



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

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ABSTRACT

Climate change is expected to negatively impact cocoa production in West and Central Africa, where over 70 % of cocoa is grown. However, effects of temperature, precipitation and atmospheric carbon dioxide concentration [CO₂] on cocoa tree physiology and productivity are poorly understood. Consequently, climate-change implications have not been adequately considered. The objective was to improve understanding of potential cocoa productivity responses to climate change by mid-century (2060).

Using a crop model, we simulated potential water-limited cocoa yields (Yw) to evaluate effects of warming and precipitation changes based on five plausible general circulation models (GCMs) climate-change scenarios, with and without elevated CO₂. We examined how variation in Yw was associated with that of climate using mixed-effects models and estimated total cocoa production on current plantation area under current low-input and high-input scenarios.

With notable exceptions, by mid-century, Yw and suitable area were projected to increase, particularly when assuming full elevated [CO₂] effects and under wetter climate-change scenarios. We identified a (south) east - west gradient with higher yield increases (~39–60 %) in Cameroon and Nigeria compared to Ghana and Côte d'Ivoire (~30–45 %). Larger yield reductions (~12 %) were identified in Côte d'Ivoire and Ghana than in Nigeria (~10 %) and Cameroon (~2 %). Additionally, gains in suitable area were projected for Nigeria (~17–20 Mha), Cameroon (~11–12 Mha), and Ghana (~2 Mha) while Côte d'Ivoire could lose ~6–11 Mha (i.e., ~27–50 % of current suitable area). Inter-annual yield variability was higher in areas with low yields. Based on the mid climate-change scenario, country-level production on current plantation area in Côte d'Ivoire and Ghana could be maintained. Projected increases and shorter length in dry season precipitation strongly determined increases in Yw and reductions in Yw variability, respectively. Thus, despite projected warming and precipitation changes, many current cocoa-growing areas may maintain or increase their productivity, particularly if full effects of elevated [CO₂] are assumed.

1. Introduction

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 (Trisos et al., 2023). 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 and Gaetani, 2016). Since pre-industrial times (1850–1900), increases in fossil fuel use and land-use changes have increased atmospheric greenhouse gas concentrations which are driving increases in global average temperature and changing precipitation patterns (Pörtner et al., 2023). With continued emissions and land-use changes, increases in global average temperature of ~1.4–4.4 °C above pre-industrial levels depending on socio-economic scenario, and changes in precipitation patterns are expected by the end of the 21st

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century (Pörtner et al., 2023). In West Africa, average temperature increase is expected to reach or surpass 1.5 °C 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 and Wood, 2008; Trisos et al., 2023). 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 and Quist-Wessel, 2015). Thus a tree planted today will experience the effects of climate change at least up to mid-century during its economic life span. More quantitative knowledge of how projected climate change and variability could impact productivity of such crops is therefore urgently needed to inform policies that may counteract the adverse effects on livelihoods and local and regional economies.

Progressive climate change is expected to impact cocoa production in West and Central Africa, where over 70 % of cocoa is produced (Black et al., 2020; Läderach et al., 2013; Schroth et al., 2016, 2017). Impacts are predicted to vary regionally with geographic shifts in climate suitability of production areas and a potential loss of ~50 % of current climatically suitable area by 2050 (Läderach et al., 2013; Schroth et al., 2016, 2017). This could drive producers to new areas which may further accelerate deforestation as cocoa is grown mainly in regions that used to be covered by tropical forests, and cocoa production generally replaces forests (Abu et al., 2021; Masolele et al., 2024). 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) which are not designed to predict cocoa yield responses to climate change (Läderach et al., 2013; Schroth et al., 2016, 2017). To predict cocoa yield responses to climate change, the use of physiological crop models that consider processes underlying growth and yield, including effects of elevated atmospheric carbon dioxide concentration [CO₂] on cocoa productivity are needed. Elevated [CO₂] has a direct effect on the rate of photosynthesis in terrestrial C₃ plants (like cocoa), as the maximum carboxylation rate is achieved under roughly double the current [CO₂] (Long et al., 2004; Walker et al., 2021). Therefore, elevated [CO₂] could potentially increase cocoa yields by increasing photosynthetic rates (Black et al., 2020), while stomatal conductance typically decreases, leading to higher water-use efficiency (Lahive et al., 2018, 2019; Lambers et al., 2008). Photorespiration is also expected to decrease under elevated [CO₂], since CO₂ then competes more effectively with O₂ for Rubisco (Cernusak et al., 2013; Long et al., 2004). Together, these CO₂ 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 [CO₂]. Yet, insights on cocoa yield changes based on their study are limited, as NPP is not equivalent to yield, hence, the yield response to climate change and [CO₂] rise remains poorly understood. Therefore, improving our understanding on how projected climate change and [CO₂] rise would impact cocoa tree physiology and productivity is relevant for assessing possible implications of climate change impacts on future cocoa production.

The objective of this study was to advance our understanding of potential cocoa tree physiology and productivity responses to climatic change projected by GCMs and its implications for production across the major cocoa-producing countries in West and Central Africa up to mid-century (2060). We do so by utilizing a mechanistic cocoa crop model (CASEJ based on CASE2; Zuidema et al., 2005) which simulates the relevant physical and biochemical processes that occur in the plant and their response to changing climatic conditions. The CASEJ crop model simulates growth and production of cocoa with or without water limitation and is adapted to be able to simulate effects of warming and elevated [CO₂] on cocoa yield. Given that cocoa farming in West and Central Africa is largely rain-fed, we only focused on crop model output for potential yield under water-limited conditions. However, it is

important to acknowledge that there exists a significant yield gap in cocoa production within this region. Average cocoa yields within West and Central Africa are typically between 300 and 600 kg/ha which is far below reported yields on research stations (over 3000kg/ha representing a yield gap of 73 %) (Ahenkorah et al., 1974; Appiah et al., 2000) and modelled potential water-limited yields (over 5000kg/ha representing a yield gap of 86 %) (Asante et al., 2022; Zuidema et al., 2005). Recognizing this disparity, it is crucial to consider this yield gap when interpreting anticipated water-limited yields under climate change. Nevertheless, we considered potential changes in water-limited yields because earlier research (Abdulai et al., 2020; Asante et al., 2022) demonstrated that the average yield of the top 10 % best performing farmers reach 2125 kg/ha (i.e., 4x higher than the average yield), indicating the feasibility of significantly narrowing the yield gap. This study presents two assumed yield gap scenarios: i) a low-input scenario (where yield gaps are assumed to remain unchanged in the future) and ii) a high-input scenario (where the yield gap is reduced), to assess how actual productivity might shift under climate change.

We address the following questions: 1) how will projected changes in climate (i.e., temperature, precipitation) and the underlying rise in [CO