha with and without CO_2 effects, respectively). Smaller gains in suitability (up to ~2 Mha under both CO_2 scenarios) and losses (up to ~2 Mha and ~2.5 Mha with and without CO_2, respectively) were expected in Ghana.

Results from the mixed-effects models indicated that effects of climate factors on both Yw_H and Yw_F (with and without CO_2 effects for all GCMs) were strong. Climate variables explained 56% (marginal R^2 of 56%) of the (regional and temporal) variation in Yw_H, which was lower than the explained variation in Yw_F across all GCMs both with and without CO_2 effects (marginal R^2 values between 66 and 86%) (Table 1). Explained variation by fixed effects only, given by the marginal R^2, in Yw_F under scenarios with CO_2 effects were somewhat higher (74 and 86%) than without CO_2 effects (66 and 83%) across GCMs. For both Yw_H and Yw_F a large share of the total explained variance (conditional R^2) was due to the fixed effects. Precipitation effects were stronger than temperature effects with increases in dry season precipitation consistently showing the strongest positive effect on both Yw_H and Yw_F (for both CO_2 scenarios and across GCMs). Temperature had positive effects on Yw_H and Yw_F based on the warm/wet (under both CO_2 scenarios), warm/dry (under the scenario with CO_2) and mid (without CO_2 scenario) GCMs and negative effects on Yw_F based on the hot (hot/wet, hot/dry under both CO_2 scenarios), warm/dry (under the scenario without CO_2) and mid (under the scenario with CO_2) GCMs. Thus, except for the mid GCM, temperature effects became more negative or less positive when not accounting for CO_2 effects.

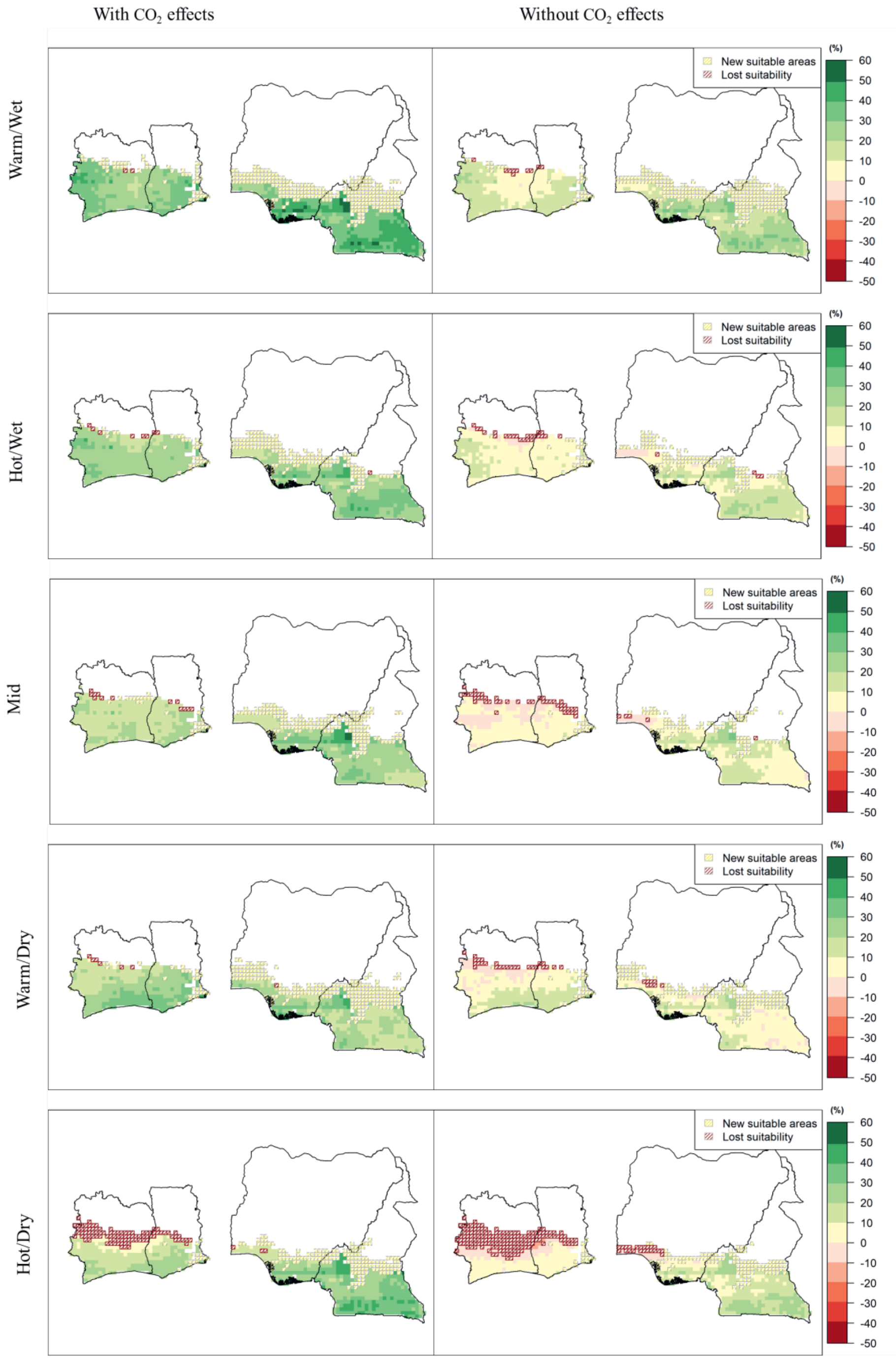

Fig. 4.3. Maps of predicted changes (future – historical in percentages) in simulated water-limited potential yield between the historical (1980-2010) and future (2030-2060) period, with and without CO_2 effects.

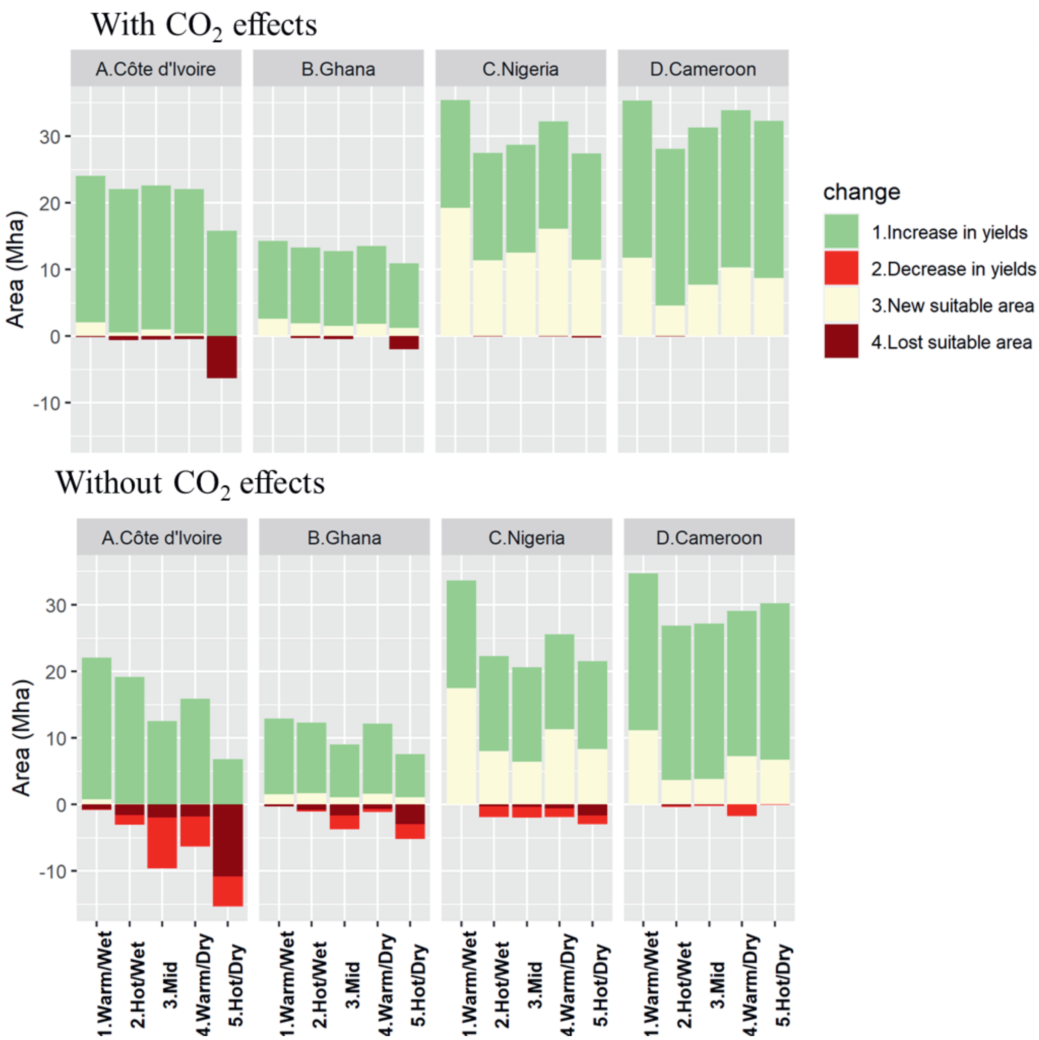

Fig. 4. 4. Predicted changes in total area suitable for cocoa production in each country where simulated water-limited potential yield is expected to change, with and without CO_2 effects.

Table 1. Results of the mixed-effects models for the historical (1980-2010) and future (2030-2060) period based on simulated water-limited potential cocoa yields as a function of climatic factors. Yields are based on five GCMs with and without CO_2 effects. Only variables retained in the final model after collinearity evaluation using variance inflation factor <3 are shown. The variable with the strongest effect for each GCM and CO_2 scenario is indicated in bold.

Predictors	**Estimates**		**Confidence Interval**		***Marginal R^2/Conditional R^2***	
			Historical			
Average temperature (dry season)	108		90 – 126			
Precipitation (dry season)	**375**		364 – 387		*0.56 / 0.89*	
Precipitation (wet season)	206		179 – 233			
			Future			
	With CO_2 effects	*Without CO_2 effects*	*With CO_2 effects*	*Without CO_2 effects*	*With CO_2 effects*	*Without CO_2 effects*
Warm/Wet						
Average temperature (dry season)	103	90	83– 123	72– 109	*0.79 / 0.90*	*0.79 / 0.89*
Precipitation (dry season)	**784**	**696**	771 – 8	683– 708		
Hot/Wet						
Annual precipitation	270	224	225 – 314	183 – 264		
Average temperature (dry season)	-26	-39	-46 – -6.1	-58 – -21	*0.74 / 0.91*	*0.74 / 0.91*
Precipitation (dry season)	**619**	**547**	604– 635	533– 560		
Mid						
Precipitation (dry season)	**633**	**511**	622 – 644	501– 522	*0.78 / 0.90*	*0.66 / 0.90*

Maximum temperature (wet season)	-63	4	-91– -36	-21 – 29		
Warm/Dry						
Annual precipitation	55	95	24 – 85	66– 124		
Average temperature (dry season)	22	-18	4.5 – 39	-32 – -2.9	*0.86 / 0.92*	*0.83 / 0.94*
Precipitation (dry season)	**720**	**594**	707 – 732	584 – 605		
Hot/Dry						
Annual precipitation	177	191	136 – 217	145 – 236		
Precipitation (dry season)	**684**	**573**	669 – 699	559– 588	*0.79 / 0.91*	*0.74 / 0.92*
Maximum temperature (wet season)	-68	-79	-100 – -36	-110 – -48		

4.3.3. *Effects of climate change on inter-annual cocoa yield variability with and without CO_2 effects*

In most areas, inter-annual cocoa yield variability is expected to decrease by mid-century but increases are expected in areas with lower yields. Inter-annual yield variability during the historical (Ywv_H) and the future (Ywv_F) periods was larger in areas with lower Yw both with and without CO_2 effects (Fig. 4.S7 & S9). Similar to Yw, predicted changes in inter-annual yield variability were more positive (reduced variability) under the scenario with CO_2 effects than without CO_2 effects. Again, across GCMs, predicted increases in inter-annual yield variability were larger for the mid and dry GCMs (some exceptions under warm/dry), than in the wet GCMs (Fig. 4.S10, Fig. 4.5). Strong increases in inter-annual yield variability ($10 - 100\%$) were expected for most of Côte d'Ivoire, particularly in the (north) western parts, under both CO_2 scenarios (Fig. 4. 5, Fig. 4. S11). In contrast, inter-annual yield variability decreased strongly (up to ~75%) for most of Cameroon and Nigeria and decreased to a lesser extent in Ghana (up to ~68%) (Fig. 4. S10-S11).

Results from the mixed-effects models indicated that effects of climate variability on both Ywv_H and Ywv_F (with and without CO_2 effects for all GCMs) were not very strong, but that effects depended on the selected climate scenario. Variability in climate explained 44% of the variation in Ywv_H whilst the explained variation in Ywv_F ranged from 35-57% under the scenario with CO_2 and from 22-54% without CO_2 effects (Table S3). For most models, a large share of the total variance was explained by the fixed effects, except for Ywv_F based on the mid, warm/dry and hot/dry GCMs where fixed effects explained a smaller part of the total variance (i.e. when both fixed and random effects are considered given by conditional R^2). Amongst the fixed effects, variability in the number of consecutive dry months consistently decreased Ywv_H and Ywv_F under both CO_2 scenarios across GCMs. Variability in precipitation and temperature had both positive and negative effects on yield variability depending on the climate scenario (Table S3). For instance, variation in annual and dry season precipitation increased Ywv_H and Ywv_F (based on hot/wet and warm/dry) whilst that of the wet-season precipitation decreased Ywv_H and Ywv_F (hot/dry). For temperature, variability in minimum temperature (wet season) generally reduced yield variability whilst that of the dry season increased it. Variability in maximum temperature (annual, wet and dry season) also increased yield variability except for Ywv_F based on the hot/wet and mid (under with-CO_2 scenario) GCMs. Likewise, variability in average temperature (annual) decreased yield variability whilst wet and dry season average temperature variation increased yield variability across all GCMs.

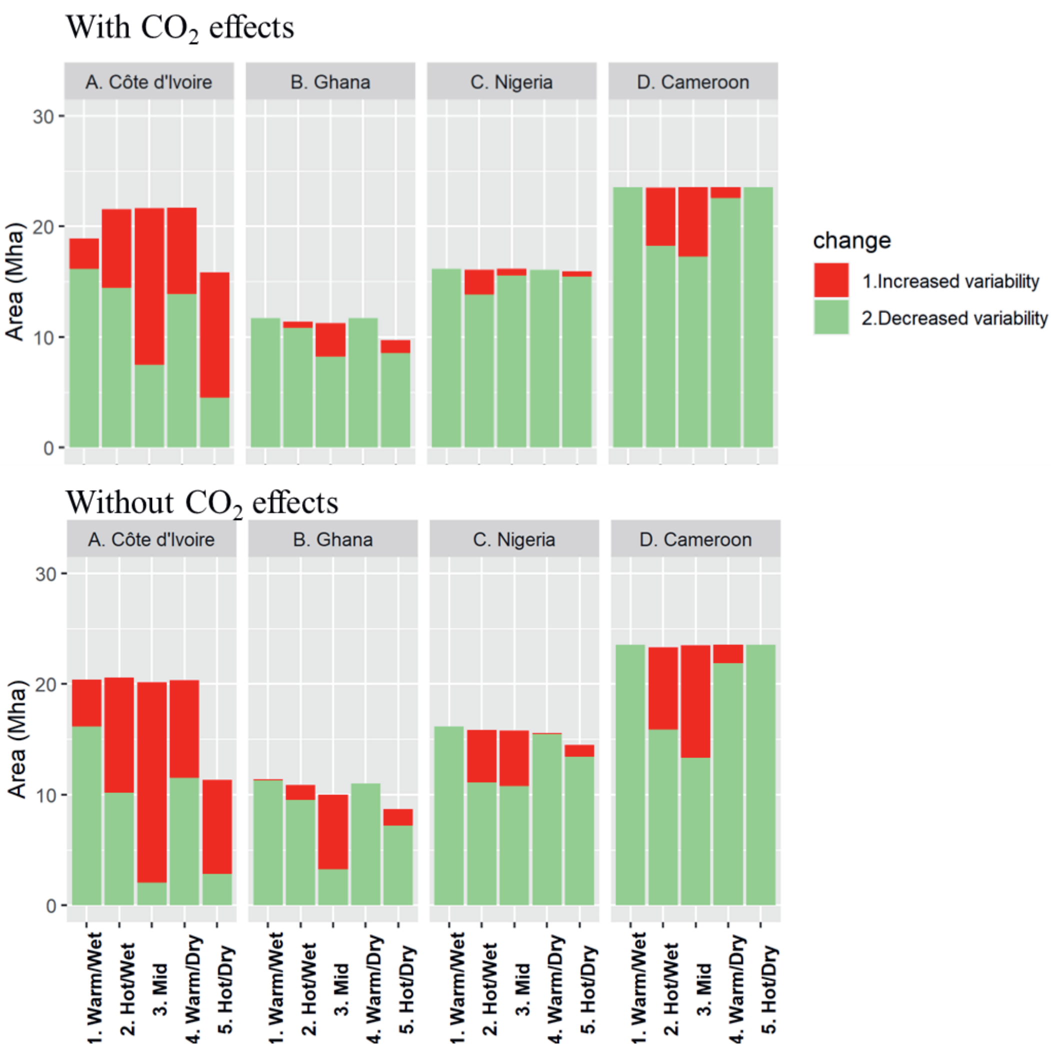

Fig. 4. 5. Expected shifts in cocoa yield variability under climate change. Shown is the area under current cocoa production where variability in yield is expected to increase or decrease, for simulations with and without CO_2 effects.

4.3.4. Future cocoa production scenarios with no expansion in the area planted

Historical and future (with and without CO_2 effects for the mid GCM only) cocoa production (in tonnes) at country level were estimated based on the current total cocoa plantation area in a country (Fig. 4.S2) and average cocoa yields for Côte d'Ivoire and Ghana. Average cocoa yields were calculated based on the current relative yield gap of 86% for the BAU scenario and 73% for the high-input scenario (to represent nearly a 100% increase in yields using high inputs) (Fig. 4. S13) (see Chapter 3 for these definitions). Current cocoa plantation area (~3.69 Mha in Côte d'Ivoire and 2.15 Mha in Ghana; Fig. 4. S2) and average predicted yields were larger in Côte d'Ivoire than in Ghana under both the BAU and high-input scenarios for both historical and future (both CO_2 scenarios) periods (Fig. 4. S12). Thus, total cocoa production in tonnes was higher in Côte d'Ivoire than in Ghana over both periods.

Under BAU, total cocoa production in Côte d'Ivoire increased from the historical value of 2,613,382 to 3,130,895 tonnes (i.e., a ~20% increase) in the future scenario with CO_2 effects and to 2,681,112 tonnes (2.6% increase) without CO_2 effects. Whilst in Ghana, production increased from a historical value of 1,208,741 to 1,566,026 tonnes (~30%) in the future with CO_2 effects and to 1,321,171 tonnes (9%) without CO_2 effects (Fig. 4.6). Under the high-input scenario, total cocoa production was about twice that of the BAU scenario, with production increasing to 6,038,154 tonnes in the future with CO_2 effects and to 5,170,715 without CO_2 effects in Côte d'Ivoire. For Ghana, total production increased to 3,020,194 tonnes with CO_2 effects and to 2,547,973 tonnes without CO_2 effects. This indicates that total cocoa production in the current cocoa plantation area is projected to increase in both countries with a stronger relative increase expected in Ghana than in Côte d'Ivoire under both BAU and high-input scenarios.

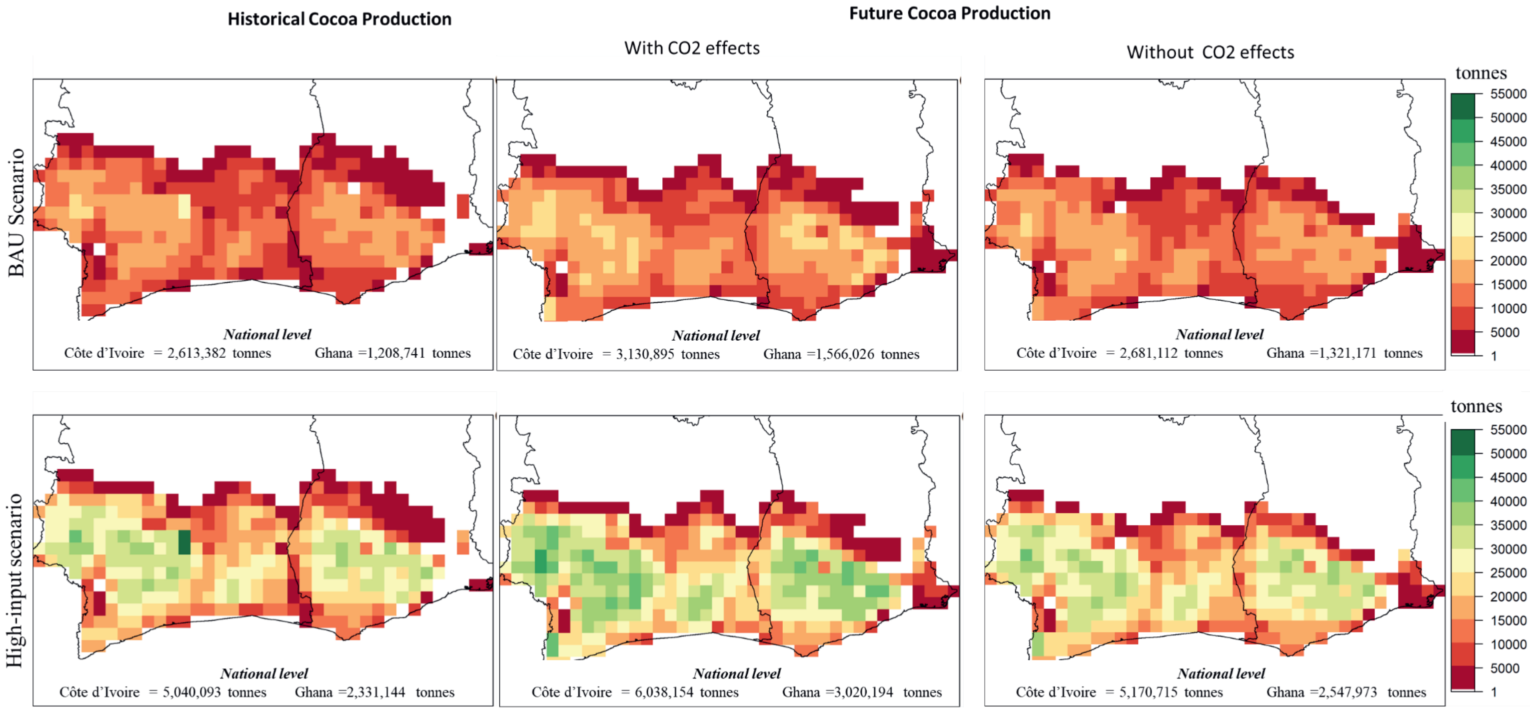

Fig. 4.6. Predicted historical and future cocoa production (tonnes) with and without CO_2 estimated based on the total cocoa plantation area and simulated annual cocoa yield based on the current relative yield gap (86%) and attainable yield gap in high-input systems (73%). Predictions are based on the mid GCM only.

4.4. Discussion

4.4.1. Overview of key results

In this study, we simulated effects of warming and elevated atmospheric [CO_2] on potential water-limited cocoa yields based on five plausible future climates projected by bias corrected and downscaled GCMs and assessed how climate change and year-to-year variation influenced mean cocoa yields and inter-annual yield variability. We then quantified how much cocoa could be produced in the future without expanding the current area under cocoa cultivation, under both low-input business-as-usual and high-input scenarios. With some notable exceptions, the overall tendency in our simulations was that under future climate scenarios up to mid-century, increases in potential water-limited cocoa yields and gains in area suitable for cocoa production are expected, particularly when the CO_2 effect is accounted for and under wetter conditions. There appeared to be a clear geographic trend, with the strongest increases in yield and in the area suitable for cocoa expected in the eastern-most country, Cameroon, whilst the lowest increases in yield and suitability were expected at the western end of Côte d'Ivoire. Inter-annual yield variability was generally expected to be higher in areas with lower yields, thus the strongest increases in future yield variability were predicted in Côte d'Ivoire. Predicted changes in water-limited potential yields were most strongly associated with projected changes in dry season precipitation. Temperature changes had both positive and negative effects on yields depending on the region and climate scenario. Lower variability in consecutive number of months with precipitation < 100 mm reduced inter-annual cocoa yield variability. Using the mid-climate scenario (with and without CO_2 effects) as example, it was also predicted that current country-level production could be maintained with current cocoa growing areas in Côte d'Ivoire and Ghana by mid-century.

4.4.2. Limitations

This study has a number of limitations which need to be taken into account when interpreting the results. First, uncertainties with regards to GCM projections of temperature and precipitation, including uncertainties resulting from the bias correction and downscaling, may impact our simulated future cocoa yields (James & Washington, 2013; Kent et al., 2015). We found that future predicted potential water-limited yields were most strongly related to dry-season precipitation, but dry-season precipitation is also one of the climate variables that current

GCMs are most uncertain about (Kent et al., 2015). GCM predictions of climate change at smaller spatial scales are not very reliable, and predictions of future precipitation in Africa are difficult due to a lack of data availability and process understanding. There is, for instance, insufficient knowledge of the future extent of land-use change and its impact on climate. Also, GCMs may not fully capture interannual climate variability as local conditions such as the harmattan winds that could trigger climate extremes are likely not captured within GCMs (Rodríguez-Fonseca et al., 2015; Saini et al., 2015). Thus, GCMs do not accurately capture the finer scale year-to-year variation yet. Nonetheless, GCM projections are based on detailed descriptions of the major physical processes controlling climate and provide coherent physical realizations of possible future changes in climate. To address the limitations outlined, we chose to look at contrasting scenarios based on multiple GCMs instead of a single GCM or unweighted ensemble averages .

Secondly, the validation of the cocoa simulation model should be considered. CASE2 was able to give reasonably good predictions of yields obtained under well-watered conditions on research stations (in Brazil, Malaysia and to a lesser extent Ghana) (Zuidema et al., 2005). However, it has not been validated in the context of climate change or CO_2 rise studies, as there are currently no free-air CO_2 concentration enrichment (FACE) experiments and warming experiments for cocoa. Furthermore, in our calculations we only included short-term effects of elevated [CO_2], but no long-term acclimation to [CO_2]. Crop responses to elevated [CO_2] in the field may be smaller than model predictions possibly because mitigating effects caused by, for example, nutrient limitations that are not adequately accounted for in models (Ainsworth & Long, 2005, and see Section 4.4.3). Thus our simulations with the full-CO_2 effects scenario may likely have overestimated CO_2 effects on cocoa productivity, and this is the reason we also included the no CO_2 effects scenario.

4.4.3. Elevated atmospheric [CO_2] could potentially offset the negative effects of warming on future cocoa production

As expected, more positive climate change effects on cocoa production (i.e., larger increases in yields, gains in suitable areas, and decreases in inter-annual cocoa yield variability) were found when assuming full CO_2 effects with no acclimation. This suggests that the rise in atmospheric [CO_2] by mid-century (454 – 650ppm between 2030-2060) could potentially offset the negative effects of warming on cocoa production in West and Central Africa under the assumption of full and unconstrained CO_2 effects.

Positive effects of increases in CO_2 and effects of adaptation on average yields of C3 crops were found to be large enough to offset negative effects of temperature increases even at +4 ^{o}C (Makowski et al., 2020). Nevertheless, some studies have reported that the negative interaction between temperature and CO_2 offsets the positive effects of elevated CO_2 on wheat and rice yields (C3 crops) (Cai et al., 2016; Makowski et al., 2020; Tubiello et al., 2000). In FACE experiments, C3 crop responses to increased atmospheric [CO_2] were found to be higher in tree crops (like cocoa), than in annual crops (Ainsworth & Long, 2005). The stronger response in tree crops to elevated CO_2 may be due to, amongst other factors, length of exposure (longer lifespan), sink size and activity (related to determinate and indeterminate growth habit), which allows more use of extra photosynthate available in higher CO_2 environments when other resources are not limited (Lee & Jarvis, 1995). In coffee for instance, responses to elevated [CO_2] in growth chambers (without restrictions to root growth) (Rodrigues et al., 2016) and under field conditions (FACE trials in Brazil) (Ghini et al., 2015) showed that elevated [CO_2] stimulated photosynthesis and increased crop yields, on average, by 28%, which is higher than the mean stimulation of 17% in FACE experiments with a range of species (C3 species; cotton yield increase by 42%, wheat and rice increase by 15% and no yield increase in sorghum, a C4 species) (Ainsworth & Long, 2005; DaMatta et al., 2019). The large yield increase reported for cotton (*Gossypium barbadense*, a woody perennial) in FACE experiments further confirms that perennial crops like cocoa might benefit more from elevated [CO_2] than annual crops like wheat and rice. Juvenile cocoa trees grown under elevated [CO_2] (700ppm) in a greenhouse experiment showed increases in photosynthetic rates, enhanced vegetative growth, improved nutrient uptake and use efficiency for several nutrients including nitrogen (Baligar et al., 2005).

Modelling studies on coffee (Rahn et al., 2018; Verhage et al., 2017) and cocoa (Black et al., 2020) concluded that elevated [CO_2] effect could potentially mitigate the negative impact of rising temperature and drought stress on coffee yields and cocoa net primary productivity under future climate. Nonetheless, benefitting from the positive effect of increasing [CO_2] may require increases in soil nitrogen supply as effects of elevated [CO_2] tend to weaken under nutrient limitation (particularly nitrogen; Ainsworth & Long, 2005; Makowski et al., 2020). This was not considered in our model simulations but could likely play a role on small-holder cocoa farms in West and Central Africa due to nutrient limitations (van Vliet & Giller, 2017). Integrated soil fertility management in combination with good agricultural practices is therefore an important adaptation strategy (Chapter 2). The positive effects of elevated [CO_2] on cocoa productivity supports our hypothesis (see Section 4.1).

4.4.4. Increases in cocoa yields, gains in suitability and decreased inter-annual yield variability expected under future climate

Increases in potential water-limited cocoa yields and gains in area suitable for cocoa production are expected under future climate scenarios, particularly when CO_2 effects are accounted for and when dry seasons become wetter. Across the four cocoa-producing countries, there was a clear (south) east – west gradient with predictions being most positive for Cameroon (strongest increases in yield, and in the area suitable for cocoa) in the east, followed by Nigeria and Ghana and least positive for Côte d'Ivoire (lowest increases in yield and suitability are expected) in the west. Inter-annual yield variability was expected to be larger in areas with lower yields, thus the spatial pattern of changes in yield variability also followed an (south) east – west gradient with reduced variability in Cameroon and the largest increases in variability in Côte d'Ivoire particularly in areas in the (north) west of the Côte d'Ivoire cocoa zone (Fig. 4. S10). The most negative predicted effects on yields were along the northern edge of the cocoa-production zone in Côte d'Ivoire and Ghana which have already become marginal for producing cocoa (Ruf et al., 2015). Our results suggest that under future climate, cocoa production may shift more from Ghana and Côte d'Ivoire, where currently over 60% of global cocoa production takes places (ICCO, 2022), towards the eastern countries, Nigeria and Cameroon, while within Ghana and Côte d'Ivoire production may become more constrained to the south. An important consequence could be that as shifts in production areas may favour Cameroon, potential increases in cocoa production in this region outside the current growing area could have serious consequences for forest areas. This is because Cameroon is one of the African countries where most rain forest and associated biodiversity is still present (Sassen et al., 2022).

The general direction of the geographic shifts in climatically suitable areas that we projected are consistent with the projections by Schroth et al. (2016). However, our projections of the overall net effect of climate change in cocoa suitability are more positive. The difference between the two approaches is that in our study we include CO_2 effects and quantify suitability changes in terms of growth and yield. Previous studies using statistical species distribution models (SDMs) predicted more negative impacts on the climate suitability of cocoa growing areas which is only comparable with our results for the most pessimistic future climate (hot/dry) without elevated [CO_2] effects (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). Thus, our results show that accounting for elevated [CO_2] effects on cocoa (which is not accounted for in SDMs) partly ameliorates the negative effects of warming even under the most pessimistic scenario. In addition, SDMs implicitly assume that the climate under which cocoa is currently grown sufficiently represents the environmental envelope in which it can grow successfully for agricultural purposes and lacks the mechanistic processes to predict crop responses outside the current growing domain (Rahn et al., 2018). Thus, projections based on SDMs may not fully represent the effects of climate change on cocoa. On the other hand, while our modelling approach intends to integrate current knowledge of cocoa growth and yield formation, including the elevated CO_2 effect, we do not consider the fact in some areas farmers may not grow cocoa because other crops are economically more advantageous. But, to the best of our knowledge, our study is the first to quantify effects of climate change and elevated [CO_2] effects on cocoa yield using a process-based approach. However, as we still lack a complete understanding of cocoa responses to climate change which is also reflected in the CASEJ model, continued research efforts are required to close these knowledge gaps (Tosto et al., 2023).

The outlook of climate change effects on cocoa until the mid-century depends on how climate change will affect precipitation, as more positive effects were expected under wetter conditions than under drier conditions (Fig. 4.3). Analyses with a mixed-effects model showed that, together, climate factors explained 74-86% of the variation in predicted yields and 22-57% of the variation in inter-annual yield variability across sites and years (Table 4.1). It also showed that increases in dry-season precipitation had the strongest positive effect on yield whilst reduction in the consecutive number of dry months (precipitation below 100 mm) decreased inter-annual yield variability. This indicates that the rainfall distribution throughout the year rather than the annual amount is most relevant for cocoa yields (Alvim, 1977; Wood, 1985; Zuidema et al., 2005). Increases in dry-season precipitation were predicted by all GCMs for coastal zones, therefore allowing cocoa production to increase. Temperature in turn had both positive and negative effects on yields, which suggests that projected temperatures in these climate change scenarios up to the mid-century bracket are close to the optimal temperature for cocoa production and whether or not they will surpass this optimum depends on the extent of warming. Warming extent largely depends on the rate of emissions and feedbacks in the climate system and the chosen horizon (Pörtner et al., 2022). As our simulations were done for the period of 2030-2060 and as this period seemed to have temperatures around the optimum, one may expect that if a longer horizon would have been chosen, more negative changes would likely have been obtained, particularly under scenarios assuming no CO_2 effect.

Overall, water availability during the dry season and the length of dry season will play a key role in determining future yields and yield variability (Carr & Lockwood, 2011), as well as the extent to which the CO_2 effect will offset the negative impacts of warming. These findings are roughly in agreement with potential effects earlier reported for cocoa in West and Central Africa (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017), but our projections are generally more positive based on the potential CO_2 effect and our approach focusses on changes in yields rather than climate suitability. It should be noted that more wet and humid conditions with increasing precipitation could increase incidence of diseases such as black pod which has considerable negative effects on cocoa yields (Anim-Kwapong & Frimpong, 2004; Cilas & Bastide, 2020). Thus, studies on pest and disease incidence in relation to spatial and temporal weather variation are needed to quantify risks on yields in the future.

4.4.5. Prospects of future cocoa production under climate change in Côte d'Ivoire and Ghana

Prospects of geographic shifts in production areas due to climate change could affect future cocoa production in Côte d'Ivoire and Ghana, the two countries supplying over 60% of cocoa beans globally (ICCO, 2022). The average historical cocoa production we estimated was 2,613,382 tonnes in Côte d'Ivoire which is slightly higher than the reported average of 2,248,000 tonnes for the 2020/2021 season whilst our predicted average of 1,208,741 tonnes in Ghana was also slightly higher than the 1,047,000 tonnes reported (ICCO, 2022). Under future climate, based on the mid-climate scenario, production increased beyond historical levels by 20% and 2.6% with and without CO_2 effects in Côte d'Ivoire and 30% and 9% in Ghana, respectively, following current management practices, i.e. business-as-usual. Nonetheless, the yield gap under BAU under the with-CO2 scenario may likely increase in the future due to nutrient limitations on most cocoa farms (van Vliet & Giller, 2017). This suggests that under these modelling assumptions, current country-level production can be maintained with current cocoa growing areas in Côte d'Ivoire and Ghana by mid-century, assuming no change in management and constant yield gaps under future climate scenarios.

Nonetheless, as cocoa demand increases (currently growing at approximately 3% per year (Beg et al., 2017)) beyond current levels (current global demand, 5,081,000 tonnes with the two countries supplying 65%, i.e. 3,295,000 tonnes, in the 2020/2021 season (ICCO & Surplus, 2022)), our results shows the possibility of doubling country-level production on current plantations if yields would increase from BAU to high-input through improved management or recommended management practices (high-input systems). This may help reduce pressure on forests and cocoa-related deforestation in major cocoa producing countries (Abu et al., 2021; Ruf et al., 2015; van Vliet & Giller, 2017).

4.5. Conclusion

With some notable exceptions, results from this study suggest that for the 2030-2060 decades, increases in potential water-limited cocoa yields and gains in the area suitable for production are expected, particularly when CO_2 effects are accounted for and under wetter conditions. Based on these climate scenarios, inter-annual yield variability is lower compared to historic climate conditions and higher in areas with lower yields. Across the four major cocoa-producing countries in West Africa (Côte d'Ivoire, Ghana, Nigeria) and Central (Cameroon), model predictions showed a clear (south) east – west gradient. The most positive effects in terms of projected changes in yield, suitability and yield variability were found in Cameroon followed by Nigeria, Ghana and the least positive effects in Côte d'Ivoire. Within Côte d'Ivoire and Ghana, the most negative effects on production areas were expected to be in the northern parts whilst the northern part of Cameroon and Nigeria might experience improvements in climate suitability. Predicted increases in water-limited potential yields were mostly associated with projected increases in dry season precipitation whilst the consecutive number of months with precipitation below 100 mm reduced inter-annual yield variability. Temperature had both positive and negative effects on yields suggesting that temperature ranges are mostly close to optimal depending on the level of warming and water stress.

These results suggest that under future climate, shifts in suitability of cocoa growing areas may likely cause production to at least partly shift from Côte d'Ivoire and Ghana, towards Nigeria and Cameroon. Within Côte d'Ivoire and Ghana production may become more constrained to the south. Nonetheless, by mid-century, current country level production can be maintained with current cocoa growing areas in Côte d'Ivoire and Ghana.

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APPENDIX B

Supplementary Materials for Chapter 4

Climate change impacts on cocoa production in the major producing countries of West and Central Africa by mid-century

1. CASEJ Parameter description

Table 4.S1. Description of parameters used in simulations of water-limited potential yields using CASEJ. For further details see Zuidema, Gerritsma, Mommer, & Leffelaar (2003). New parameters in ***bold and italized***.

Parameter	Subsection	Description	Unit	Value(s)
AGEIYR	Cocoa tree characteristics	Age of the cacao tree at the start of the simulation in years	years	10
HGHL	Cocoa tree characteristics	Lower height of cacao tree crowns	m	0.75
HGHT	Cocoa tree characteristics	Upper height of cacao tree crowns	m	3.5
WTOTI	Cocoa tree characteristics	Total initial dry weight of the cacao tree	kg DW/tree	18.5
WTOTMIN	Cocoa tree characteristics	Total dry weight of the cacao tree at which fruiting starts	kg DW/tree	10
NPL	Cropping system	Cocoa tree planting density	1/ha	1000
SHGHL	Cropping system	Lower height of shade tree crowns	m	4
SHGHT	Cropping system	Upper height of shade tree crowns	m	10
SKDFL	Cropping system	Extinction coefficient for leaves of shade trees		0.6
SLAI	Cropping system	Leaf area index of shade trees	m^2 leaf/m^2 ground	0.2
AGBIORA	Age-biomass relation	Regression coefficient for age-biomass relation		8.4648
AGBIORB	Age-biomass relation	Regression coefficient for age-biomass relation	kg DW	-40.54
STFLA	Rain intercept	Regression coefficient for stem flow		0
STFLB	Rain intercept	Regression coefficient for stem flow	mm/d	0
TFALA	Rain intercept	Regression coefficient for throughfall of rain		0.927

TFALB	Rain intercept	Regression coefficient for throughfall of rain	mm/d	-0.789
FRPAR	Light intercept	Fraction of photosynthetically active radiation	PAR	0.5
TRANSC	Potential transpiration for cocoa	Characteristic potential transpiration rate	mm/d	1.5
EES	Soil evaporation	Evaporation proportionality factor	1/m	20
WCWET	Volumetric water content at which water logging occurs	Volumetric water content where water logging begins	cm^3 H2O/cm^3 soil	0.5
alpha	***Photosynthesis***	***Low-light quantum yield of electron transport***		***0.23***
AMINIT	Photosynthesis	Factor accounting for lower photosynthesis in young leaves		0.91
AMTMPTX	Photosynthesis	Temperatures to compute reduction factor on light-saturated photosynthesis		0, 30, 33, 40
AMTMPTY	Photosynthesis	Reduction factor for temperature effect on light-saturated photosynthesis		0, 1, 1, 0
Gstar	***Photosynthesis***	***CO2 compensation point in the absence of respiration***	***umol CO2/mol air***	***36.9***
Jmax	***Photosynthesis***	***Maximum rate of electron transport***	***umol/m^2/s***	***105 * 1.2***
KDFL	Photosynthesis	Extinction coefficient for cacao leaves		0.6
KDFT	Photosynthesis	Extinction coefficient for cacao trunk		0.5
Kmc	***Photosynthesis***	***Michaelis-Menten constant with respect to CO2***	***umol CO_2/mol air***	***404***
Kmo	***Photosynthesis***	***Michaelis-Menten constant with respect to O2***	***mmol CO_2/mol air***	***248***
MAXLAI	Photosynthesis	Maximum LAI used in the photosynthesis subroutines	m2 leaves/m^2 ground	10

O2	***Photosynthesis***	***Oxygen concentration***	***mmol O_2/mol air***	***210***
theta	***Photosynthesis***	***Curvature parameter of the light response curvature***		***0.7***
Vcmax	***Photosynthesis***	***Maximum rate of carboxylation***	***umol CO_2/m^2 leaf/s***	***45 * 1.2***
MAINLRT	Maintenance respiration	Maintenance respiration coefficient for lateral roots	kg CH2O/kg DW/d	0.0047
MAINLV	Maintenance respiration	Maintenance respiration coefficient of leaves	kg CH2O/kg DW/d	0.0069
MAINPD	Maintenance respiration	Maintenance respiration coefficient for pods	kg CH2O/kg DW/d	0.016
MAINTRT	Maintenance respiration	Maintenance respiration coefficient for taproot	kg CH2O/kg DW/d	0.0024
MAINWD	Maintenance respiration	Maintenance respiration coefficient for wood	kg CH2O/kg DW/d	0.0024
Q10	Maintenance respiration	Factor accounting for increase of maintenance		2
TREF	Maintenance respiration	Reference temperature for calculation of maintenance respiration	C	25
ASRQLRT	Growth respiration	Assimilate requirement for the production of 1 kg lateral roots	kg CH2O/kg DW	1.4941 5
ASRQLV	Growth respiration	Assimilate requirement for the production of 1 kg leaves	kg CH2O/kg DW	1.656
ASRQTRT	Growth respiration	Assimilate requirement for the production of 1 kg taproot	kg CH2O/kg DW	1.5687 1
ASRQWD	Growth respiration	Assimilate requirement for the production of 1 kg wood	kg CH2O/kg DW	1.5687 1
FLRTRA	Biomass partitioning	Regression coefficient on relation between lateral root and total biomass	kg DW lateral roots/kg DW whole plant	0.11

FLRTRB	Biomass partitioning	Regression coefficient on relation between lateral root and total biomass	kg DW lateral root	0.67
FLVRA	Biomass partitioning	Regression coefficient on relation between leaf and total biomass	kg DW leaf/kg DW whole plant	0.14
FLVRB	Biomass partitioning	Regression coefficient on relation between leaf and total biomass	kg DW leaves	0.43
FPDRA	Biomass partitioning	Regression coefficient on relation between pod and total biomass	kg DW pod/kg DW whole plant	0.026
FPDRB	Biomass partitioning	Regression coefficient on relation between pod and total biomass	kg DW pod	0.5
FTRTRA	Biomass partitioning	Regression coefficient on relation between taproot and total biomass	kg DW taproot/kg DW whole plant	0.039
FTRTRB	Biomass partitioning	Regression coefficient on relation between taproot and total biomass	kg DW taproot	0.36
FWDRA	Biomass partitioning	Regression coefficient on relation between wood and total biomass	kg DW wood/kg DW whole plant	0.62
FWDRB	Biomass partitioning	Regression coefficient on relation between wood and total biomass	kg DW wood	-0.7
MINCON	Minimum concentration of reserves	Minimum concentration of carbohydrate reserves	kg CH2O/kg DW	0.07
CFPDTBX	Growth C-content of pods	Fat content values to compute mass fraction carbon in pods		0.5, 0.55, 0.6
CFPDTBY	Growth C-content of pods	Mass fraction carbon in pods		0.5037, 0.50895, 0.51413

ASRQPDTBX	Growth pods	Fat content values to compute pod assimilate requirement		0.5, 0.55, 0.6
CFLRT	Growth carbon content plant	Mass fraction carbon in the lateral roots	kg C/kg DW	0.5008
CFLV	Growth carbon content plant	Mass fraction carbon in the leaves	kg C/kg DW	0.4673 7
CFTRT	Growth carbon content plant	Mass fraction carbon in the taproot	kg C/kg DW	0.5199 6
CFWD	Growth carbon content plant	Mass fraction carbon in the wood	kg C/kg DW	0.5199 6
AVGLVAGE	Leaves	Maximum leaf life span without water stress	d	210L
MINLVAGE	Leaves	Minimum leaf age		90
SLARA1	Leaves	Regression coefficient on leaf area per unit leaf biomass	ha leaf/kg DW leaf/kg DW plant	7.32e-06
SLARA2	Leaves	Regression coefficient on leaf area per unit leaf biomass	ha leaf/kg DW leaf/kg DW plant	-1.772
SLARB1	Leaves	Regression coefficient on leaf area per unit leaf biomass	ha leaf/kg DW leaf	0.0008 98
SLARB2	Leaves	Regression coefficient on leaf area per unit leaf biomass	ha leaf/kg DW leaf	0.9651
BHRA	Pods	Butter hardness regression coefficient	1/C	0.1
BHRB	Pods	Butter hardness regression coefficient		-1.01
DEVRRA1	Pods	Regression coefficient on relation between temperature and pod ripening	1/d/C	0.0003 6

DEVRRA2	Pods	Regression coefficient on relation between temperature and pod ripening	1/d/C	0.0002 048
DEVRRB1	Pods	Regression coefficient on relation between temperature and pod ripening	1/d	- 0.0022 6
DEVRRB2	Pods	Regression coefficient on relation between temperature and pod ripening	1/d	0.0015 4
FMTA	Pods	Regression coefficient on biomass loss due to fermentation		-0.015
FMTB	Pods	Regression coefficient on biomass loss due to fermentation	1/d	0.96
KCONTBN	Pods	K content of dry beans	kg K/kg DW bean	0.0095
NCONTBN	Pods	N content of dry beans	kg N/kg DW bean	0.021
PCONTBN	Pods	P content of dry beans	kg P/kg DW bean	0.004
SSTBX	Pods	Developmental stages to compute pod sink strength		0, 0.3, 0.467, 0.533, 0.633, 0.667, 0.778, 0.867, 1, 1.1
SSTBY	Pods	Values of pod sink strength at different developmental stages		0, 0.05, 0.17, 0.41, 0.94, 1, 0.94, 0.17, 0, 0
DIAM1	Roots	Mean diameter of fine roots	diameter < 1 mm	0.0002 2

DIAM2	Roots	Mean diameter of fine roots	diameter between 1 and 2 mm	0.0015
FWURT	Roots	Fraction of lateral roots that is able to extract water		0.2
LRTWURTDR	Roots	Loss of coarse lateral roots relative to that of water-uptaking roots	kg dead lateral roots/ kg C	0.1
RTOWURT	Roots	Relative turnover rate of water-uptaking roots	1/d	0.0027 4
SPRTL1	Roots	Specific root length, root diameter < 1 mm	m/kg DW	36000
SPRTL2	Roots	Specific root length, root diameter between 1-2 mm	m/kg DW	3000
SW	Roots	Specific weight of wood	kg/m^3	600
VDWURTRA	Roots	Regression coefficient on vertical distribution of fine roots		-1.06
VDWURTRB	Roots	Regression coefficient on vertical distribution of fine roots	$kg DW/ha/m^2$	199.9
HRTWDAGE	Wood	Age at which softwood is transformed into non-respiring heartwood	d	10
WDLVDR	Wood	Loss of wood relative to that of leaves	kg dead wood/kg dead leaves	0.077
FATCONTENT	Pod characteristics & processing	Fat content of nibs		0.55
FBEANS	Pod characteristics & processing	Dry weight fraction of beans in pod		0.55
FMTDUR	Pod characteristics & processing	Duration of the fermentation process	d	5
MOISTC	Pod characteristics & processing	Moisture content of dry, fermented beans		0.075
PODVALUE	Pod characteristics & processing	Number of pods per kg dry beans	1/kg DW	30

2. *Selection of GCMs*

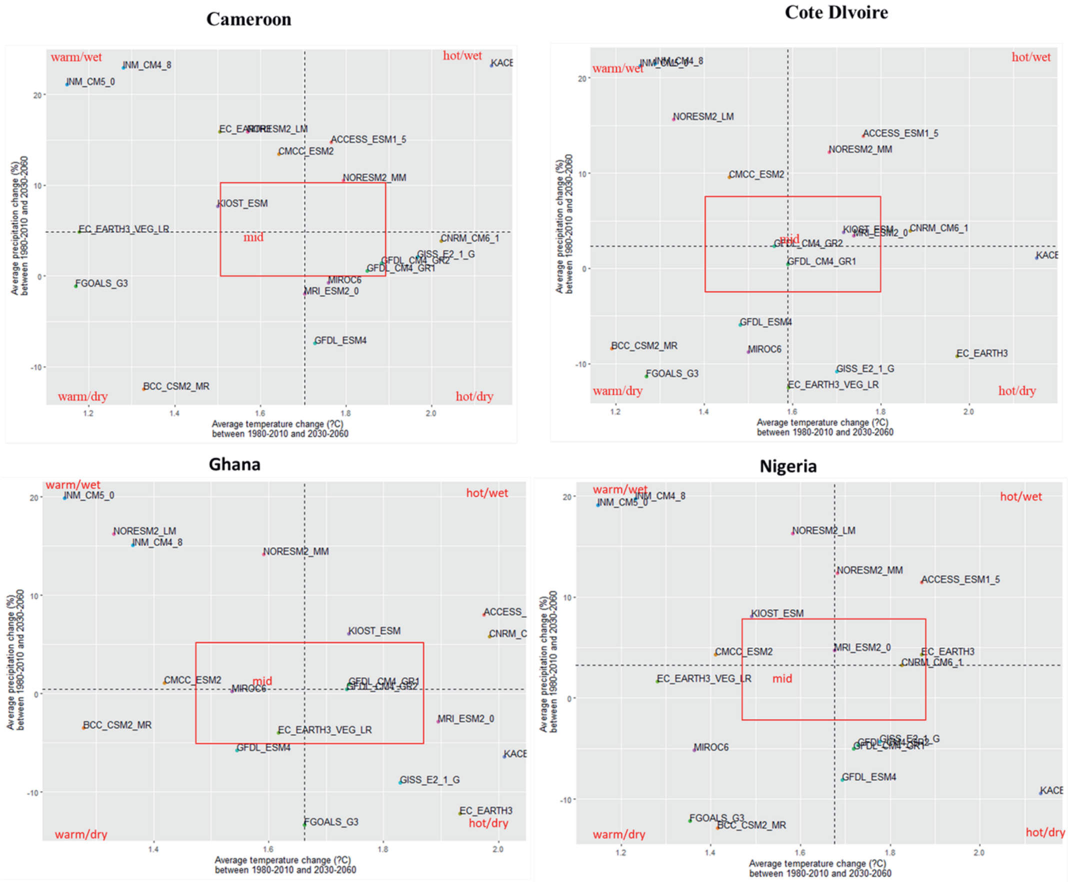
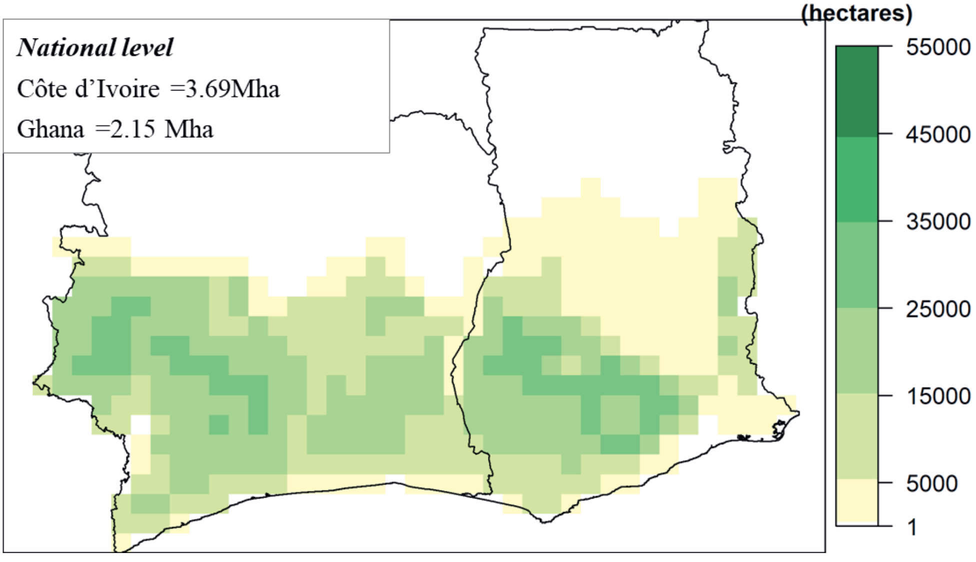


Fig. 4.S1: GCMs grouping based on changes in average precipitation and average temperature for four locations one in each of the included countries (Côte d'Ivoire, Ghana, Nigeria and Cameroon). Dotted lines indicate the median and the red box indicates the mid climate change quadrant. Selected representative GCMs are shown in Table S1.

Table 4.S2: Selected representative GCMs based on GCMs groupings (Fig, 4 S1) based on changes in average precipitation and average temperature for four locations one in each of the included countries (Côte d'Ivoire, Ghana, Nigeria and Cameroon).

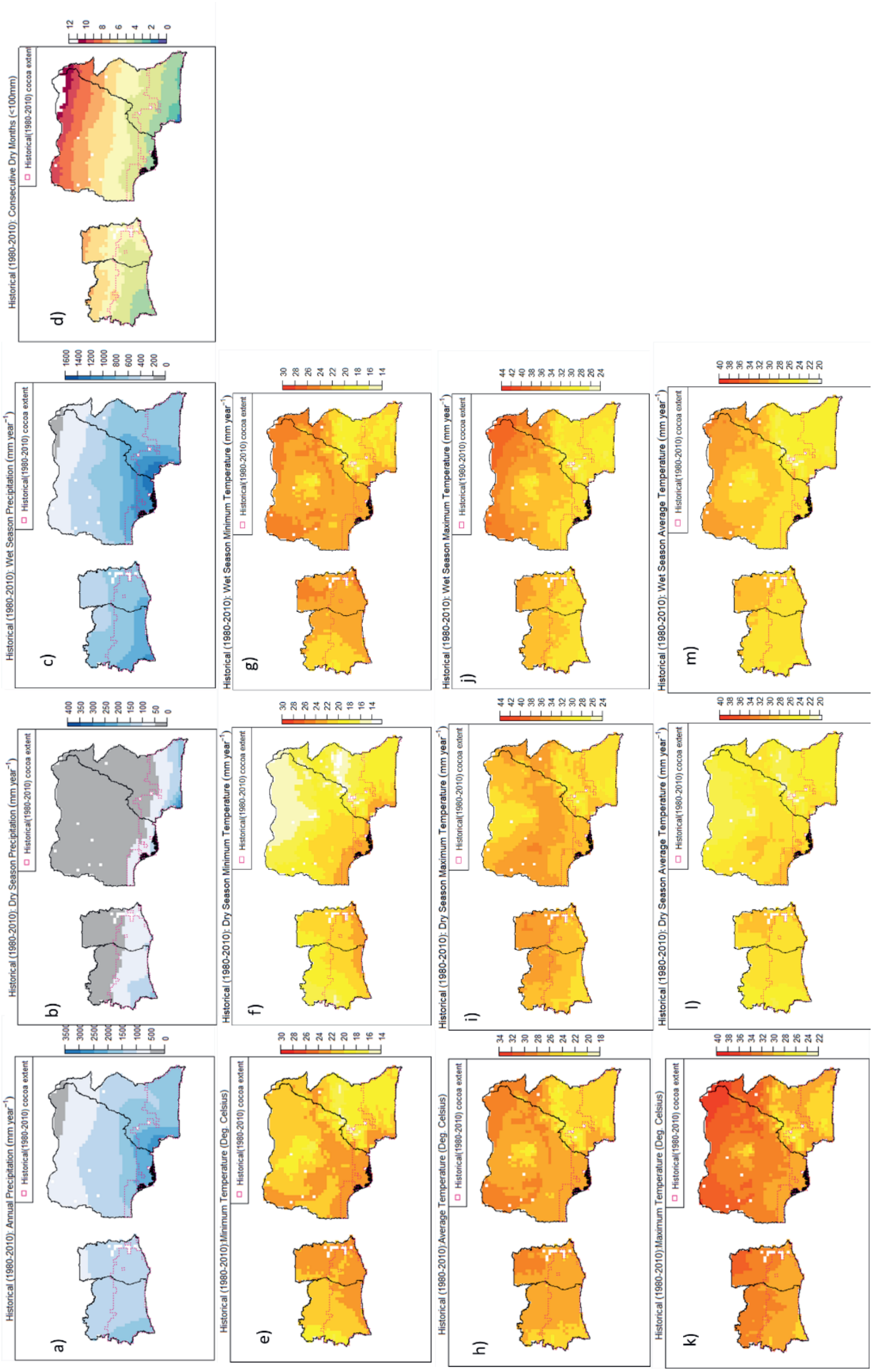
	Group	Representative GCM
1	Warm/Wet	INM-CM4-8
2	Hot/Wet	ACCESS-ESM1-5
3	Mid	GFDL_CM4_GR2
4	Warm/Dry	BCC-CSM2-MR
5	Hot/Dry	GISS-E2-1-G

3. Total cocoa plantation area



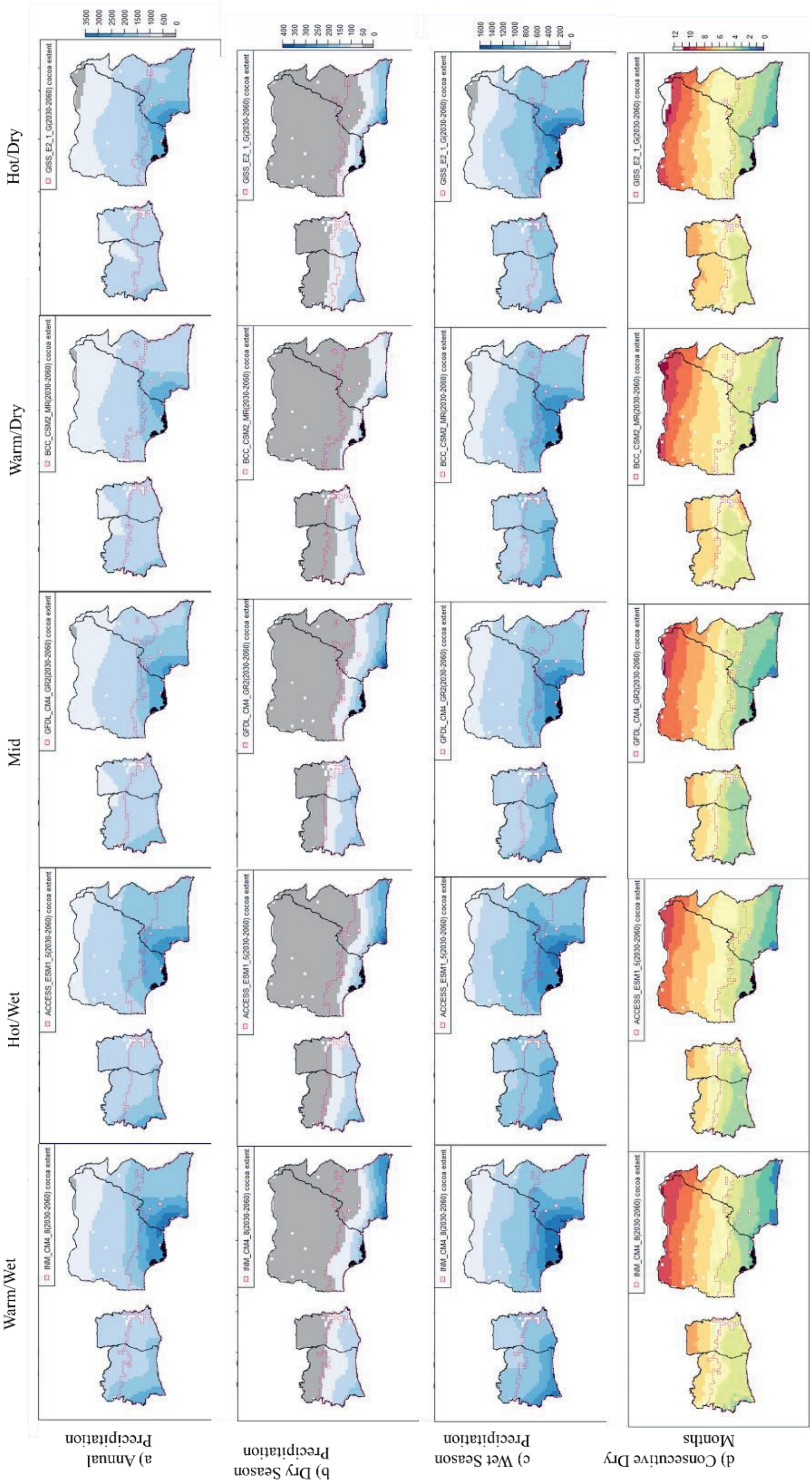
Fig, 4. S2. Total cocoa plantation area per 0.25° (~25-km) grid cell in Côte d'Ivoire and Ghana estimated using a map of cocoa growing areas based on remote-sensing imagery (Abu et al., 2021).

4. Historical precipitation and temperature

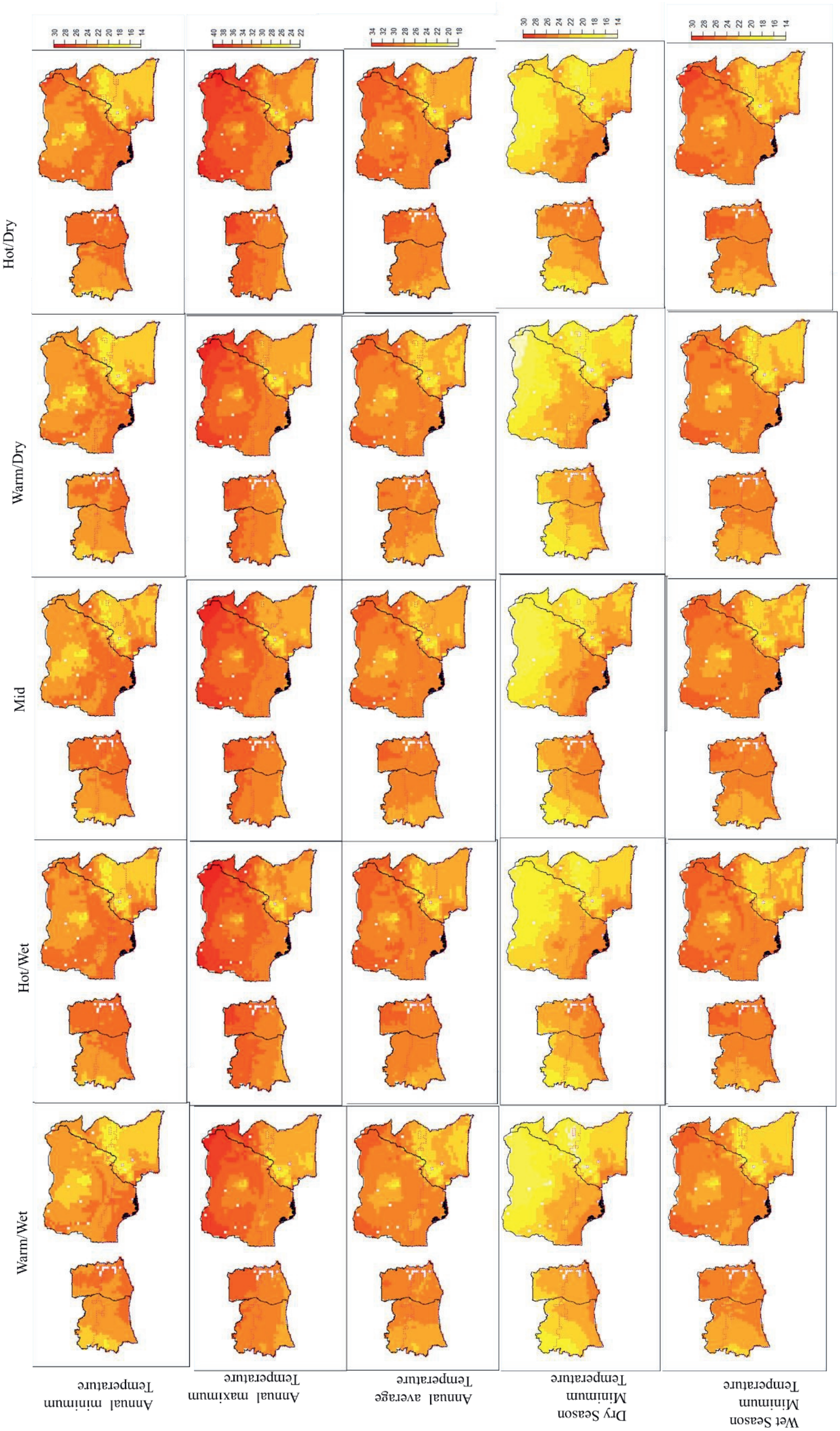


Fig, 4.S3. Historical a) annual precipitation (mm), b) dry and c) wet season precipitation (mm), d) consecutive months with precipitation less than 100mm e) annual, f) dry and g) wet season minimum temperature, h) annual, i) dry and j) wet season average temperature and k) annual, l) dry and m) wet season maximum temperature, across Côte d'Ivoire, Ghana, Nigeria and Cameroon. The red line indicates the border of the current suitable cocoa production area, based on yield simulations

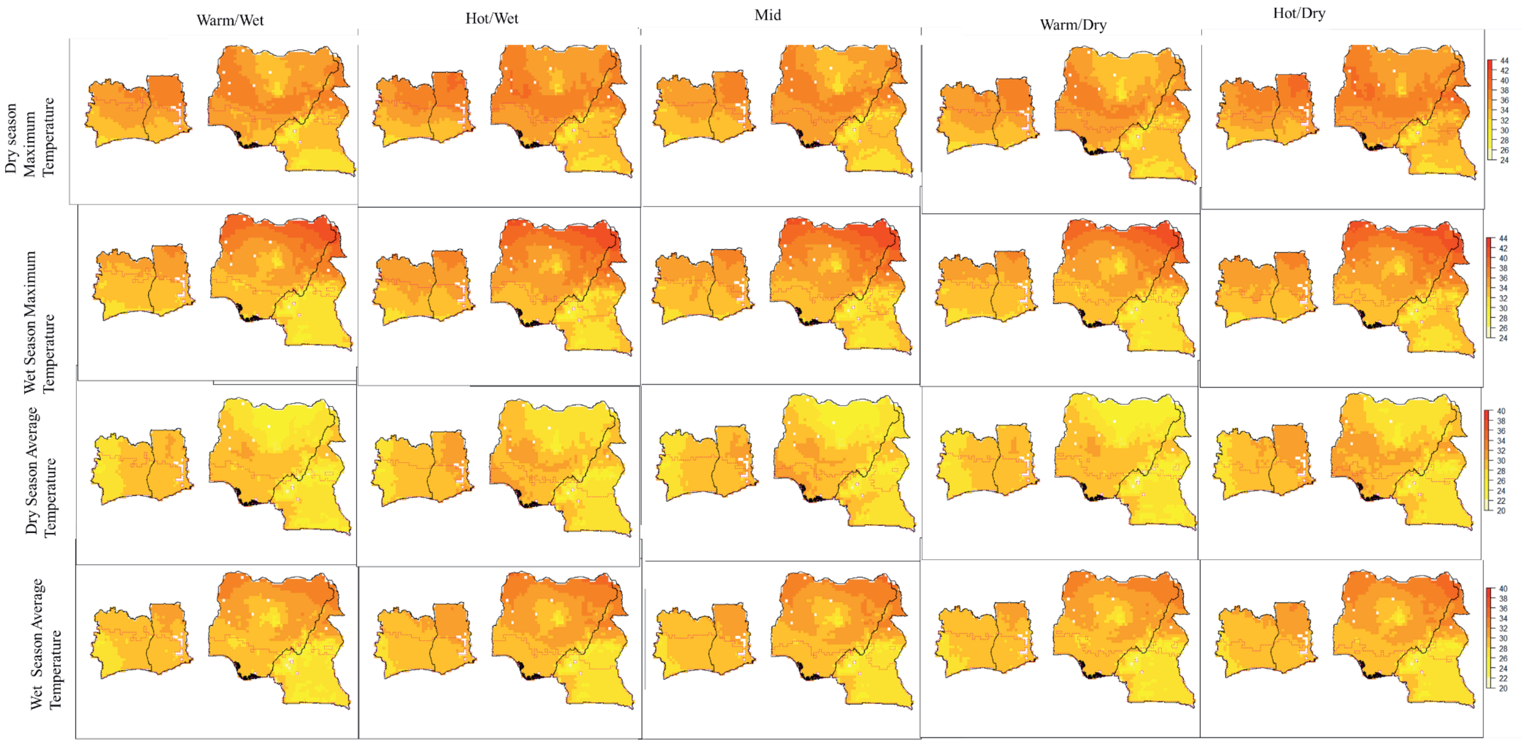
5. Future precipitation and temperature changes



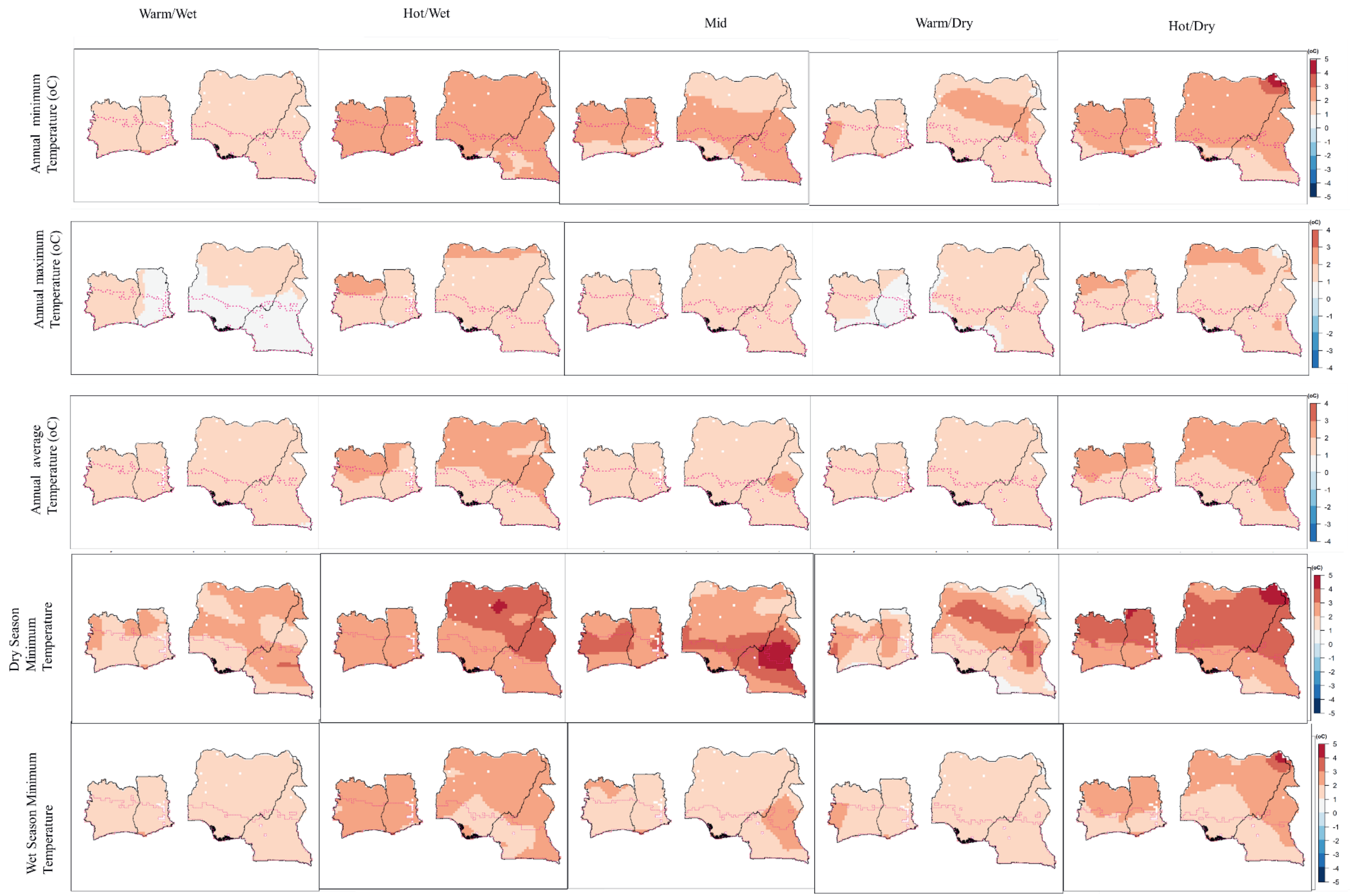
Fig, 4.S4. Predicted future (a) mean annual precipitation (mm), (b) dry and (c) wet season precipitation (mm), (d) number of consecutive months with precipitation less 100mm (dry months) across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). The red line indicates the border of the current suitable cocoa production area, based on yield simulations



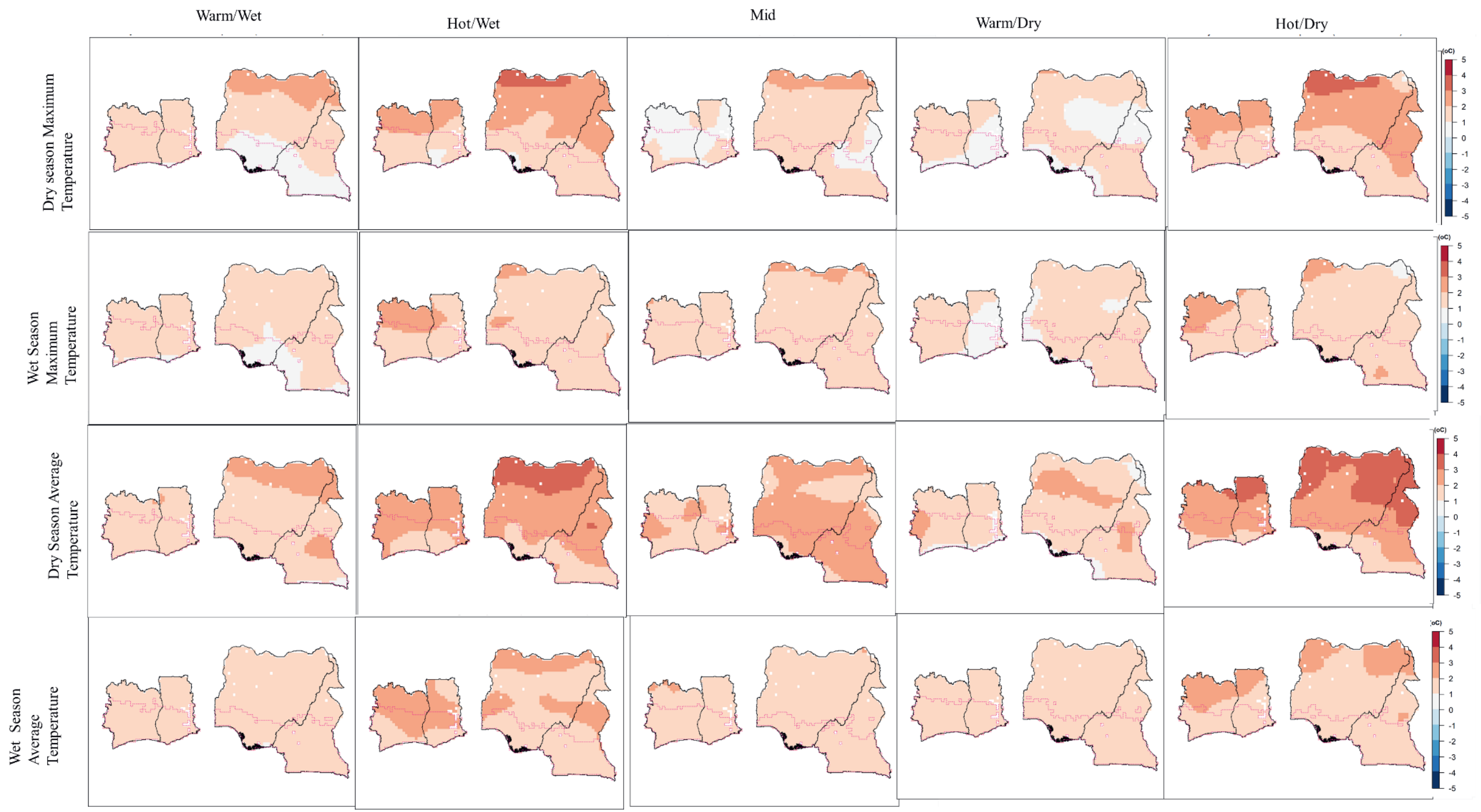
Fig, 4.S5a. Predicted future mean annual and seasonal minimum temperature (ºC) across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). The red line indicates the border of the current suitable cocoa production area, based on yield simulations.



Fig, 4.S5b. Predicted future mean seasonal maximum and average temperature (°C) across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). The red line indicates the border of the current suitable cocoa production area, based on yield simulations.



Fig, 4.S6a. Projected change between future (2030-2060) and historical (1980-2010) annual and seasonal minimum temperature (ºC) across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). The red line indicates the border of the current suitable cocoa production area, based on yield simulations.



Fig, 4.S6b. Projected change between future (2030-2060) and historical (1980-2010) seasonal maximum and average temperature (°C) across Côte d'Ivoire, Ghana, Nigeria and Cameroon based on five representative GCMs under the high emission scenario (SSP585). The red line indicates the border of the current suitable cocoa production area, based on yield simulations.

6. Simulated mean annual potential water-limited cocoa yield

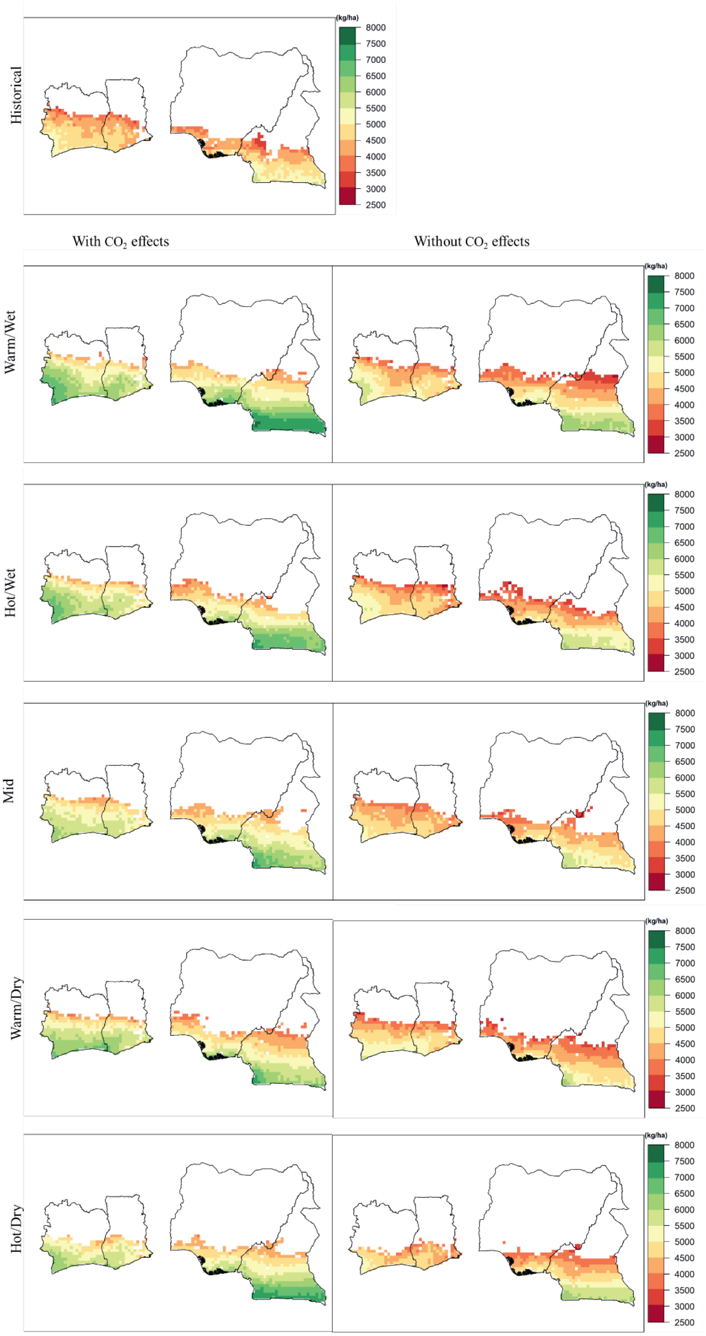
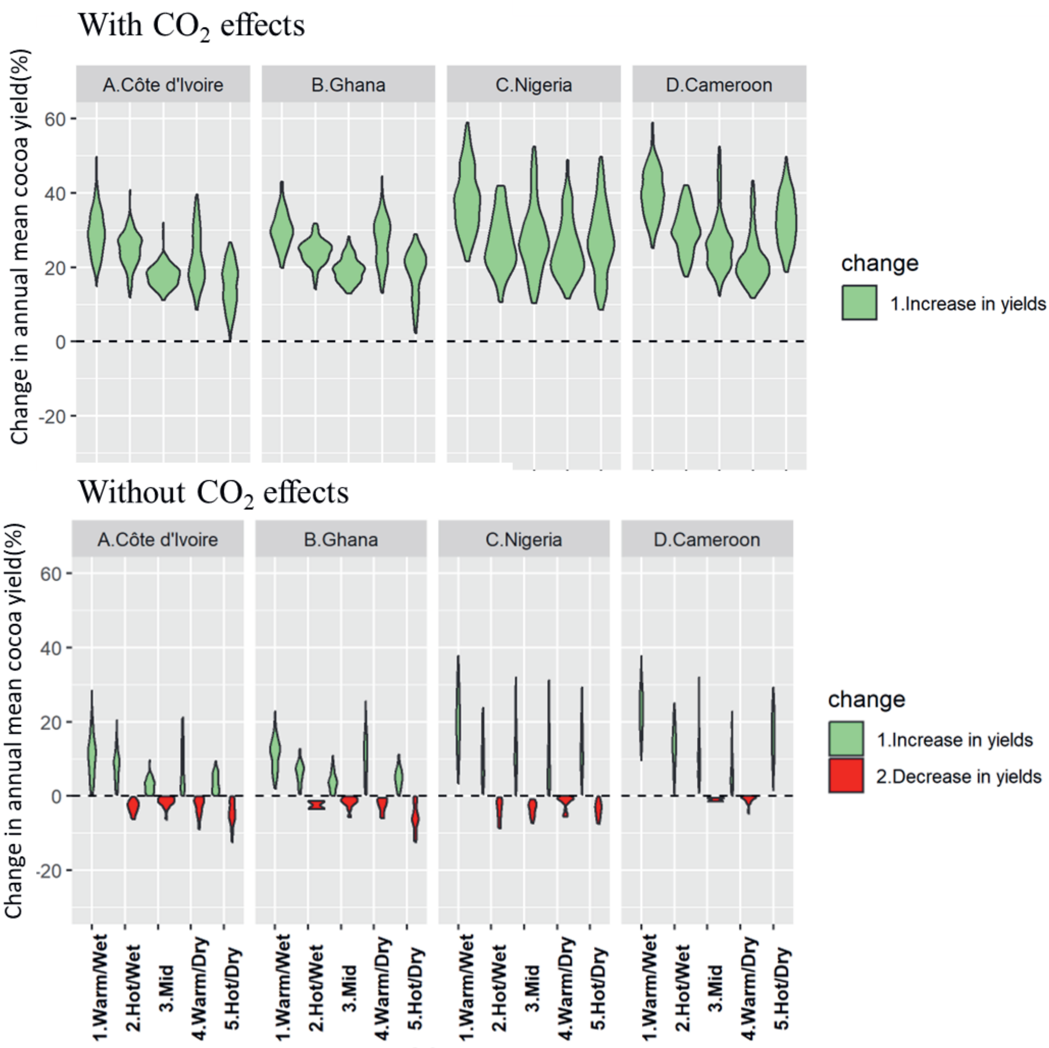
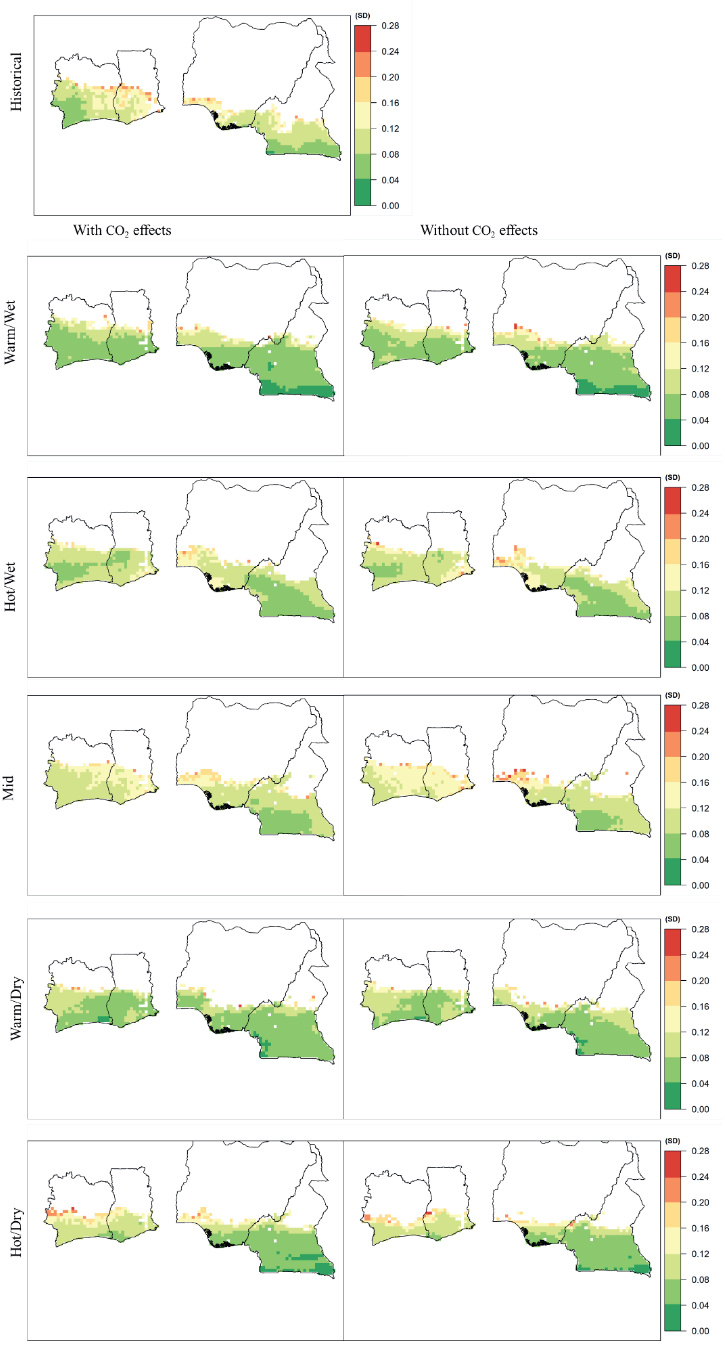


Fig. 4.S7 Historical and future simulated mean Yw for five representative GCMs with and without CO_2 effects.

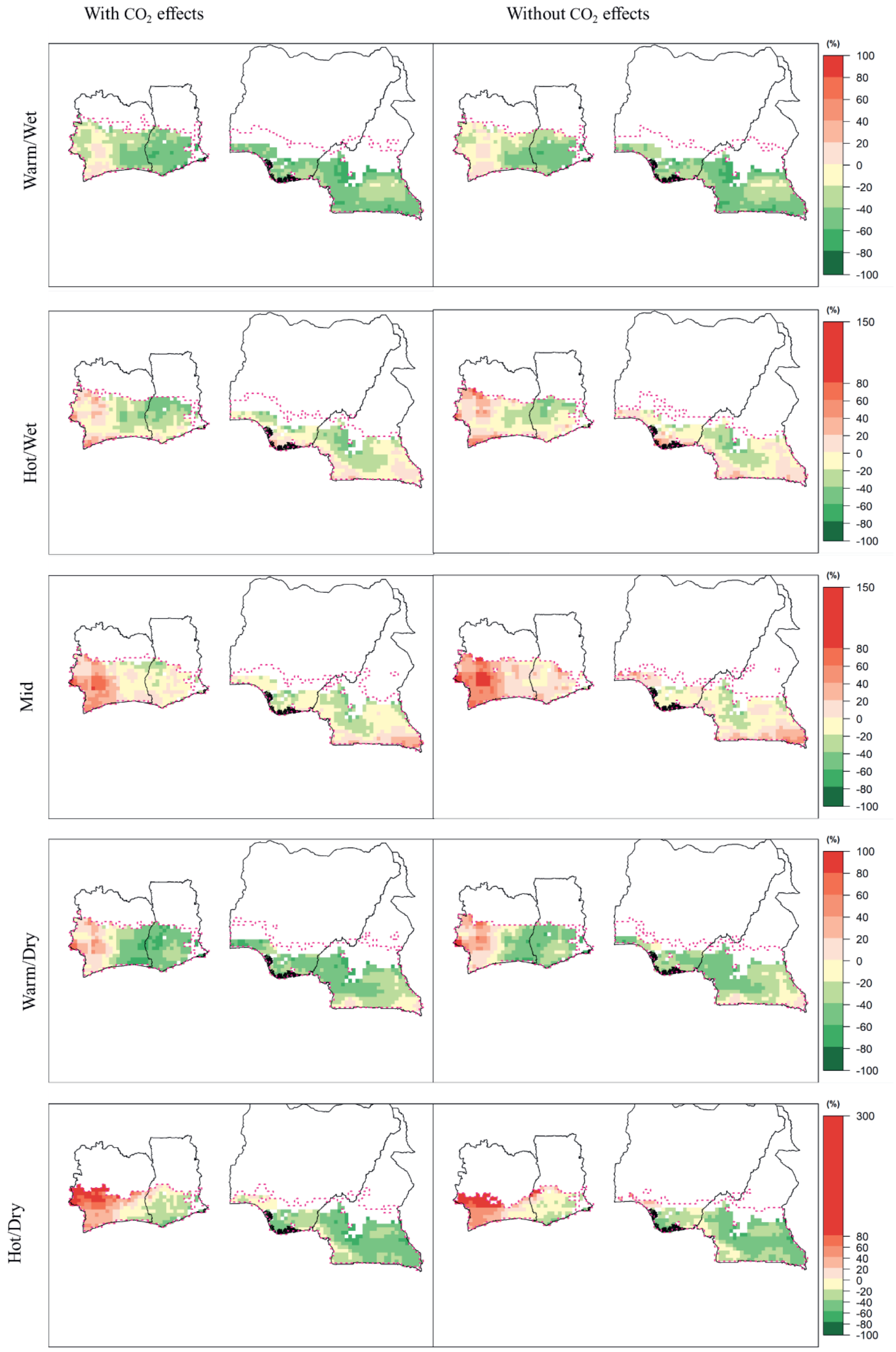


Fig, 4.S8. Predicted change (future-historical) in simulated water-limited potential yield between historical and future with and without CO_2 effects based on five GCM projections for the four major cocoa producing countries in West and Central Africa.

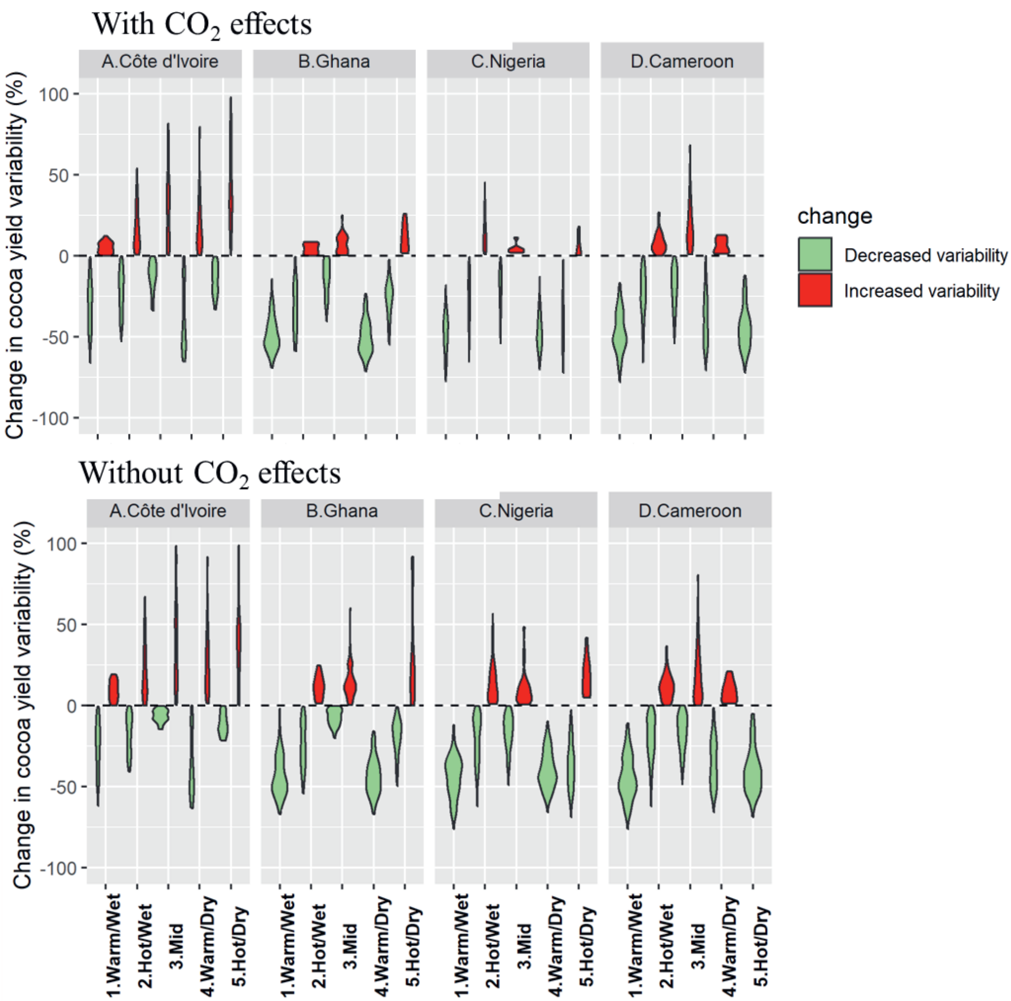
7. Yield variability



Fig, 4.S9 Historical and future cocoa yield variability (standard deviation of detrended Yw data), with and without CO_2 effects based on all five GCMs projections.



Fig, 4.S10. Map showing predicted changes (future - historical) in cocoa yield variability in cocoa production areas with and without CO_2 effects. The red line indicates the border of the current suitable cocoa production area, based on yield simulations.



Fig, 4.S11. Predicted change (future-historical) in yield variability between the historical and future period with and without CO_2 effects based on five GCMs projections for the four major cocoa producing countries in West and Central Africa.

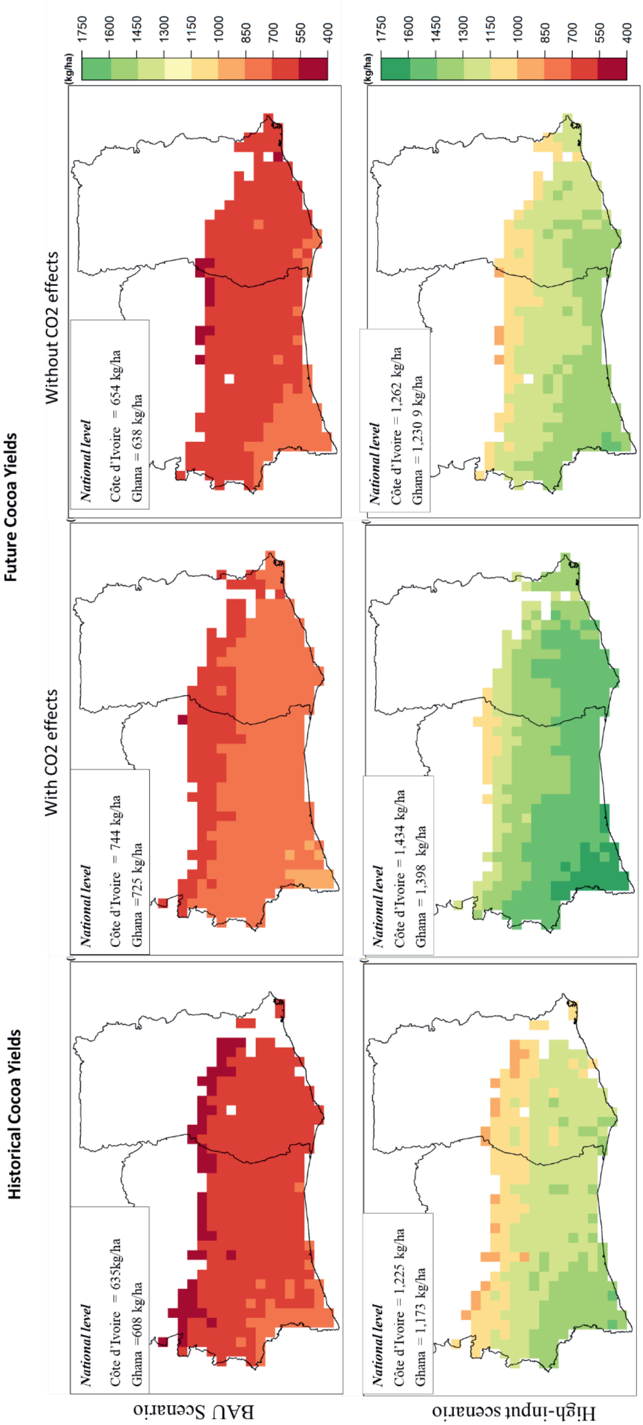
Table 4.S3. Results of the mixed-effects models for the historical and future (for five GCMs under with and without CO_2 effects scenarios) inter-annual cocoa yield variability as a function of variability in climatic factors. Only variables retained in the best model are shown.

Predictors	**Estimates**		**Confidence Interval**		***Marginal R2/Conditional R2***	
			Historical			
Annual average temperature	-0.00		0.11 – 0.12			
Annual precipitation	0.01		-0.01 – -0.00			
Consecutive dry months	-0.01		0.01 – 0.01			
Maximum temperature (dry season)	0.00		-0.01 – -0.00			
Average temperature (dry season)	0.00		0.00 – 0.01		*0.44 / 0.80*	
Precipitation (dry season)	0.02		-0.00 – 0.00			
Precipitation (wet season)	-0.00		0.01 – 0.02			
			-0.00 – 0.00			
			Future			
	With CO_2 effects	*Without CO_2 effects*	*With CO_2 effects*	*Without CO_2 effects*	*With CO_2 effects*	*Without CO_2 effects*
Warm/Wet			0.07 – 0.08	0.08 – 0.09		
Consecutive dry months	-0.01	-0.01	-0.01 – -0.01	-0.01 – -0.01		
Maximum temperature (dry season)	0.01	0.01	0.01 – 0.01	0.01 – 0.01	*0.52 / 0.76*	*0.54 / 0.81*
Minimum temperature (wet season)	-0.01	-0.01	-0.01 – -0.01	-0.01 – -0.01		
Average temperature (wet season)	0.02	0.03	0.02 – 0.02	0.03 – 0.04		

Hot/Wet						
Annual maximum temperature	0.00	0.01	0.09 – 0.10	0.01 – 0.01		
Annual precipitation	0.01	0.01	0.00 – 0.01	0.01 – 0.01		
Consecutive dry months	-0.00	-0.00	0.01 – 0.01	-0.00 – -0.00		
Maximum temperature (dry season)	**-0.01**	**-0.01**	-0.00 – -0.00	-0.01 – -0.01	*0.57 / 0.73*	*0.52/ 0.77*
Precipitation (dry season)	0.02	0.02	-0.01 – -0.01	0.02 – 0.02		
Minimum temperature (wet season)	-0.00	-0.01	0.01 – 0.02	-0.01 – -0.01		
Precipitation (wet season)	0.00	0.00	-0.00 – -0.00	0.00 – 0.00		
Mid			-0.00 – 0.00			
Consecutive dry months	-0.00	-0.00	-0.00 – -0.00	-0.00 – -0.00		
Minimum temperature (dry season)	0	0.00	-0.00 – 0.00	0.00 – 0.00		
Maximum temperature (dry season)	-0.00	0.00	-0.00 – -0.00	0.00 – 0.00	*0.53 / 0.76*	*0.33 / 0.90*
Maximum temperature (wet season)	0.01	0.00	0.01 – 0.01	0.00 – 0.00		
Precipitation (wet season)	0.01	0.02	0.01 – 0.02	0.02 – 0.02		
Warm/Dry						
Annual precipitation	0.01	0.01	0.01 – 0.01	0.01 – 0.01		
Consecutive dry months	-0.01	- 0.01	-0.01 – -0.00	-0.01 – -0.01		
Minimum temperature (dry season)	0	-0.00	-0.00 – 0.00	-0.01 – -0.00	*0.35 / 0.42*	*0.22/ 0.45*
Maximum temperature (dry season)	0	0	-0.00 – 0.00	-0.00 – 0.00		
Average temperature (wet season)	0.01	0.01	0.01 – 0.01	0.01 – 0.01		

Hot/Dry						
Consecutive dry months	-0.00	-0.00	-0.01 – -0.00	-0.01 – -0.00		
Minimum temperature (dry season)	0.01	0.01	0.01 – 0.02	0.01 – 0.01		
Maximum temperature (wet season)	0.01	0.02	0.01 – 0.01	0.01 – 0.02	*0.39 / 0.82*	*0.24 / 0.89*
Minimum temperature (wet season)	-0.01	-0.01	-0.01 – -0.01	-0.01 – -0.01		
Maximum temperature (wet season)	0.01	0.01	0.01 – 0.01	0.00 – 0.01		
Precipitation (wet season)	0	-0.01	-0.00 – 0.01	-0.02 – -0.01		

8. *Future cocoa production scenarios*



Fig, 4.S12. Simulated historical and future cocoa yield (kg/ha) under with and without CO_2 effects based on the current relative yield gap (86%) and attainable yield in high-input systems (73%). Predictions are based on the mid GCM only.

Chapter 5

General Discussion

5.1. Introduction

Cocoa production has strong economic importance for cocoa producing countries, the confectionary industry, the millions of smallholder farmers that grow the crop and the people that work in the cocoa industries. Global demand for cocoa is growing (Beg et al., 2017; CacaoNet, 2022) and increases in production over the past three decades have been made possible through the expansion in area planted, rather than increases in yield (van Vliet & Giller, 2017). This has occurred at the expense of both tropical forests (Abu et al., 2021; Ruf et al., 2015) and land availability for food crop production (Ajagun et al., 2021). Furthermore, increasing yield can contribute to poverty alleviation of vulnerable cocoa farmers (van Vliet et al., 2021). Therefore, it is imperative to identify opportunities to increase cocoa productivity on existing land as a means to improve farmers' livelihoods, meet global demand and at the same time reduce pressure on forest and other land uses.

Future cocoa production is threatened by climate change with the potential to negatively affect production through decreasing suitability (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017). However, effects of temperature, rainfall, and atmospheric carbon dioxide concentration [CO_2] on cocoa physiology and productivity are poorly understood. Hence, projected climate change effects on production and adaptation have not been adequately considered. This thesis therefore aimed to (1) assess how current climate, soil and management factors affect current cocoa yields (***Chapter 2***) ; (2) quantify the cocoa yield gap and the factors that can narrow the gap (***Chapter 3***); and (3) assess the impacts of projected changes in climate and the underlying rise in atmospheric [CO_2] on future cocoa production (***Chapter 4***).

This Chapter synthesizes the main findings found in Chapters 2 to 4 of this thesis and draws conclusions on the relative importance of climate, soil and agronomic management effects on cocoa yields and the yield gap and the potential impact of climate change on future cocoa production. Recommendations for future research are provided.

5.2. The relative importance of climate, soil and agronomic management effects on cocoa yields and yield gaps.

Many studies have identified numerous climate, soil and management factors limiting cocoa yields, but the relative importance of these factors in explaining variation in yields is largely unknown. Quantifying the relative contributions of yield limiting factors is important for prioritizing interventions aimed at improving yields and climate adaptation. In this thesis, the relative importance of environmental (climate and soil) and management drivers of cocoa yield variability and the cocoa yield gap was evaluated for Ghana. On-farm data on cocoa yields were combined with simulations with a cocoa crop growth model.

In Chapter 2, I showed the relative importance of climate and soil effects on cocoa yield on farms with different production levels using an unprecedented yield dataset from 3,827 farms in Ghana. The relative role of management was evaluated based on a subset of 134 farms for which such data was available. Agronomic management was identified as the dominant determinant of variation in on-farm cocoa yields in Ghana, more so than environmental conditions. Across the 3,827 cocoa farms, a large cocoa yield variability (~100 to >1000 kg ha^{-1}) was observed within rainfall zones, while mean yield differences across rainfall zones were notably small. The observed high variability in cocoa yields was attributed mainly to management-related factors. Surprisingly, environmental factors explained only 7-10% of the variation in yields, which was a very small portion of the total variance explained when both environment (as fixed effect) and farm-to-farm variation (as random effect) was considered (55-85%). For the subset of 134 farms, explained variation in cocoa yields increased from 10% to 25% when including management factors in addition to environmental factors confirming the important role of management for increasing cocoa yields. In cocoa growing areas in West Africa, large farm-to-farm variation in yields has been observed and attributed to the large variation in management within growing areas (Fig. 5.1) (Daymond et al., 2017; van Vliet & Giller, 2017). For instance, management factors including cocoa planting density, fertilizer application and spraying with fungicides against black pod were key factors underlying farm-to-farm yield variability in Ghana, Cote d'Ivoire and Indonesia (Aneani & Ofori-Frimpong, 2013; Daymond et al., 2017) and the cocoa yield gap in Ghana (Abdulai et al., 2020). Fungal black pod disease caused by *Phytophthora palmivora* and *Phytophthora megakarya* is one of the highly destructive diseases in cocoa which attacks both developing and ripening pods and can thus cause over 60% production losses if the disease is not managed (Akrofi et al., 2015;

Asitoakor, Asare, et al., 2022). In Chapter 2, I found strong effects of cocoa planting density on cocoa yields. Shade-tree density also influenced yields negatively, but effects were weak. Similarly, in Chapter 3, I found that absolute yields in low-input systems and relative yield gaps were driven by management factors only, which included cocoa planting density and black pod control, highlighting the importance of agronomic management for narrowing the cocoa yield gap.

Nonetheless, in Chapter 2 and 3, fertilizer application (use vs. no use) had no effect on cocoa yields or yield gaps, as was also found by Aneani & Ofori-Frimpong (2013) for cocoa yields in Ghana. This result was contrary to what has been reported in other studies on the positive effects of fertilizer use on cocoa yields and on closing yield gaps (Abdulai et al., 2020; Ruf, 2011). The effectiveness of fertilizer application in improving on-farm cocoa productivity was found to depend on the level of agronomic management on the farm (Aneani & Ofori-Frimpong, 2013; Baah et al., 2011). For instance, effective control of black pod disease and capsids, pruning and shade management are considered important for improving cocoa productivity response to fertilizer application (Baah et al., 2011). Hence, the lack of response of cocoa yields and yield gaps to fertilizer application observed in Chapter 2 and 3, respectively, could have been due to the poor level of agronomic management on most cocoa farms in Ghana (Aneani & Ofori-Frimpong, 2013). Furthermore, it is noted that the data on fertilizer use (i.e. use vs. no use) may poorly represent information on the source, rate, placement and timing of fertilizer application which is important for determining the effects of fertilizer use on yield. I therefore strongly recommend that such data be collected to assess the extent to which farmer cocoa yields in West Africa are related to the amount, type and timing of fertilizer use.

Regarding the strong positive effects of cocoa planting density on cocoa yields (Chapter 2) and on closing cocoa yield gaps (Chapter 3), it is important to note that planting densities across cocoa farms varied strongly (276 to 3626 trees ha, mean 1221 trees ha). Large variation in density makes it easier to assess its effect on yield, however, how effects change with cocoa age is not determined. Souza et al., (2009) reported the presence of a density-year interaction for cocoa, i.e. high cocoa planting densities were found to increase cocoa yields in the first half of a 14-year period and in the second half low planting densities attained the highest yields. This is important to consider when determining optimal density for maximizing yields. Cocoa has a 20-30-year economic lifespan and the optimal density in the earlier years may differ from that in later years. The chosen plant density by the farmer would then depend on the economic horizon of the farmer. In addition, increasing cocoa planting densities might increase the need for other management practices such as pruning (Tosto et al., 2022). This would entail extra labour costs. But more importantly, there is still little knowledge on how different pruning methods influence yield and other factors such as disease incidence (Tosto et al. 2022). Such factors like pruning effects on yield or their interaction with density were not assessed in this thesis due to lack of data availability.

Fig.5.1. Cocoa farms showing different forms of farm management conditions in Ghana. Full-sun (top left) and shaded cocoa farm (bottom left), un-weeded farm (top right), cocoa husk management on farm (bottom right) (Photos taken during fieldwork 2019).

In Chapter 2, the role of environmental conditions was found to vary amongst farms with different overall mean yields. Cocoa farms with higher yields were more sensitive to environmental conditions (e.g., solar radiation in the main dry season) than farms with lower yields. In Chapter 3, effects of environmental conditions also varied across absolute yield gap levels. Absolute yield gaps in low-input systems were driven by management factors only. However, absolute yield gaps attainable in high-input systems (where improved management practices are applied) were influenced by both management and climate factors (temperature and rainfall). These results show that effect of environmental conditions on cocoa yields becomes more important when limiting management factors are removed. Thus, the surprisingly weak effect of environmental conditions on mean yields in Ghana suggests that the overall management level of cocoa farms may be low, which may explain the lower sensitivity of yields to environmental conditions.

This result points to a significant opportunity for farmers to increase current yields through improved management practices independent of environmental conditions. Furthermore, the dependence of environmental effects on overall production levels also suggests that there is a need for differing climate adaptation strategies tailored to the management level of the crop. For instance, farmers with lower yields may need to put in place good agricultural practices before investing in additional climate adaptation practices . On the other hand, farmers with higher yields may need to invest in management practices that can facilitate better adaptation of cocoa to local climate conditions as needed. It is important to recognize that climate extremes might impact cocoa yields of both low and high management levels, but our data set lacks observations of these effects. Current climate adaptation strategies for cocoa are guided by climate-smart agriculture (CSA) which aims broadly at sustainably increasing productivity and climate resilience (adaptation), reducing/removing greenhouse gas emissions (Asare, 2014; CFI, 2021). Governments of Côte d'Ivoire and Ghana together with several companies are providing support to cocoa farmers in adopting climate-smart cocoa practices (Kroeger et al., 2017). Recommended climate smart cocoa interventions (such as capacity building, access to planting material, access to inputs, ecosystem service payments, access to markets, enabling environmental, e.g. forest, protection) emphasize adaptation of practices to specific climate conditions (Dohmen et al., 2018), whereby our insights show that in the case of cocoa farmers with low yields, enabling general good agricultural practices should be prioritized before investing in climate specific adaptation of practices. Introduction of climate adaptive strategies without adequate consideration of improving basic agronomic practices holds the danger of primarily helping those farmers that are already doing relatively well, which could, at least in theory, increase inequality.

Overall, this was the first study to report differential effects of management and environmental conditions on cocoa yields providing some novel insights on production challenges faced by different farmer groups. The general direction of importance of yield limiting factors (Fig. 5.2) also provides some ideas on the sequence for addressing yield limiting factors on cocoa farms taking initial conditions of the farmer into account (Fig. 5.2). Thus, based on my analysis, I argue that to close the cocoa yield gap, priority in extension work and farmer support (depending on management level) should be given to improve agronomic practices.

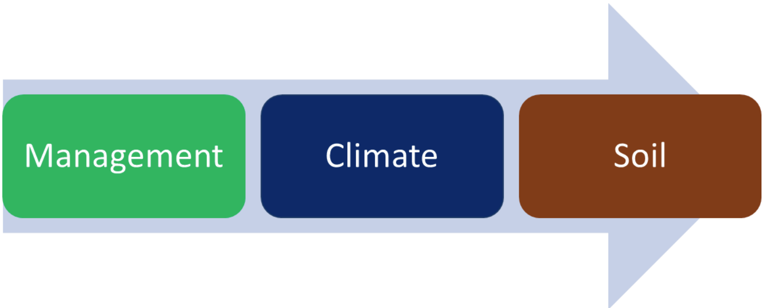


Fig.5.2. General direction of importance of yield limiting factors on cocoa farms in Ghana (Chapter 2).

5.3. The cocoa yield gap

Increasing cocoa yields per unit area is a means to meet growing demand, securing food security and reducing pressure on forest and other land uses. As previously noted, in Chapter 2, we found an enormous cocoa yield variability across cocoa farms in Ghana ranging from ~100 to >1000 kg ha^{-1} pointing to a significant opportunity for a large fraction of the farmers to increase yields beyond current levels, which is in agreement with Daymond et al. (2017). In Chapter 3, we quantified the scope for yield increase per unit area on existing cocoa plantations and the factors that determine this potential for increased yield. We did so by calculating the cocoa yield gap on farms which is the difference between the potential yield and actual yield achieved by the farmer. Three approaches were used to estimate the potential yield as reference for our cocoa yield gap calculations. These included: i) simulated water-limited potential cocoa yield estimated using the CASE2 cocoa model (Zuidema et al., 2005), ii) attainable yield in high-input systems based on average yields from experimental trials, and iii) attainable yield in low-input systems based on average yield of the 10% best performing farmers. Three cocoa yield gap estimates in absolute and relative terms based on these yield references were presented to provide a comprehensive estimate of the potential yield gains that could be achieved at different levels of intensification (Fig. 5.3).

The results showed that irrespective of the definition of potential yield, there were considerable yield gaps across all cocoa farms showing large opportunities to increase cocoa yields beyond current levels. Maximum water-limited yield gaps (mean absolute yield gap of 4,577 kg/ha and the mean relative yield gap of 86%) were much larger than yield gaps attainable in high-input (mean absolute yield gap of 1930 kg/ha and relative yield gap of 73%) and low-input systems (mean absolute yield gap of 469 kg/ha and relative yield gap of 42%). Our yield gap estimates were comparable to reported yield gaps in low input systems (434 to 1126 kg/ha, relative yield gaps of 53 to 67%) (Abdulai et al., (2020) and also to values reported for high-input systems (1553.4 kg/ha, relative yield gap of 82.1%) (Aneani & Ofori-Frimpong, 2013) for Ghana. Our study, however, was the first to quantify cocoa yield gaps using a crop modelling approach. The relationship between the three yield gap estimates were consistent with yield-gap trends (i.e. maximum water-limited yield gap < attainable yield gap in high-input systems < attainable yield gap in low-input systems) found for several annual crops including maize, rice, millet, sorghum in Ghana and other areas (Global Yield Gap Atlas, 2022). The trends were also comparable to reported yield gaps for perennial crops in smallholder farming systems including, coffee (Bhattarai et al., 2017; Wang et al., 2015) and oil palm (Euler et al., 2016; Hoffmann et al., 2017; Rhebergen et al., 2018). Thus, the large yield gaps were not specific to cocoa only, but comparable to what has been found for other crops in this region under rainfed conditions. This indicates that in our region the issue of large yield gaps is not specific to cocoa but reflects more general problems with crop production. In intensively managed systems, where farmers attempt to exclude all yield-limiting and reducing factors (e.g. nutrients, weeds, pests and diseases), the three values would be closer, however in low-input systems, yield gaps are expected to be considerably lower than maximum water-limited yield gaps and yield gaps attainable in high-inputs systems as shown in this study (Fig. 5.3) (Lobell et al., 2009).

Regarding the factors that explain variation in the cocoa yield gaps, I found that climate factors were important for the absolute maximum water-limited and attainable yield gaps in high-input systems, but not in low-input systems. Climate factors explained 22% of the variation in absolute maximum water-limited yield gaps and were larger at sites with higher precipitation in the minor wet, and higher minimum temperature in the minor dry, season. The same climate factors together with the cocoa planting density explained 28% of the variation in absolute attainable yield gaps in high-input systems. Regardless of climate, absolute attainable yield gaps in low-input systems and relative yield gaps (of the three approaches) were reduced by management practices including cocoa planting density and black pod control (see 5.2.). In Ghana, Abdulai et al., (2020) identified drivers of cocoa yield gaps in low-input systems along a climate gradient. Across the dry, mid and wet zones, management related factors including cocoa planting density, quantity of fungicide applied, plantation size, plantation age, proportion of hybrid planting material in the plantation as well as socio-economic (labor cost, farmer age, number of trainings received) and soil-related factors (plant available phosphorus (P) in the soil, proportion of sand) were significant in explaining variation in cocoa yield gaps in that study. In chapter 3, whilst our study confirmed the importance of cocoa tree planting density and spraying of fungicides against black pod for narrowing the yield gap, we did not find any effects of plantation size, plantation age, nor available P on the cocoa yield gap. Our study differed from the study of Abdulai et al., (2020) in that we did not analyse data per climate zone, but for the whole cocoa growing area. This was because in Chapter 2 we found that average cocoa yields based on a large dataset (~3800) were less sensitive to climate, and that variability in yields were driven by management (see section 5.2). This could explain the difference between our results and those of Abdulai et al. (2020). But these differences may also be due to other factors (e.g. difference in yield data acquisition methods). The other significant variables included in their study, i.e. the proportion of sand, cocoa variety and socio-economic variables, were not included in our models because data were not available, and hence we could not evaluate how these factors affected cocoa yield gaps. Factors explaining variation in yield gaps attainable in high-input systems have not been evaluated for cocoa in Ghana. A previous study by Aneani & Ofori-Frimpong, (2013) only reported drivers of cocoa yield and not of the yield gap.

These results show that there are still considerable yield gaps on cocoa farms that can be closed in the future to meet the increasing demand for cocoa without the need to further expand the area planted.

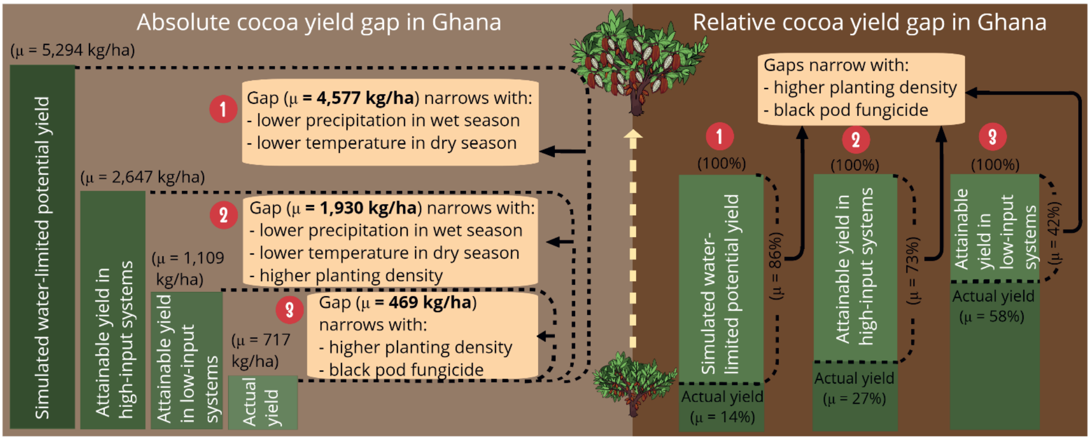


Fig.5.3. The absolute and relative cocoa yield gaps across farms in Ghana based on maximum yield attainable in rain-fed systems (simulated water-limited potential yield) and the attainable yields in high- and low-input systems (Chapter 3).

5.4. The future of cocoa production under changes in climate and atmospheric [CO_2] levels

Climate change through warming, shifts in rainfall patterns and occurrence of extreme climate events is expected to impact crop production systems globally. In Chapter 4, I showed the potential impact of projected changes in climate on cocoa production in West and Central Africa up to the mid-century (2060). We examined this based on five plausible future climate scenarios (warm/wet, warm/dry, mid, hot/wet, hot/dry) projected by general circulation models (GCMs) and also quantified effects of elevated atmospheric [CO_2] on cocoa yield. With notable exceptions, model predictions showed that under the projected future climate scenarios, increases in simulated water-limited yields and in area suitable for growing cocoa were expected whilst inter-annual yield variability was predicted to decrease particularly when assuming full CO_2 effects and under wetter conditions (i.e., shorter dry season). Impacts were expected to follow a clear (south) east – west geographic gradient with predictions being most positive in the eastern-most country, Cameroon, where strong increases in yield (~39-60%) and in suitable area for cocoa (~11-12Mha) were found, and the least positive for the western-most country, Côte d'Ivoire, where strong yield reductions of up to 12% and major losses of current suitable area (~6-11Mha) were estimated. Nigeria followed Cameroon in terms of positive effects (except that Nigeria had the largest increase in suitable area ~17-20Mha) and Ghana

(30-45% increases in yield and 12% reduction in yield, ~2Mha gain in suitable area and ~2-2.5Mha loss in suitability) followed after Nigeria. Inter-annual yield variability was higher in areas with lower yields, thus a similar geographic trend was seen with reduced variability in Cameroon and the largest increases in Côte d'Ivoire.

The predicted geographic trend in climate suitability was comparable to previous predictions of climate change impacts based on species distribution models (SDMs) (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017) but the overall net effect of climate change on suitability based on SDMs was less positive compared to our results. This difference can be explained by different climate data (both current and future climate scenarios) and the use of different impact models. Regarding the impact model, we included effects of physiological acclimation of cocoa to changes in climate and quantified suitability changes in terms of yields, while SDMs lack the mechanistic process to predict physiological responses of cocoa trees to changing climatic conditions. For instance, it was assumed in studies based on SDMs (Läderach et al., 2013; Schroth et al., 2016; Schroth & Läderach, 2017) that cocoa will increasingly be influenced by maximum dry season temperatures as GCMs projected moderate changes in precipitation in combination with the overall shortening of dry season length. In our study, increases in dry-season precipitation along the coastal zones were predicted by all GCMs, which had strong positive effects on simulated water-limited potential cocoa yields therefore allowing cocoa production to increase while the projected reduction in the dry-season length reduced inter-annual cocoa yield variability. Thus, our study shows more positive effects of climate change on suitability than previous studies. Also, we showed that assuming full effects of elevated atmospheric [CO_2] on cocoa partly ameliorates the negative effects of warming on suitability which is not accounted for in SDMs. Using a physiology-based approach, similar conclusions on the impact of elevated atmospheric [CO_2] on cocoa net primary productivity (NPP) were drawn by Black et al. (2020) who reported that elevated atmospheric [CO_2] offsets negative effects of increased temperature and rainfall variation for the whole of the 21st century. Nevertheless, the Black et al. (2020) study focused on NPP without calculating effects on yield. Thus, our study was the first to quantify effects of climate change and elevated atmospheric [CO_2] on cocoa yield using a process-based approach.

This thesis indicates that the extent to which climate change will impact cocoa by mid-century depends on how precipitation will change and its corresponding effects on cocoa growth and production. Wetter scenarios predicted more positive effects than dry scenarios. As noted, predicted increases in simulated potential yields in the future were mostly due to projected increases in dry season precipitation whilst inter-annual yield variability was reduced by projected shortening of the length of the dry season. Increased dry season water availability could be beneficial for cocoa trees, as cocoa is described to be drought-sensitive (Gateau-Rey et al., 2018; Keil et al., 2008; Schwendenmann et al., 2010; Zuidema et al., 2005). Effects of temperature were both positive and negative suggesting that projected temperatures in the climate scenarios up to the mid-century are close to the optimal temperature for cocoa production. However, whether they will surpass this optimum depends on the extent of the warming.

In chapter 2, we found that solar radiation during the main dry season of the current and previous year was important for increasing yields but this may depend on water availability during such periods (Baligar et al., 2008; Jaimez et al., 2018). Using a crop growth model, it was shown that solar radiation and precipitation in the two driest months together explained over 70% of the variation in modelled cocoa yields (Zuidema et al., 2005). In chapter 3, we found that absolute maximum water-limited and attainable yield gaps in high-input systems were larger in sites with higher precipitation in the minor wet season, due to positive effects of water availability on simulated water-limited yields. Nonetheless, in chapter 2, I found that cocoa yields were significantly reduced with increasing precipitation of the minor dry season which seems contradictory to the result in chapter 3 but could likely be related to high humidity levels associated with more precipitation favouring diseases during pod development. For instance, incidence of black pod disease is prevalent under wet and humid conditions, thus increasing precipitation may increase the incidence of black pod (Anim-Kwapong & Frimpong, 2004; Cilas & Bastide, 2020). On the other hand, high temperature can increase the incidence and severity of insect pests such as mirids and shield bugs in cocoa (Asitoakor, Asare, et al., 2022). In CASE2, effects of humidity and or temperature changes on pests and diseases are not accounted for but are important to take into account when considering yield predictions and climate effects. Understanding pests and disease dynamics in relation to spatial and temporal changes in weather conditions is important for quantifying risks for cocoa under future climate.

Implications of climate change effects on future cocoa production were assessed in chapter 4. Under future climate, we found that the upper limit of yields in rainfed systems (simulated water-limited potential yields) were altered by projected changes in climate by mid-century (2060). Simulated water-limited yields under future climate were higher than historical (1980-

2010) yields particularly when assuming full CO_2 effects. This indicates that future cocoa yield gaps may be larger than current yield gaps, if management levels stay the same. We showed that country-level production on the current cocoa growing area in Côte d'Ivoire and Ghana could increase by about 2.6% beyond historical levels following current management practices (relative yield gap of 86%; business-as-usual scenario). When assuming full CO_2 effects, production could increase by 20% under this business-as-usual scenario. Furthermore, we illustrate that current production levels could potentially double in these countries in the future, if relative yield gaps were reduced from 86% to 73% (i.e. by doubling yields which is a realistic yield target for farmers; high-input scenario) through improved management practices.

Overall, our results show a less negative impact of climate change on cocoa production by mid-century than previously expected. Although it should be noted that extreme climate events are not well represented in this thesis as there was no case of extreme climatic conditions during the period in which yield data were collected (chapter 2 and 3), and the downscaled GCM data used in chapter 4 do not fully capture extremes yet (Rodríguez-Fonseca et al., 2015; Saini et al., 2015). Thus, further improvement on assessing climate change impacts on cocoa using data that better represent climate extremes could be achieved in future studies. Also, the implications of climate change effects on shifts in suitable cocoa areas and resulting effects on forests and other land uses need to be examined. Assessing the impact of climate change on cocoa, we found a clear geographic trend with predictions being most positive for Cameroon in the east, and Côte d'Ivoire in the west. Whilst geographic shifts in climate suitability may favour Cameroon for instance, potential increases in cocoa production outside the current growing area could have serious consequences for forest and biodiversity conservation. Historically, expansion in the area planted with cocoa have directly contributed to forest loss (Fig. 5.4) and degradation of the West African Upper Guinea biodiversity hotspot. Further risks of expansion might impact on ecologically important areas in West Africa (Sassen et al., 2022). Cameroon is one such area where most rainforest and associated biodiversity is still present. It is therefore important to recognise how geographic shifts in cocoa suitability might affect forest cover and its possible implications for biodiversity.

Fig.5.4. Tree felling on cocoa farms. (Photos taken during fieldwork 2019)

5.5. Recommendations for further research

As noted, management factors were identified as the most important drivers of current cocoa yields (Chapter 2) and yield gaps (Chapter 3) but the role of environmental conditions becomes more important as yield increases. However, how cocoa trees respond to management practices and how best management practices should be adapted to different climatic conditions and cropping systems needs to be properly defined (Tosto et al., 2023). Furthermore, though this study provides some ideas on the general direction of importance of cocoa yield limiting factors, there was a lack of accurate data on management practices and hence further examination of the relationship between yield, environmental and management variables is needed to properly define the set of activities and resources (e.g. labour, fertilizers, fungicides, pesticides) needed to achieve higher yields. A stepwise management approach using integrated soil fertility management (ISFM) has been recommended, which targets yield limiting practices step-by-step (CocoaSoils, 2019; Kihara et al., 2022; Vanlauwe et al., 2010, 2015). Our results contribute insights to such an approach for cocoa. For instance, this study shows that the relative importance of different factors in determining cocoa yields depends very much on the yield-level, which calls for a differentiated approach that addresses the needs of farmers operating at different production levels. This differentiation has to my knowledge not been made as such before, making it urgent that more work on this is needed

In Chapter 4, we found that the extent to which effects of future climate change by mid-century would affect cocoa production likely depends on water availability to cocoa, while increasing temperature seems not to be an issue yet. In CASEJ (updated version of CASE2), modelled processes on the response of cocoa to water availability were based on general tree physiological knowledge rather than specific physiological knowledge of cocoa (Tosto et al., 2023; Zuidema et al., 2003). For many physiological processes, availability of cocoa specific data is very limited or unavailable. For instance, coupling photosynthesis and stomatal conductance in a crop model is important for evaluating crop response to simultaneous changes in temperature and precipitation. However, such coupling does not yet exist in CASEJ as information on relations between photosynthesis and stomatal conductance under different environmental conditions are unavailable (Tosto et al., 2023). To improve physiology-based modelling of cocoa yields more ecophysiological work on cocoa is needed, especially work conducted on mature trees in field conditions. Also, we found that assuming full effects of elevated atmospheric [CO_2] on cocoa yields partly compensated for negative effects of warming on cocoa yields. However, these results need to be validated, as outputs of CASEJ have only been validated under current CO_2 levels. Long-term cocoa responses to elevated [CO_2] and warming have not been studied and there are currently no free-air CO_2 concentration enrichment (FACE) or warming experiments for cocoa (Black et al., 2020; Tosto et al., 2023). Also, it is important to note that positive effects of elevated [CO_2] on cocoa would depend on soil nutrient availability (Ainsworth & Long, 2005; Makowski et al., 2020). For instance, availability of nitrogen (N) to plants, has been suggested to be the most important environmental factor that determines plant responses to elevated [CO_2] (Ellsworth et al., 2004), however, enhanced [CO_2] resulted in decreased N concentration in the leaf and plant (Ainsworth & Long, 2005). Acclimation of photosynthesis is also reported to be more pronounced when plants are N-limited. Trees grown under nutrient limitations in four studies were found to have a non-significant, 14% stimulation in above-ground biomass (Ainsworth & Long, 2005). Currently, nutrient dynamics and effects on cocoa yield are not included in CASEJ (Tosto et al., 2023), and this could therefore not be evaluated in this thesis. Hence, further model improvement is needed to address this and other questions related to nutrition and fertilizer requirements under future climatic conditions.

It is important to explore climate adaptation strategies for cocoa under changing climate. Cocoa agroforestry for instance is considered an important strategy which is expected to buffer cocoa from climate change as shade trees have a cooling effect during the day and also tend to reduce the vapour pressure deficit of the air. Agroforestry may also help improve soil fertility and regulate pests and diseases whilst also serving as climate-change mitigation strategy through increased carbon sequestration and maintaining diversity of associated species (Abdulai et al., 2018; Andres et al., 2018; Blaser et al., 2018; Wartenberg et al., 2017). However, contrasting views exist on the effects of shade on cocoa (Abdulai et al., 2018; Asare et al., 2017, 2019). For instance, the study by Abdulai et al. (2018) showed that cocoa trees were less resistant to drought when grown under shade trees than when grown in full sun light. This was explained by the association of competitive trees (Norgrove, 2018; van Noordwijk, 2021; Wanger et al., 2018) and perhaps differences in soil texture between treatments (Borden et al., 2020) and highlights the importance of careful tree selection (Asitoakor et al., 2022). Also, results from a study by Asare et al., (2017) showed that cocoa trees under shade trees have lower yields compared to full sun, but also that yields under shade trees increase with increasing amounts of shade at plot level. Negative effects of shade on cocoa yield were interpreted in that study as being due to competition from shade trees for water and nutrients whilst shade itself had a positive effect on yield. In Chapter 2, we found that shade tree density had significantly negative effects on cocoa yields, but effects were weak. However, shade tree density may not be a very accurate predictor of shading as it also depends on crown size of shade trees which in turn differs between shade tree species, changes with shade tree age and tends to decline with tree density due to competition. Shade cover or shade tree basal area are better predictors. In chapter 3, the absolute maximum cocoa yield gap was strongly, positively correlated to radiation interception by shade trees (0% to 31% shade) but was not included in the list of variables retained in the final model following the model selection procedure (correlation analysis and stepwise regression) so we could not determine its effect on yield. This then shows that shade tree density apparently was a good proxy for the amount of radiation intercepted by shade trees in Chapter 2. In addition, the costs and benefits involved in the implementation of agroforestry need to be taken into account as these are often untested (Blaser et al., 2018). For instance, as noted, shade trees may reduce crop production through competition, and species richness in cocoa-based agroforestry systems were lower than in primary forests (Maney et al., 2022). But on other hand shade trees may themselves yield harvestable products such as timber or fruits, that can contribute to and help diversify farm income.

Finally, it is important to acknowledge that not all cocoa farmers might have the primary objective to increase yields as this thesis implicitly assumes but may have other alternative motivations such as to diversify production. Related to this is the question how important cocoa is for farmers compared to other crops on their farm or other forms of income and hence the extent to which farmers are willing to spend limited resources or time on their cocoa crop.

Recognizing farmers' needs and motivations is important for the implementation of any intervention program aimed at improving yields or climate adaptation for that matter (Messmer et al., 2021). Also, effects of increased yields on cocoa prices need to be examined in future steps to ensure the profitability for increasing yields.

5.6. Concluding remarks

In this thesis, the drivers of cocoa yield under current and future climate were examined by linking cocoa crop modelling, statistical and spatial analysis. Under current climate, agronomic management was identified as the dominant determinant of on-farm cocoa yields in Ghana, more so than environmental (climate and soil) conditions whilst climate effects on yields were stronger than soil effects. Nonetheless, the role of environmental conditions on cocoa yield becomes more important with increasing yields. Large cocoa yield gaps were found on farms revealing large opportunities to increase yield beyond current levels. Maximum water-limited yield gaps were much larger than yield gaps attainable in high-input and low-input systems. Climate factors were the important drivers of the absolute maximum water-limited and attainable yield gaps in high-input systems, but not in low-input systems. Relative yield gaps (maximum water-limited, attainable in high- and low-input systems) were reduced by management practices, particularly cocoa tree density and black pod control. This shows that improved agronomic practices offer opportunities to substantially increase production of present-day cocoa plantations. Under future climate by mid-century, modelling results indicate that, despite the increases in temperature, projected increase in dry-season precipitation and the reduction in dry-season length by the general circulation models, will either maintain or increase productivity of many areas where cocoa is currently grown, particularly if full elevated [CO_2] effects are assumed.

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Summary

Cocoa production is economically of great importance for: producing countries, the confectionary industry, the millions of smallholder farmers that grow the crop and the people that work in the cocoa industries. Global demand for cocoa is growing and production has increased more than fourfold since the 1960s. Over the past three decades, increases in cocoa production have been achieved mainly through expansion in area planted, while yields per unit area have remained rather constant. This expansion of land under cocoa cultivation is driving deforestation in cocoa producing countries and increasing food insecurity in some areas as cocoa replaces croplands. With increasing demand, it is important to identify opportunities to increase cocoa productivity on existing land as a means to meet demand and at the same time reduce pressure on forest and other land uses. Whilst numerous environmental (climate and soil) and management factors that limit current cocoa yields have been identified, their relative importance in explaining variation in yields remains unknown. Quantifying this is important for prioritizing interventions aimed at improving yields. Future cocoa production is threatened by climate change which is expected to negatively impact cocoa through decreasing climate suitability in West Africa, where over 70% of cocoa is grown. However, effects of temperature, rainfall and atmospheric carbon dioxide concentration [CO_2] on cocoa tree physiology and productivity are poorly understood. As a consequence, possible implications of climate change for cocoa productivity and adaptations have not yet been considered. Climate-induced geographic shifts in the West African cocoa belt may have serious implications for farmers, cocoa supply and forests.

In this regard, this thesis aimed to improve understanding on the drivers of cocoa yield under current and future climates. Specifically, the objective was to identify and assess the factors that drive cocoa yields and the cocoa yield gap and to assess the impacts of climate change on cocoa production. This objective was addressed throughout the three core chapters (Chapter 2-4) of this thesis.

In **Chapter 1,** the general context of the thesis is presented, describing the knowledge gaps in research and the relevance of assessing the drivers of cocoa yields and cocoa yield gaps and the impacts of climate change on cocoa production. The chapter concludes with a description of the general research objectives and questions, a brief description of the study area and thesis outline.

In **Chapter 2**, the extent to which climate and soil factors drive cocoa yields and how it differs for farms achieving on average low- and high mean production levels was assessed based on an unprecedented dataset of 3,827 cocoa farms spanning the environmental gradients of Ghana. The relative role of management was evaluated based on a subset of 134 farms for which such data were available. Results showed that, agronomic management was the dominant determinant of variation in on-farm cocoa yields in Ghana, more so than environmental conditions. Across the 3,827 cocoa farms, a large cocoa yield variability (~100 to >1000 kg ha^{-1}) was observed within rainfall zones but across rainfall zones mean yield differences were notably small. The observed high variability in cocoa yields was attributed mainly to management-related factors. This was because environmental factors surprisingly explained only 7-10% of the variation in yields, which was a very small portion of the total variance explained when both environment and farm-to-farm variation was considered (55-85%). For the subset of 134 farms, explained variation in cocoa yields increased from 10% to 25% when including management factors in addition to environmental factors confirming the important role of management for increasing current cocoa yields. Nonetheless, the role of environmental conditions was found to vary amongst farms with different overall mean yields. Cocoa farms with higher yields were more sensitive to environmental conditions than farms with lower yields. These findings suggested that effects of environmental conditions on cocoa yields become more important when limiting management factors are removed. Thus, good agricultural practices need to be in place before investing in additional climate adaptation practices.

In **Chapter 3**, the cocoa yield gap and the factors that contribute to narrowing the gap were quantified. The yield gap was calculated as the difference between the potential yield and actual yield achieved by the farmer. Three potential yield estimates were used as reference in yield gap calculations: i) simulated water-limited potential cocoa yield estimated using the CASE2 cocoa model, ii) attainable yield in high-input systems based on average yields from experimental trials, and iii) attainable yield in low-input systems based on average yield of the 10% best performing farmers. Three cocoa yield gap estimates in absolute and relative terms based on these yield references were presented to provide a comprehensive estimate of the potential yield gains that could be achieved at different levels of intensification. The results showed that irrespective of the definition of potential yield, there were considerable yield gaps across all cocoa farms showing large opportunities to increase cocoa yields beyond current levels. Maximum water-limited yield gaps (mean absolute 4,577 kg/ha, relative yield gap of

86%) were much larger than yield gaps attainable in high-input (mean absolute of 1930 kg/ha, relative yield gap of 73%) and low-input systems (mean absolute of 469 kg/ha, relative yield gap of 42%). In terms of factors that explain variation in the cocoa yield gaps, climate factors (temperature and precipitation) were important for the absolute maximum water-limited and attainable yield gaps in high-input systems, but not in low-input systems. These two yield gap estimates (absolute maximum water-limited and attainable yield gaps in high-input systems) increased with increasing precipitation of the minor wet season and minimum temperature of the minor dry season. Regardless of climate, absolute yield gap in low-input systems and relative yield gaps were reduced by management practices including increasing cocoa planting density and the presence of black pod control. These results show that there are still considerable yield gaps on cocoa farms that can be bridged in the future to meet the increasing demand for cocoa without the need to further expand the area planted.

In **Chapter 4**, the potential impact of projected changes in climate on cocoa production in West and Central Africa up to the mid-century (2060) and the extent to which these effects were mediated by elevated atmospheric CO_2 concentration was assessed. This was done based on five plausible future climate scenarios projected by general circulation models and using a cocoa crop growth model that simulated the physiological effects of climate and CO_2 on cocoa growth, growth-related processes and yield. With notable exceptions, model predictions showed that under future climate, increases in simulated water-potential limited yields and in area suitable for growing cocoa were expected whilst inter-annual yield variability was predicted to become less, particularly when assuming full CO_2 effects and under wetter conditions. Impacts were expected to follow a clear (south) east – west geographic gradient with predictions being most positive in the eastern-most country, Cameroon where strong increases in yield, (~39-60%), and in suitable area for cocoa (~11-12 Mha) were found, and the least positive for the western-most country, Côte d'Ivoire where strong yield reductions of up to 12% and major losses of current suitable area (~6-11 Mha) were found. Nigeria followed Cameroon in terms of positive effects (except for having the largest increase in suitability that was found in this region ~17-20 Mha) and Ghana (30-45% increases and strong reduction in yield, 12%, ~2 Mha gain and ~2-2.5 Mha loss in suitability) followed after Nigeria. Predicted inter-annual yield variability was higher in areas with lower yields, thus a similar geographic trend was observed with reduced variability in Cameroon and the largest increases in Côte d'Ivoire. Predicted increases in simulated water-potential limited yields were mostly associated

with projected increases in dry season precipitation whilst projected shortening of the dry season reduced yield variability.

In **Chapter 5**, a general discussion of the main findings found in Chapters 2 to 4 of this thesis are presented in the light of existing literature. Conclusions on the relative importance of climate, soil and agronomic management effects on cocoa yields and yield gap and the potential impact of climate change on future cocoa production are drawn and recommendations for future research provided based on remaining research/open questions.

In conclusion, this thesis shows that improved agronomic management practices offer opportunities to substantially increase production of present-day cocoa plantations, and that such practices should be properly in place before introducing specific climate adaptive strategies. Under future climate, modelling results indicate that, despite the increases in temperature and changes in rainfall distribution as projected by the general circulation models, projected increases in dry-season precipitation and shorter dry-season length would allow many areas where cocoa is currently grown to either maintain or increase productivity by mid-century, particularly if full elevated [CO_2] effects are assumed.

Tɔfabɔ

Kokoo a wɔyɛ no ho hia kɛse wɔ sikasɛm mu ma: aman a wɔyɛ kokoo, nnwuma a wɔyɛ nnɔkɔnnɔkɔdeɛ, akuafo nkumaa ɔpepem pii a wodua nnɔbae no ne nnipa a wɔyɛ adwuma wɔ kokoo adwumayɛbea ahodow no. Wiase nyinaa ahwehwɛde a ɛfa kokoo ho no renya nkɔanim na efiri 1960 mu no, kokoo dodoɔ a wɔyɛ no akɔ soro bɛboro mpɛn nan. Wɔ mfeɛ aduasa a atwam mu no, nkɔanim a wɔanya wɔ kokoo mu no abaso ensane ntrɛwmu a wɔyɛe wɔ beae a wodua kokoo no titiriw. Nanso, kokoo aba soɔ wɔ beaeɛ a wodua hɔ no deɛ ɛnnya nkɔanim titiriw bia. Asase a wɔatrɛw mu de dua kokoo no ama kwae atutu wɔ aman a wɔyɛ kokoo mu. Na afei nso, kokoo esi mfuw nsase ananmu wɔ mmeae mmeae bi. Eyi rema ɛkɔm ano yɛ den wɔ mmeae a saa adeɛ yi kɔ so. Esiane sɛ ahwehwɛde a efa kokoo ho no rekɔ soro nti, ɛho hia sɛ wɔkyerɛ hokwan ahodow a ɛbɛma kokoo aba soɔ akɔ anim wɔ asase a ɛwɔ hɔ dada no so. Saa kwan yi bɛtumi aboa ama wɔate nhyɛso a ɛba kwae ne asase afoforo a wɔde di dwuma so. Bere a kokoo ho nimdeɛ nhwehwemu akyerɛ nneɛma pii ɛte mprempren kokoo aba soɔ so no, wonnim sɛnea nneɛma yi ho hia nnidisoɔ wɔ ɔkwan a wɔfa so kyerɛkyerɛ nsakrae yehunu wɔ kokoo aba soɔ mu. Eyi ho hia sɛ yehunu na ama nneɛma ahodoɔ a esɛsɛ wɔde wɔn ani si so a ebɛboa ama kokoo aba aso yie atu mpɔn. Wim nsakrae a wɔhwɛ kwan sɛ ɛbɛka kokoo wɔ ɔkwan a enye so wɔ Afrika Atɔe fam, baabi a wodua kokoo bɛboro 70% wiase nyinaa no de daakye kokoo wɔbɛnya reto asiane mu. Nanso, sɛnea ɔhyew, nsutɔ ne wim "carbon dioxide" dodoɔ ("CO_2") nya nsunsuansoɔ wɔ kokoo dua so ne aba soɔ so no wɔnte aseɛ yiye. Nea afi mu aba ne sɛ, wonnya nsusuw ɔkwan a wim nsakrae betumi anya nsunsuansoɔ wɔ kokoo aba soɔ ne sɛnea ɛbɛsakra ho. Asasesin mu nsakrae a wim tebea de betumi aba wɔ Afrika Atɔe Fam kokoo so no betumi anya nsunsuansoɔ kɛseɛ wɔ akuafo, kokoo a wɔde ma ne kwae ahoroɔ so.

Wɔ eyi mu no, saa adesua asɛmti botae ne sɛ ɛbɛma yenya ntease wɔ nneɛma a ɛma kokoo aba wɔnya mprempren ne daakye wim tebea ase atu mpɔn. Titiriw no, adesua yi botaeɛ ne sɛ wɔbɛhunu na wɔasusu nneɛma a ɛma kokoo aba soɔ, ne kokoo aba soɔ mu nsonsonoeɛ eda aba a akuafo nya ne dodoɔ anka ɔbetumi anya, na wɔasusu nsunsuansoɔ a wim nsakraeɛ de ba kokoo a wɔyɛ so. Saa adesua yi dii botaeɛ yi ho dwuma wɔ eti 2 kosi 4 mu.

Wɔ **Ti 1** mu no, ɔda adesua yi asɛmti no adi. Ti yi mu no, ɔkyerɛkyerɛ nimdeɛ dada a onim fa asemfua no ho. Na ɔkyerɛ mfasoɔ a ɛwɔho sɛ wɔbɛsusu nneɛma a ɛma kokoo aba soɔ, nea ɛde aba soɔ mu nsonsonoeɛ ba, ne nsunsuansoɔ a wim nsakraeɛ nya wɔ kokoo so. Ti no da nhwehwɛmu no botaeɛ, adesua nsɛmmisa, beaeɛ ɔyɛɛ adesua no, ne sɛnea w'ahyehyɛ no wɔ saa nnwoma yi mu.

Wɔ **Ti 2** mu no, wɔgyinaa nsɛm a ɛfa kokoo mfuo 3,827 ho wɔ Ghana so hwɛhwɛɛ sɛnea wim tebea ne asase ho nsɛm ma kokoo aba soɔ ne sɛnea ɛyɛ soronko ma mfuw a sɛ wɔkyekyem pɛpɛɛpɛ a, wonya nnɔbae ɛkɔ soro ne nea wɔn deɛ wɔ fam. Wɔgyinaa nsɛm a ɛfa mfuo 134 so hwɛɛ hia kokoo mfuw sohwɛ nhyehyɛe ho hia. Nea efiri mu bae no kyerɛe sɛ, mfuw sohwɛ ho nhyehyɛe ne ade titiriw a ɛkyerɛ nsakrae a ɛba wɔ kokoo aba soɔ a wonya wɔ Ghana. Na saa mfuw sohwɛ nhyehyɛe yi ho hia sene nneɛma efa wim tebea ne asase tebea ho nsunsuansoɔ. Wɔ kokoo mfuo 3,827 no nyinaa mu no, wɔhunuu kokoo aba soɔ mu nsakraeɛ kɛseɛ (~100 kɔsi >1000 kg ha^{-1}) wɔ mmeaeɛ nyinaa. Na na nsonsonoe a ɛda kokoo aba soɔ wɔ mmeae a nsuo tɔ kɛseɛ ne nea nsuo ntɔ kɛse no sua titiriw. Wɔhunu sɛ kokoo aba soɔ nsakrae kɛseɛ a ɔhunui no mmeaeɛ nyinaa gyina nneɛma a ɛfa afuom mu adwumayɛ ho anaa nhyehyɛe ho. Na ete saa kyerɛ sɛ nsunsuansoɔ ɛnam wim tebea ne asaase tebea so ba kokoo aba soɔ so no yɛ ketewa bi pɛ (7-10%). Wɔ mfuw 134 no fam mu no, nsunsuansoɔ ɛnam mfuw sohwɛ nhyehyɛe so ba kokoo aba soɔ so no kɔɔ anim (10-25%). Wei kyerɛ se afuom dwuma titiriw a akuafoɔ di no na ɛma mprempren kokoo aba soɔ kɔ soro. Ne nyinaa akyi no, wɔhunuu nso sɛ ɛsono sɛnea wim tebea ne asase tebea ho nsɛm di dwuma wɔ mfuw a kokoo aba so pii wɔ mu kyɛn mfuw kokoo nso papa. Na kokoo mfuw a ɛso pii no te wim tebea ne asase tebea ho nsakrae ho nsunsuansoɔ nka kɛse sene mfuw a ɛnso pii no. Saa nsɛm yi kyerɛe sɛ nsunsuansoɔ a wim tebea ne asase tebea nya wɔ kokoo aba soɔ so no bɛyɛ nea ɛho hia kɛse, woberɛ a w'ayi mfuw sohwɛ nhyehyɛe ɛmmoa kokoo aba soɔ no afiri hɔ. Enti, ɛsɛ sɛ wɔyɛ kuayɛ ho nhyehyeɛ pa ansa na wɔde wɔn sika ahyɛ wim tebea mu nsakrae ho nneama foforo ho daakye.

Wɔ **Ti 3** mu no, wɔkyerɛɛ nsonsonoeɛ ɛda kokoo aba a wobetumi anya wɔ beaeɛ biako biara ne nea akuafoɔ nya mprempren yi. Afei nso, ti yi da nneɛma a ɛbetumi ama saa nsonsonoeɛ yi so ate. Ɔde aba wobɛtumi anya wɔ beaeɛ biako biara ho akontabuo mmiɛnsa yɛɛ nhwɛsoɔ: i) kokoo aba wobetumi anya wɔ tebea ahodow nsuo tɔ nkutoo na ete kokoo aba soɔ so (wɔde "CASE2" kokoo nhwɛso na ɛbuu saa akontaa no) ii) kokoo dodoɔ a wonya wɔ mmeae a wɔyɛ kokoo adesua nhwehwɛmu iii) kokoo aba dodoɔ akuafo a wɔyɛ wɔn kokoo mfuw yiye no nya. Wɔde saa akontabuo mmiɛnsa yi totoo nea akuafo nnya mu de kyerɛ aba dodoɔ a wɔbɛtumi anya wɔ ahoɔden ahodoɔ mu. Nea efii mu bae no kyerɛe sɛ, nsonsonoeɛ kɛseɛ da aba wɔbɛtumi anya ne nea akuafoɔ nya mprempren wɔ wɔn kokoo mfuw nyinaa mu. Wei kyerɛ sɛ akwanya kɛseɛ da hɔ sɛ wɔbɛma kokoo aba soɔ akɔ soro asen mprempren dodoɔ. Sɛ yehwɛ nsonsonoeɛ ɛda kokoo aba wobetumi anya wɔ tebea ahodow a nsuo tɔ nkutoo ne adea ete kokoo aba soɔ so ne nea akuafo nya a, na eso koraa (4,577 kg/ha, kokoo aba soɔ no mu nsonsonoeɛ yɛ 86%) sen akontabuo mmmienu a ɛhwɛ dodoɔ wɔnya wɔ kokoo sua bea mfum mu (1930 kg/ha, kokoo aba soɔ no mu nsonsonoeɛ yɛ 73%) ne nea akuafoɔ a woyɛ wɔn mfuw yie no nya (469 kg/ha, kokoo aba soɔ no mu nsonsonoeɛ yɛ 42%). Wɔ nneɛma a ɛkyerɛkyerɛ saa nsonsonoeɛ yi mu no, ɔhunuu sɛ wim tebea (nsutɔ ne ɔhyeɛ) ho hia ma akontabuo a edi kan no ne nea eto so mmienu no, nanso na ɛnte saa wɔ akontabuo eto so mmiensa ne mu. Wɔ nkontabuo mmienu a edikan no mu no, nsuo a ɛtɔ bampro berɛ mu no ne ɔhyeɛ a ɛba fam koraa wɔ ɔfupɛ berɛ mu (ɔpɛ berɛ kumaa) no na ɛmaa kokoo aba soo yie. Na ɛmfa ho sɛnea wim tebea te bia, ɔhunuu sɛ dwumadie a ɛte anunum/gyansruku ("black pod") kokoo yareɛ so ne kokoo ndua dodoɔ a ɛwɔ kokoo afu saase so no te nsonsonoeɛ ɛda kokoo aba a wɔbɛtumi anya ne nea akuafo nya no mpremprem no so. Wei kyerɛ sɛ akwanya kɛseɛ da hɔ sɛ wɔbɛtumi ama kokoo aba aso yie na yɛnya kokoo dodoɔ a ekɔ anim a ɛho nnhia sɛ wɔtrɛ beaeɛ a wɔdua kokoo mu bio.

Wɔ **Ti 4** mu no, ɔhwɛɛ nsunsuansoɔ a nsakraeɛ a wɔahyɛ ho nkɔm sɛ ɛbɛba wɔ wim tebea mu benya wɔ kokoo so wɔ Afrika Atɔeɛ ne Mfinimfini fam mu kɔsi afeha mu mfimfini (2060). Wɔhwɛɛ baabi a saa nsunsuanso ahodow yi kɔ so, ne kwan a wim "CO_2" dodoɔ a ɛkɔ soro no bɛnya wɔ so. Wɔgyinaa wim tebea ho nsɛm ɛnum a wɔhwɛ kwan sɛ ɛbɛba daakye nhwɛso ahodow so na ɛyɛɛ saa nhwɛhwɛmu no. Wɔ saa adesua yi mu no, ɔde kokoo nnɔbae nyin ho nhwɛso ("CASEJ") a etumi kyerɛ sɛnea wim tebea ne "CO_2" nya nsunsuansoɔ wɔ kokoo nyin ne aba soɔ ho no mfonini na ɛyɛɛ nhwɛhwɛmu. Nea efii mu baayɛ no kyerɛ sɛ, sɛ yɛyi nea ɛda nsow a, nhwɛsoɔ nkɔmhyɛ kyerɛe sɛ wɔ daakye wim tebea ase no, nkɔanim bɛba wɔ kokoo aba soɔ ne beaeɛ a ɛfata sɛ wɔdua kokoo no mu. Afei nso, nsakrae a ɛba afe afe kokoo aba soɔ mu no bɛyɛ kakraa bi, titiriw wɔ bere a woafa no sɛ "CO_2" nsunsuansoɔ edi mu ne tebea ahodow a nsuo wɔ hɔ. Na wɔhwɛ kwan sɛ nsunsuansoɔ ahodow no beyɛ kesɛɛ wɔ apuei kosi atɔe asasesin aman a wodua kokoo wɔ Afrika Atɔeɛ ne Mfinimfini fam. Cameroon a ɛwɔ apuei fam na ɛbɛnya nsunsuansoɔ pa paa (kokoo aba soɔ kɔ soro bɛyɛ ~39-60% ne beaeɛ ɛfata ma kokoo dua bɛyɛ ~11-12 Mha). Na Nigeria edii Cameroon akyi wɔ nsunsuansoɔ pa mu (kokoo aba soɔ kɔ soro bɛyɛ ~39-60%), nanso na beaeɛ ɛfata ma kokoo dua deɛ na eso wɔ saa mantam yi mu (~17 - 20 Mha). Na Ghana dii Nigeria akyi (kokoo aba soɔ kɔ soro bɛyɛ 30-45%) nanso kokoo aba soɔ so tee bɛyɛ 12% wɔ saa mantam yi mu. Afei nso, ɔnyaa beaeɛ efata se wodua kokoo nkɔanimu bɛyɛ ~2 Mha nanso wɔhwere bɛyɛ ~2-2.5 Mha. Na ɔman a ɛwɔ atɔe fam, ɛyɛ Côte d'Ivoire deɛ, wɔhunuu sɛ kokoo aba soɔ so betumi ate bɛyɛ 12% na wɔhwere mprempren beaeɛ ɛfata bɛyɛ ~6 -11 Mha. Nsakrae a ɛbetumi aba afe afe kokoo soɔ mu no bekɔ soro wɔ mmeae a wɔhwɛ anim sɛ kokoo aba soɔ so bɛ te. Nkɔanim a wɔhwɛhwɛ sɛ kokoo aba soɔ betumi akɔ anim no begyina nsutɔ a wɔhwɛ kwan sɛ ebetɔ wɔ ɔpɛ berɛ mu no bɛkɔ soro. Na afei, ɔpɛ bere no tenten a wɔhwɛ kwan sɛ eso bɛte no bɛma afe afe kokoo soɔ nsakrae so ate.

Wɔ **Ti 5** mu no, ɔde nhoma ahodow a ɛwɔ hɔ no mu nsɛm atitiriw a wɔahunu wɔ Ti 2 kosi 4 mu no ho nkɔmmɔbɔ a ɛkɔ akyiri kyerɛ yɛ. Wɔ saa nkɔmmɔbɔ no mu no, wɔde nsɛm a ɛfa hia a wim tebea, asase tebea ne mfuw sohwɛ ho nsunsuansoɔ nya wɔ kokoo aba soɔ so, aba soɔ mu nsonsonoeɛ, ne nsunsuansoɔ a wim nsakraeɛ bɛtumi anya wɔ daakye kokoo so kyerɛ yɛ. Afei nso, ɔsane maa nyansahyɛ ahodow ɛfa daakye nhwehwɛmu ho a egyina nsɛmmisa a wɔabue ano a aka no wɔ saa ti yi mu.

Sɛ yɛde rewie no, adesua yi nhwɛhwɛ mu kyerɛ sɛ, kokoo mfuw sohwɛ ho nhyehyeɛ a ɛtu mpɔn na ɛma ɛnnɛyi kokoo aba soɔ kɔ soro kɛse. Ne saa nti no ɛsɛ sɛ wɔde nhyehyeɛ pa a ɛtete saa no si hɔ yie ansa na wɔde akwan foforo pɔtee a wɔfa so sesa wim tebea ho nsunsuansoɔ aba. Wɔ daakye wim tebea ase no, nea efiri nhwɛsoɔ no mu bae no kyerɛ sɛ, ɛmfa ho ɔhyew a wɔhwɛ ho kwan sɛ ebɛkɔ soro, ne nsakrae a ɛbɛba nsutɔ mu, ɔpɛ bere mu nsutɔ ne ɔpɛ bere mu tenten a ayɛ tia no bɛma kwan ama mmeae pii a wodua kokoo mprempren no atumi akura kokoo dwumadie mu anaasɛ anya nkɔsoɔ akɔsi afeha mu mfinimfini, titiriw wɔbere a woafa no sɛ "CO_2" benya nsunsuansoɔ pa.

Samenvatting

Cacaoproductie is economisch van groot belang voor: producerende landen, de zoetwarenindustrie, de miljoenen kleine boeren die het gewas verbouwen en de mensen die in de cacao-industrie werken. De wereldwijde vraag naar cacao groeit en de productie is sinds de jaren zestig meer dan verviervoudigd. In de afgelopen drie decennia is de toename van de cacaoproductie voornamelijk bereikt door uitbreiding van het beplante areaal, terwijl de opbrengsten per oppervlakte-eenheid vrij constant zijn gebleven. Deze uitbreiding van land onder cacaoteelt leidt tot ontbossing in cacaoproducerende landen en verhoogt de voedselonzekerheid in sommige gebieden, omdat cacao de akkerlanden vervangt. Met de toenemende vraag is het belangrijk om mogelijkheden te identificeren om de cacaoproductiviteit op bestaande grond te verhogen als een middel om aan de vraag te voldoen en tegelijkertijd de druk op bos- en ander landgebruik te verminderen. Hoewel tal van milieu- (klimaat en bodem) en managementfactoren zijn geïdentificeerd die de huidige cacaoopbrengsten beperken, blijft hun relatieve belang bij het verklaren van variatie in opbrengsten onbekend. Het kwantificeren hiervan is belangrijk voor het prioriteren van interventies gericht op het verbeteren van de opbrengsten. De toekomstige cacaoproductie wordt bedreigd door klimaatverandering die naar verwachting een negatieve invloed zal hebben op cacao door de afnemende klimaatgeschiktheid in West-Afrika, waar meer dan 70% van de cacao wordt geteeld. Kennis over de effecten van temperatuur, regenval en atmosferische kooldioxideconcentratie [CO_2] op de fysiologie en productiviteit van cacaobomen is echter nog beperkt. Als gevolg hiervan zijn mogelijke implicaties van klimaatverandering voor cacaoproductiviteit en aanpassingen nog niet overwogen. Door het klimaat veroorzaakte geografische verschuivingen in de West-Afrikaanse cacaogordel kunnen ernstige gevolgen hebben voor boeren, cacao en bossen.

In dit verband was dit proefschrift gericht op het verbeteren van het inzicht in de drijfveren van de cacaoopbrengst onder het huidige en toekomstige klimaat. Specifiek was het doel om de factoren te identificeren en te beoordelen die de cacao-opbrengsten en de cacao-opbrengstkloof stimuleren en om de effecten van klimaatverandering op de cacaoproductie te beoordelen. Dit doel werd behandeld in de drie kernhoofdstukken (hoofdstuk 2-4) van dit proefschrift.

In **hoofdstuk 1** wordt de algemene context van het proefschrift gepresenteerd, waarin de kennislacunes in onderzoek worden beschreven, de relevantie van het beoordelen van de oorzaken van cacaoopbrengsten en cacaoopbrengstkloven, alsook de effecten van klimaatverandering op de cacaoproductie. Het hoofdstuk eindigt met een beschrijving van de algemene onderzoeksdoelstellingen en -vragen, een korte beschrijving van het studiegebied en het scriptieoverzicht.

In **hoofdstuk 2** werd de mate waarin klimaat- en bodemfactoren de cacaoopbrengsten bepalen en hoe deze verschilt voor boerderijen die gemiddeld lage en hoge gemiddelde productieniveaus bereiken, beoordeeld op basis van een ongekende dataset van 3.827 cacaoboerderijen verspreid over de klimaat- en bodemgradiënten van Ghana. De relatieve rol van het management werd geëvalueerd op basis van een subset van 134 bedrijven waarvoor dergelijke gegevens beschikbaar waren. De resultaten toonden aan dat agronomisch management de dominante verklarende factor was voor variatie in cacaoopbrengsten in Ghana, meer dan klimaat- en bodemomstandigheden. Op de 3.827 cacaoplantages werd een grote cacaoopbrengstvariabiliteit (~ 100 tot >1000 kg $^{\text{ha-1}}$) waargenomen binnen neerslagzones, maar tussen neerslagzones waren de opbrengstverschillen opmerkelijk klein. De waargenomen hoge variabiliteit in cacaoopbrengsten werd voornamelijk toegeschreven aan managementgerelateerde factoren. Dit kwam omdat klimaat- en bodemfactoren verrassend genoeg slechts 7-10% van de variatie in opbrengsten verklaarden, wat een zeer klein deel was van de totale variatie die werd verklaard wanneer zowel klimaat en bodem als boerderij-tot-boerderijvariatie werd overwogen (55-85%). Voor de subgroep van 134 cacaoplantages steeg de verklaarde variatie in cacaoopbrengsten van 10% naar 25% wanneer managementfactoren worden meegerekend naast klimaat- en bodemfactoren, wat de belangrijke rol van het management voor het verhogen van de huidige cacaoopbrengsten bevestigt. Niettemin bleek de rol van de klimaat- en bodemomstandigheden te variëren tussen cacaoplantages met verschillende totale gemiddelde opbrengsten. Cacaoboerderijen met hogere opbrengsten waren gevoeliger voor milieuomstandigheden dan boerderijen met lagere opbrengsten. Deze bevindingen suggereerden dat effecten van klimaat- en bodemomstandigheden op cacaoopbrengsten belangrijker worden wanneer beperkende managementfactoren worden verwijderd. Er moeten dus goede landbouwpraktijken zijn voordat wordt geïnvesteerd in aanvullende klimaatadaptatiepraktijken.

In **hoofdstuk 3** werden de cacaoopbrengstkloof en de factoren die bijdragen aan het verkleinen van deze kloof gekwantificeerd. De opbrengstkloof werd berekend als het verschil tussen de potentiële opbrengst en de werkelijke opbrengst van de landbouwer. Drie schattingen van de potentiële opbrengst werden gebruikt als referentie in de berekeningen van de opbrengstkloof: i) gesimuleerde waterbeperkte potentiële cacaoopbrengst geschat met behulp van het CASE2-cacaomodel, ii) haalbare opbrengst in systemen met een hoge input op basis van gemiddelde opbrengsten uit experimentele proeven, en iii) haalbare opbrengst in systemen met een lage input op basis van de gemiddelde opbrengst van de 10% best presterende boeren. Drie schattingen van de cacaoopbrengstkloof in absolute en relatieve termen op basis van deze opbrengstreferenties werden gepresenteerd om een uitgebreide schatting te geven van de potentiële opbrengstwinsten die op verschillende niveaus van intensivering kunnen worden bereikt. De resultaten toonden aan dat, ongeacht de definitie van potentiële opbrengst, er aanzienlijke opbrengstverschillen waren tussen alle cacaobedrijven met dus grote kansen om de cacaoopbrengsten boven het huidige niveau te verhogen. De maximale waterbeperkte opbrengstverschillen (gemiddeld absoluut 4.577 kg/ha, relatieve opbrengstkloof van 86%) waren veel groter dan de opbrengstverschillen die haalbaar waren in hoge input (gemiddeld absoluut 1930 kg/ha, relatieve opbrengstkloof van 73%) en systemen met een lage input (gemiddeld absoluut 469 kg/ha, relatieve opbrengstkloof van 42%). In termen van factoren die de variatie in de cacaoopbrengstverschillen verklaren, waren klimaatfactoren (temperatuur en neerslag) belangrijk voor de absolute maximale waterbeperkte en haalbare opbrengstkloven in systemen met een hoge input, maar niet in systemen met een lage input. Deze twee schattingen van de opbrengstkloof (absolute maximale waterbeperkte en haalbare opbrengstverschillen in systemen met een hoge input) namen toe met toenemende neerslag van het kleine regenseizoen en de minimumtemperatuur van het kleine droogseizoen. Ongeacht het klimaat werden de absolute opbrengstkloof in systemen met een lage input en relatieve opbrengstverschillen verkleind door managementpraktijken, waaronder het verhogen van de dichtheid van cacaoplanten en de controle op de aanwezigheid van door ziekte aangetaste peulen. Deze resultaten laten zien dat er nog steeds aanzienlijke opbrengstverschillen zijn op cacaoplantages die in de toekomst kunnen worden overbrugd om aan de toenemende vraag naar cacao te voldoen zonder de noodzaak om het beplante gebied verder uit te breiden.

In **hoofdstuk 4** werd de potentiële impact van de verwachte klimaatveranderingen op de cacaoproductie in West- en Centraal-Afrika tot het midden van de huidige eeuw (2060) geprojecteerd en de mate waarin deze effecten werden gemedieerd door een verhoogde atmosferische CO_2-concentratie beoordeeld. Dit werd gedaan op basis van vijf plausibele toekomstige klimaatscenario's geprojecteerd door algemene circulatiemodellen en met behulp van een groeimodel voor cacaogewassen dat de fysiologische effecten van klimaat en CO_2 op cacaogroei, groeigerelateerde processen en opbrengst simuleerde. Op opmerkelijke uitzonderingen na toonden modelvoorspellingen aan dat onder het toekomstige klimaat een toename van gesimuleerde waterbeperkte potentiële opbrengsten en van het gebied dat geschikt is voor het verbouwen van cacao werd verwacht, terwijl de interjaarlijkse opbrengstvariabiliteit naar verwachting minder zou worden, vooral wanneer volledige CO_2-effecten en nattere omstandigheden werden aangenomen. Verwacht werd dat de effecten een duidelijke (zuid-) oost - west geografische gradiënt zouden volgen, waarbij voorspellingen het meest positief waren in het meest oostelijke land, Kameroen, waar sterke stijgingen in opbrengst (~ 39-60%) en in geschikt gebied voor cacao (~ 11-12 Mha) werden gevonden, en het minst positief voor het meest westelijke land, Ivoorkust, waar sterke opbrengstverminderingen tot 12% en grote verliezen van het huidige geschikte gebied (~ 6-11 Mha) werden gevonden. Nigeria volgde Kameroen in termen van positieve effecten (behalve de grootste toename in geschiktheid die werd gevonden in deze regio ~ 17-20 Mha) en Ghana (30-45% stijgingen en sterke vermindering van de opbrengst, 12%, ~ 2 Mha winst en ~ 2-2,5 Mha verlies in geschiktheid) volgde na Nigeria. De voorspelde jaarlijkse opbrengstvariabiliteit was hoger in gebieden met lagere opbrengsten, dus een vergelijkbare geografische trend werd waargenomen met verminderde variabiliteit in Kameroen en de grootste toenames in Ivoorkust. Voorspelde toenames van gesimuleerde waterbeperkte potentiële opbrengsten werden meestal geassocieerd met de verwachte toename van neerslag in het droogseizoen, terwijl de verwachte verkorting van het droogseizoen de opbrengstvariabiliteit verminderde.

In **hoofdstuk 5 wordt** een algemene synthese van de belangrijkste bevindingen in de hoofdstukken 2 tot en met 4 van dit proefschrift gepresenteerd in het licht van de bestaande literatuur. Conclusies over het relatieve belang van klimaat-, bodem- en agronomische beheerseffecten op cacaoopbrengsten en de -opbrengstkloof zowel als de potentiële impact van klimaatverandering op de toekomstige cacaoproductie worden getrokken en aanbevelingen voor toekomstig onderzoek worden verstrekt op basis van resterende onderzoeks-/open vragen.

Concluderend, dit proefschrift laat zien dat verbeterde agronomische managementpraktijken kansen bieden om de productie van hedendaagse cacaoplantages aanzienlijk te verhogen, en dat dergelijke praktijken goed moeten zijn ingevoerd voordat specifieke klimaatadaptieve strategieën worden geïntroduceerd. Onder het toekomstige klimaat geven modelleringsresultaten aan dat, ondanks de temperatuurstijgingen en veranderingen in de neerslagverdeling zoals geprojecteerd door de algemene circulatiemodellen, de verwachte toename van de neerslag in het droge seizoen en de kortere lengte van het droge seizoen veel gebieden waar momenteel cacao wordt verbouwd in staat zou stellen om de productiviteit tegen het midden van de 21ste eeuw te handhaven of te verhogen, vooral als volledig effecten van verhoogd [CO_2] worden verondersteld.

Résumé

La production de cacao est d'une grande importance économique pour les pays producteurs, l'industrie de la confiserie, les millions de petits agriculteurs le cultivent et les personnes qui travaillent dans les industries du cacao. La demande mondiale de cacao augmente et la production a plus que quadruplé depuis les années 1960. Au cours des trois dernières décennies, l'augmentation de la production de cacao a été obtenue principalement grâce à l'expansion des superficies emblavées, tandis que les rendements sont restés relativement stagnants. Cette expansion des terres consacrées à la culture du cacao entraîne la déforestation dans les pays producteurs de cacao et accroît l'insécurité alimentaire dans certaines régions, car le cacao occupe les terres cultivables. Compte tenu de l'augmentation de la demande, il est important d'identifier les opportunités pour une augmentation de la productivité du cacao dans les plantations actuelles afin de répondre à la demande tout en réduisant la pression sur les forêts et les autres besoins en terres. Bien que de nombreux facteurs environnementaux (climat et sol) et de gestion limitant les rendements actuels du cacao aient été identifiés, leur importance relative dans l'explication de la variation des rendements reste inconnue. Il est important de quantifier cela pour hiérarchiser les interventions visant à améliorer les rendements. La production future de cacao est menacée par le changement climatique qui devrait avoir un impact négatif sur le cacao en dégradant les conditions de culture en Afrique de l'Ouest, où plus de 70% du cacao est cultivé. Cependant, les effets de la température, des précipitations et de la concentration atmosphérique de dioxyde de carbone [CO_2] sur la physiologie et la productivité du cacaoyer sont peu compris. En conséquence, les implications possibles du changement climatique sur la productivité du cacao et son adaptation n'ont pas encore été prises en compte. Le déplacement des zones de culture lié au changement climatique au sein de la ceinture cacaoyère ouest-africaine peuvent avoir de graves implications pour les agriculteurs, la production de cacao et les forêts.

À cet égard, cette thèse visait à améliorer la compréhension des facteurs qui déterminent le rendement du cacao avec les climats actuel et futur. Plus précisément, l'objectif était d'identifier et d'évaluer les facteurs qui déterminent les rendements de cacao et l'écart de rendement du cacao, et d'évaluer les impacts du changement climatique sur la production de cacao. Cet objectif a été abordé à travers les trois principaux chapitres (chapitre 2-4) de cette thèse.

Au **chapitre 1**, le contexte général de la thèse est présenté, décrivant les manques de connaissances et la pertinence d'une évaluation des facteurs qui déterminent le rendement du

cacao, les écarts de rendement du cacao, et les impacts du changement climatique sur la production de cacao. Le chapitre se termine par une description des objectifs généraux et des questions de recherche, et une brève présentation du site d'étude et le plan de la thèse.

Dans le **chapitre 2**, le degré auquel les facteurs climatiques et pédologiques déterminent les rendements de cacao et leurs variations entre exploitations atteignant des niveaux de production faibles, moyens et élevés a été évaluée sur la base d'un ensemble de données inédit de 3 827 exploitations cacaoyères couvrant les gradients environnementaux du Ghana. Le rôle relatif de la gestion de plantation a été évalué sur la base d'un sous-ensemble de 134 exploitations pour lesquelles de telles données étaient disponibles. Les résultats ont montré que la gestion agronomique était le principal facteur déterminant la variation des rendements du cacao dans les exploitations au Ghana, plus que ne le sont les conditions environnementales. Dans les 3 827 exploitations cacaoyères, une grande variabilité du rendement du cacao (~100 à >1000 kg ha^{-1}) a été observée dans les zones pluviométriques, mais les différences de rendement moyennes entre les zones pluviométriques étaient très faibles. La forte variabilité observée dans les rendements de cacao a été attribuée principalement à des facteurs liés à la gestion. Cela s'explique par le fait que les facteurs environnementaux n'expliquaient que 7 à 10 % de la variation des rendements, ce qui représentait une très petite proportion de la variance totale expliquée lorsque l'on tenait compte à la fois de la variation de l'environnement et l'hétérogénéité entre exploitations (55 à 85 %). Pour le groupe de 134 exploitations, la variation expliquée des rendements de cacao est passée de 10% à 25% en incluant des facteurs de gestion en plus des facteurs environnementaux, confirmant le rôle important de la gestion dans l'augmentation des rendements actuels du cacao. Néanmoins, il a été constaté que le rôle des conditions environnementales variait d'une exploitation à l'autre avec des rendements moyens différents. Les exploitations cacaoyères ayant des rendements plus élevés étaient plus sensibles aux conditions environnementales que les celles ayant des rendements plus faibles. Ces résultats suggèrent que les effets des conditions environnementales sur les rendements du cacao deviennent plus importants lorsque les contraintes de gestion sont supprimées. Ainsi, de bonnes pratiques agricoles doivent être mises en place avant d'investir dans des pratiques complémentaires d'adaptation au changement climatique.

Dans le **chapitre 3**, l'écart de rendement du cacao et les facteurs qui contribuent à le réduire ont été quantifiés. L'écart de rendement a été calculé comme la différence entre le rendement potentiel et le rendement réel atteint par l'agriculteur. Trois estimations de rendement potentiel ont été utilisées comme référence dans les calculs de l'écart de rendement: i) le rendement potentiel de cacao simulé en culture pluviale estimé à l'aide du modèle de cacao CASE2, ii) le rendement atteignable dans les systèmes intensifs basé sur les rendements moyens des essais expérimentaux, et iii) le rendement atteignable dans les systèmes à faible utilisation d'intrants basé sur le rendement moyen des 10% d'agriculteurs les plus performants. Trois estimations de l'écart de rendement du cacao en termes absolus et relatifs basées sur ces références de rendement ont été présentées afin de fournir une estimation complète des gains de rendement potentiels qui pourraient être réalisés à différents niveaux d'intensification. Les résultats ont montré que, quelle que soit la définition du rendement potentiel, il existait des écarts de rendement considérables dans toutes les exploitations cacaoyères, ce qui offrirait d'énormes opportunités d'augmenter les rendements de cacao au-delà des niveaux actuels. Les écarts maximaux de rendement en culture pluviale (moyenne absolue de 4577 kg/ha, écart relatif de 86 %) étaient beaucoup plus importants que les écarts de rendement réalisables dans les systèmes intensifs (moyenne absolue de 1930 kg/ha, écart relatif de 73 %) et à faible utilisation d'intrants (moyenne absolue de 469 kg/ha, écart de rendement relatif de 42 %). En ce qui concerne les facteurs qui expliquent la variation des écarts de rendement en cacao, les facteurs climatiques (température et précipitations) étaient importants pour les écarts de rendement maximum absolus en culture pluviale et ceux réalisables dans les systèmes intensifs, mais pas dans les systèmes à faible utilisation d'intrants. Ces deux estimations de l'écart de rendement (écarts de rendement absolus maximaux en culture pluviale et écarts de rendement atteignables dans les systèmes intensifs) augmentaient avec les précipitations de la petite saison pluvieuse et la température minimale de la petite saison sèche. Quel que soit le climat, l'écart de rendement absolu dans les systèmes à faible utilisation d'intrants et les écarts de rendement relatif ont été réduits par des pratiques de gestion, notamment l'augmentation de la densité de plantation de cacao et un meilleur contrôle de la pourriture brune des cabosses. Ces résultats montrent qu'il existe encore des écarts de rendement considérables dans les exploitations cacaoyères qui peuvent être comblés à l'avenir pour répondre à la demande croissante de cacao sans qu'il soit nécessaire d'étendre davantage les superficies plantées.

Dans le **chapitre 4**, l'impact potentiel des changements climat sur la production de cacao en Afrique de l'Ouest et du Centre jusqu'au milieu du siècle (2060) et la mesure dans laquelle ces effets ont été modérés par une concentration atmosphérique élevée de CO_2 ont été évalués. Cela a été fait sur la base de cinq scénarios climatiques futurs plausibles projetés par des modèles de circulation générale et en utilisant un modèle de croissance des cultures de cacao qui simulait les effets physiologiques du climat et du CO_2 sur la croissance du cacao, les processus liés à la croissance et le rendement. À quelques exceptions près, les prévisions des modèles ont montré que, dans le climat futur, on s'attendrait à une augmentation des rendements simulés en culture pluviale et de la superficie propice à la culture du cacao, tandis que la variabilité interannuelle des rendements devrait diminuer, en particulier en y intégrant tous les effets potentiels du CO_2 dans des conditions plus humides. On devrait s'attendre à ce que les impacts suivent un clair gradient géographique (sud) est-ouest, avec des prévisions positives les plus importantes au Cameroun, où de fortes augmentations de rendement (~39-60%) et un élargissement de la zone propice au cacao (~11-12 Mha) devraient s'observer. Par contre, les impacts les plus néfastes s'observeraient en Côte d'Ivoire, avec de fortes réductions de rendements (allant jusqu'à 12%) et des pertes importantes de superficies propices au cacao (~6-11 Mha). Le Nigéria a suivi le Cameroun en termes d'effets positifs (à l'exception de la plus forte augmentation de l'adéquation constatée dans cette région ~17-20 Mha) et le Ghana (augmentation de 30 à 45% et forte réduction du rendement, gain de ~2 Mha et ~2-2,5 Mha de perte d'adéquation) a suivi le Nigeria. La variabilité prévue des rendements interannuels était plus élevée dans les zones où les rendements étaient plus faibles, de sorte qu'une tendance géographique similaire a été observée avec une variabilité réduite au Cameroun et les plus fortes variations en Côte d'Ivoire. Les augmentations prévues des rendements potentiels simulés en culture pluviale étaient principalement associées aux augmentations prévues des précipitations durant la saison sèche, tandis que le raccourcissement projeté de la saison sèche réduirait la variabilité des rendements.

Au **chapitre 5**, une discussion générale des principales conclusions des chapitres 2 à 4 de cette thèse est présentée à la lumière de la littérature existante. Des conclusions sur l'importance relative des effets du climat, du sol et de la gestion agronomique sur les rendements et l'écart de rendement du cacao et l'impact potentiel du changement climatique sur la production future de cacao sont tirées et des recommandations pour les recherches futures sont formulées sur la base des questions de recherche/restantes.

En conclusion, cette thèse montre que l'amélioration des pratiques de gestion agronomique offre la possibilité d'augmenter considérablement la production des plantations de cacao actuelles, et que de telles pratiques devraient être correctement mises en place avant d'introduire des stratégies spécifiques d'adaptation au changement climatique. Dans le climat futur, les résultats de la modélisation indiquent que, malgré les augmentations de température et les changements dans la répartition des précipitations, telles que projetées par les modèles de circulation générale, les augmentations prédites des précipitations en saison sèche et la durée plus courte de la saison sèche permettraient à de nombreuses régions où le cacao est

actuellement cultivé de maintenir ou d'augmenter la productivité d'ici le milieu du siècle, en particulier si l'on tient compte des effets potentiels du [CO_2].

Resumen

La producción de cacao es de gran importancia económicamente para: los países productores, la industria de confitería, los millones de pequeños agricultores que lo cultivan y las personas que trabajan en las industrias del cacao. La demanda mundial de cacao está creciendo y la producción se ha cuadruplicado con creces desde la década de 1960. En las últimas tres décadas, los incrementos en la producción de cacao se han logrado principalmente a través de la expansión en el área cultivada, mientras que los rendimientos por unidad de área se han mantenido más bien constantes. Esta expansión de área cultivada con cacao está impulsando la deforestación en los países productores y aumentando la inseguridad alimentaria en algunas áreas a medida que el cacao reemplaza las tierras de cultivo. Con el aumento de la demanda, es importante identificar oportunidades para aumentar la productividad del cacao en las tierras existentes como un medio para satisfacer la demanda y al mismo tiempo reducir la presión sobre los bosques y otros usos de la tierra. Si bien se han identificado numerosos factores ambientales (clima y suelo) y de manejo, que limitan los rendimientos actuales de cacao, su importancia relativa para explicar la variación en los rendimientos sigue siendo desconocida. Cuantificar esto es importante para priorizar las intervenciones destinadas a mejorar los rendimientos. La producción futura de cacao se encuentra amenazada por el cambio climático, que se espera tenga un impacto negativo en el cacao debido a la reducción de condiciones climáticas ideales en África occidental, donde se cultiva más del 70% del cacao. Sin embargo, los efectos de la temperatura, precipitación y concentración atmosférica de dióxido de carbono [CO_2] en la fisiología y productividad del árbol de cacao son poco comprendidos. Como consecuencia, aún no se han considerado las posibles implicancias del cambio climático en la productividad y adaptabilidad del cacao. Los cambios geográficos inducidos por el clima en el cinturón productor de cacao en África occidental pueden tener graves consecuencias para los agricultores, el suministro de cacao y los bosques.

En este sentido, esta tesis tuvo como objetivo mejorar la comprensión de los factores que afectan al rendimiento de cacao en los climas actuales y futuros. Específicamente, el objetivo fue: identificar y evaluar a los factores que influyen en los rendimientos de cacao y en la brecha de rendimiento, así como evaluar los impactos del cambio climático en la producción de cacao. Este objetivo fue abordado a lo largo de los tres capítulos centrales (Capítulos 2, 3 y 4) de esta tesis.

En el **Capítulo 1**, se presenta el contexto general de la tesis**,** describiendo las brechas de conocimiento en la investigación y la relevancia de evaluar los factores que influyen en los rendimientos de cacao y en las brechas de su rendimiento así como los impactos del cambio climático en la producción de cacao. El capítulo concluye con una descripción de los objetivos y preguntas generales de la investigación, una breve descripción del área de estudio y el esquema de la tesis.

En el **Capítulo 2**, se evaluó en qué medida los factores climáticos y del suelo impulsan los rendimientos del cacao y cuáles son las diferencias entre las fincas que alcanzan niveles promedios de producción bajos y altos sobre la base de un conjunto de datos sin precedentes de 3.827 fincas de cacao que abarcan los gradientes ambientales en Ghana. El rol relativo del manejo se evaluó sobre la base de un subconjunto de 134 fincas, las cuales contaban con dichos datos. Los resultados mostraron que el manejo agronómico fue el determinante dominante de variación en los rendimientos de cacao en las fincas en Ghana, más que las condiciones ambientales. En las 3.827 fincas de cacao, se observó una gran variabilidad del rendimiento del cacao (~ 100 a >1000 kg ha^{-1}) dentro de las mismas zonas de precipitación, pero entre las zonas de precipitación las diferencias de rendimiento medias fueron notablemente pequeñas. La alta variabilidad observada en los rendimientos de cacao se atribuyó principalmente a factores relacionados con el manejo. Esto se debió a que, sorprendentemente, los factores ambientales explicaron solo el 7-10% de la variación en los rendimientos, porción muy pequeña de la varianza total explicada cuando se consideró tanto la variación ambiental como la de finca a finca (55-85%). Para el subconjunto de 134 fincas, la variación explicada en los rendimientos de cacao aumentó del 10% al 25% al incluir factores de manejo además de factores ambientales que confirman el importante papel del manejo para aumentar los rendimientos actuales de cacao. No obstante, se encontró que el rol de las condiciones ambientales variaba entre las granjas con diferentes rendimientos promedios generales. Las fincas de cacao con mayores rendimientos eran más sensibles a las condiciones ambientales que las fincas con rendimientos más bajos. Estos hallazgos sugieren que los efectos de las condiciones ambientales en los rendimientos de cacao se vuelven más importantes cuando se eliminan los factores de manejo limitantes. Por lo tanto, es necesario establecer buenas prácticas agrícolas antes de invertir en prácticas adicionales de adaptación al clima.

En el **capítulo 3**, se cuantificó la brecha de rendimiento del cacao y los factores que contribuyen a reducirla. La brecha de rendimiento se calculó como la diferencia entre el rendimiento potencial y el rendimiento real alcanzado por el agricultor. Se utilizaron tres estimaciones de rendimiento potencial como referencia en los cálculos de la brecha de rendimiento: i) estimado del rendimiento potencial de cacao simulado limitado por agua utilizando el modelo de cacao CASE2, ii) rendimiento potencial en sistemas de altos insumos basado en rendimientos promedio de ensayos experimentales, y iii) rendimiento potencial en sistemas de bajos insumos basado en el rendimiento promedio del 10% de los agricultores con mejor desempeño. Se presentaron tres estimaciones de la brecha de rendimiento del cacao en términos absolutos y relativos basadas en estas referencias de rendimiento para proporcionar una estimación completa de los posibles aumentos del rendimiento que podrían lograrse en diferentes niveles de intensificación. Los resultados mostraron que, independientemente de la definición de rendimiento potencial, había considerables brechas de rendimiento en todas las fincas de cacao que mostraban grandes oportunidades para aumentar los rendimientos de cacao más allá de los niveles actuales. Las brechas de rendimiento máximas limitadas por agua (media absoluta 4.577 kg/ha, brecha de rendimiento relativo del 86%) fueron mucho mayores que las brechas del rendimiento potencial en sistemas de alto insumo (media absoluta de 1930 kg/ha, brecha de rendimiento relativa del 73%) y baja de insumos (media absoluta de 469 kg/ha, brecha de rendimiento relativa del 42%). En términos de factores que explican la variación en las brechas de rendimiento del cacao, los factores climáticos (temperatura y precipitación) fueron importantes para las brechas de rendimiento máximas absolutas limitadas por agua y potenciales en los sistemas de altos insumos, pero no en los sistemas de bajos insumos. Estas dos estimaciones de la brecha de rendimiento (brechas de rendimiento máximas absolutas limitadas por agua y potenciales en sistemas de altos insumos) incrementaron con el aumento de la precipitación de la temporada de lluvias menores y la temperatura mínima de la estación seca menor. Independientemente del clima, la brecha de rendimiento absoluta en los sistemas de bajos insumos y las brechas de rendimiento relativo se redujeron mediante prácticas de manejo, incluido el aumento de la densidad de siembra de cacao y la presencia de control de podredumbre negra. Estos resultados muestran que todavía hay considerables brechas de rendimiento en las fincas de cacao que se pueden cerrar en el futuro para satisfacer la creciente demanda de cacao sin la necesidad de expandir aún más el área plantada.

En el **capítulo 4**, se evaluó el impacto potencial de los cambios climáticos proyectados en la producción de cacao en África occidental y central hasta mediados de siglo (2060) y el grado en que estos efectos fueron mediados por una elevada concentración atmosférica de CO_2. Esto se hizo sobre la base de cinco posibles escenarios climáticos futuros proyectados por modelos de circulación general y utilizando un modelo de crecimiento del cultivo de cacao que simuló los efectos fisiológicos del clima y el CO_2 en el crecimiento del cacao, los procesos relacionados con el crecimiento y el rendimiento. Con notables excepciones, las predicciones del modelo mostraron que bajo el clima futuro, se esperaban aumentos en los rendimientos limitados de potencial hídrico simulado y en el área adecuada para el cultivo de cacao, mientras que se predijo que la variabilidad del rendimiento interanual disminuiría, particularmente cuando se asumían efectos completos de CO_2 y en condiciones más húmedas. Se espera que los impactos sigan un gradiente geográfico claro (sur) este-oeste, con predicciones más positivas en el país más oriental, Camerún, donde se encontraron fuertes aumentos en el rendimiento (~ 39-60%), y en el área adecuada para el cacao (~ 11-12 Mha), y el menos positivo para el país más occidental, Costa de Marfil, donde se encontraron fuertes reducciones de rendimiento de hasta el 12% y grandes pérdidas del área adecuada actual (~ 6-11 Mha). Nigeria siguió a Camerún en términos de efectos positivos (excepto por tener el mayor aumento en la idoneidad que se encontró en esta región ~ 17-20 Mha) y Ghana (30-45% de aumento y fuerte reducción en el rendimiento, 12%, ~ 2 Mha de ganancia y ~ 2-2.5 Mha de pérdida en idoneidad) siguió después de Nigeria. La variabilidad del rendimiento interanual prevista fue mayor en las zonas con rendimientos más bajos, por lo que se observó una tendencia geográfica similar con una variabilidad reducida en Camerún y los mayores aumentos en Côte d'Ivoire. Los aumentos previstos en los rendimientos limitados del potencial hídrico simulado se asociaron principalmente con los aumentos proyectados en la precipitación de la estación seca, mientras que la reducción proyectada de la estación seca reduciría la variabilidad del rendimiento.

En el **capítulo 5**, se presenta una discusión general de los principales hallazgos encontrados en los capítulos del 2 al 4 de esta tesis y literatura existente. Se plantean conclusiones sobre la importancia relativa de los efectos del clima, el suelo y el manejo agronómico en los rendimientos y en la brecha de rendimiento del cacao y el posible impacto del cambio climático en la producción futura de cacao. Asimismo se proporcionan recomendaciones para futuras investigaciones basadas en investigación pendiente/preguntas abiertas.

En conclusión, esta tesis muestra que las prácticas mejoradas de manejo agronómico ofrecen oportunidades para aumentar sustancialmente la producción de las plantaciones de cacao actuales, y que estas prácticas deben de estar adecuadamente implementadas antes de introducir estrategias específicas de adaptación al cambio climático. Bajo el clima futuro, los resultados de los modelos indican que, a pesar de los aumentos en la temperatura y los cambios en la distribución de las precipitaciones según lo proyectado por los modelos de circulación general, los aumentos proyectados en la precipitación de la estación seca y la duración más corta de la estación seca permitirían que muchas áreas donde actualmente se cultiva cacao mantengan o aumenten la productividad para mediados de siglo, particularmente si se asumen efectos de [CO_2] totalmente elevados.

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Well, they say we save the best for the last, my wonderful family, my life's blessing, this is for you. It breaks my heart Dad that you are not here, but I know you are in a better place and happy to see what the Lord has made out of your little girl. You live on in my heart. To my cheerleaders, Mum (my practical cocoa 'prɔf'), my siblings' (Louisa, Daniel, Bernice, Genevieve, Jane, Emmanuel, Kate, Kofi), my brother and sister in-laws (Dad. Alex, Bro. Isaac, Sis. Naomi, Nana Akyea), my nephews and nieces, thank you. You guys are a blessing!

List of Publications

Peer-reviewed Journal Articles

Asante P.A., Rahn, E., Anten, N.P.R., Zuidema, P.A., Alejandro S. Morales, Rozendaal, D.M.A. (2023). Climate change impacts on cocoa production in the major producing countries of West and Central Africa by mid-century. (*submitted*)

Asante P.A., Rahn, E., Zuidema, P.A., Rozendaal, D.M.A., van der Baan, M.E.G., Läderach, P., Asare, R., Cryer, N.C., Anten, N.P.R. (2022). The cocoa yield gap in Ghana: a quantification and an analysis of factors that could narrow the gap. Agricultural Systems, 201, 103473. https://doi.org/10.1016/j.agsy.2022.103473

Asante, P. A., Rozendaal, D. M. A., Rahn, E., Zuidema, P. A., Quaye, A. K., Asare, R., … Anten, N. P. R. (2021). Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. Agricultural Systems, 193, 103214. https://doi.org/10.1016/J.AGSY.2021.103214

Conferences, Seminars & Workshops

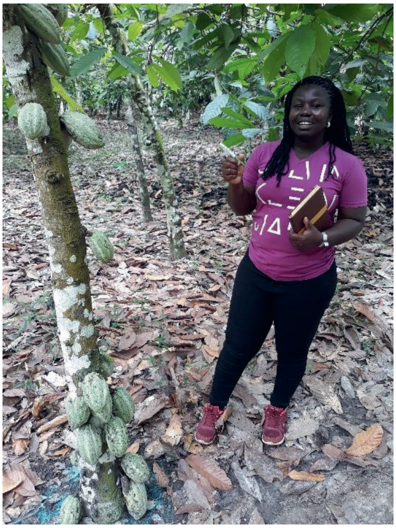
Asante P.A. (Presenter), Rahn, E., Zuidema, P.A., Rozendaal, D.M.A., van der Baan, M.E.G., Läderach, P., Asare, R., Cryer, N.C., Anten, N.P.R. (2022). The cocoa yield gap in Ghana: a quantification and an analysis of factors that could narrow the gap. Poster Presentation at International Symposium on Cocoa Research. Montpellier, France. 5 – 7 December 2022.

Asante, P. A., Rozendaal, D. M. A., Zuidema, P. A., Rahn, E., Anten, N. P. R (Presenter) (2022). Tree crop adaptation and yield in a changing environment Living on a chocolate cloud. Presented at Building bridges in cloudy atmospheres event science | technology | art. Wageningen University & Research, 27 October, 2022.

Asante, P. A (Presenter), Rozendaal, D. M. A., Rahn, E., Zuidema, P. A., Quaye, A. K., Asare, R., … Anten, N. P. R..(2021). Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. Presented at the INCOCOA Webinar "Working Together to Tackle the Cocoa Challenges of Tomorrow". 20th October 2021.

Asante, P. A. Climate change and Cocoa (2021) Presented at the Montpellier Global days for Science, Education and Innovation: Africa 2021. Montpellier, France. 4-7 October 2021.

About the author



Paulina Ansaa Asante was born on 1st May 1989 in Bekwai, Ashanti Region, Ghana. She had her Junior High School training at Victory International School in Bekwai and completed her West African Secondary School certificate program at St. Monica's Girls Senior High School, with Geography, Economics, Government and History as her major subjects. In 2012, she completed her Bachelor of Arts (Honors) degree in Geography and Resource Development Major with Political Science from the University of Ghana, Accra, Ghana. After graduation, she worked as Teaching and Research Assistant and later as Geographic Information Science (GIS) specialist at the Remote Sensing and GIS Laboratory of the University of Ghana for three years.

In 2015, Paulina was awarded the Netherlands Fellowship Programme (NFP) scholarship, managed by NUFFIC which allowed her to complete the Master of Science in Geo-information Science and Earth Observation for Natural Resources Management in 2017 at the Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, The Netherlands. In 2018, Paulina started her PhD at Centre for Crop Systems Analysis and Forest Ecology and Management groups of Wageningen University & Research, The Netherlands. Her PhD research focused on analyzing drivers of cocoa yield under current and future climates. This project was part of CocoaSoils, a multi-institutional research consortium working on integrated soil fertility management options with long-term trails across environmental and management gradients.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review/project proposal (10.5 ECTS)

- Climate change effects on cocoa production and consequences on forest conservation
- Analyzing climate change effects on cocoa production and its potential consequences for forest conservation

Post-graduate courses (8 ECTS)

- Ecophysiology techniques workshop; PEPG, Portugal (2018)
- Uncertainty propagation in spatial environmental modelling; PE&RC and SENSE, Wageningen, the Netherlands (2018)
- Basic statistics; PE&RC and WIMEK, Wageningen, the Netherlands (2020)
- Crop physiology and climate change: understanding fundamental processes to counter the challenge; PE&RC & Agricultural and Biological Engineering Department, University of Florida (2022)
- Cropping system analysis of smallholder agriculture multi-model crop simulation workshop; International Maize and Wheat Improvement Center (CIMMYT), Harare, Zimbabwe (2023)

Deficiency, refresh, brush-up courses (3 ECTS)

- Programming in Python; WUR (2018)
- Climate smart agriculture; WUR (2019)

Competence strengthening/skills courses (2.9 ECTS)

- Searching and organising literature, EndNote introduction; WUR Library course (2018)
- Ethics in plant and environmental sciences; WGS (2022)
- Writing grant proposals; Wageningen in'to Languages (2023)

Scientific integrity/ethics in science activities (0.6 ECTS)

- Research integrity; WGS (2019)

PE&RC Annual meetings, seminars and the PE&RC retreat (2.1 ECTS)

- Workshop models, improving photosynthesis and better crop yields: is this the future? (2018)
- Symposium drought, plant hydraulic traits and vegetation modelling (2018)
- PE&RC First years weekend (2018)
- PE&RC Last Year's weekend (2022)

Discussion groups/local seminars or scientific meetings (7.2 ECTS)

- Journal club FEM discussion group (2018-2022)
- FEM & WEC R-Club discussion group (2020-2022)
- Sustainable cacao & coffee discussion group (2021-2022)
- CIAT Science seminar; online (2021)
- Annual CocoaSoils forum (2019-2022)
- VTB Zero-net-deforestation commitments event; Utrecht (2019)
- Cocoa workshop scaling bio-positive innovations in food systems; WUR (2022)
- CocoaSoils science committee meeting; Montpellier, France (2022)

International symposia, workshops and conferences (5.4 ECTS)

- Science, education and innovation Africa; Montpellier, France (2021)
- INCOCOA Webinar (2021)
- International Cocoa Research Symposium (ISCR) (2022)
- INCOCOA workshop: building research collaborations to deliver impact; Montpellier, France (2022)

Lecturing/supervision of practicals/tutorials (0.3 ECTS)

- Agroforestry modelling assignment (2022)

BSc/MSc thesis supervision (3 ECTS)

- The water limited yield, yield gap and their driving factors of Theobroma cacao in Ghana

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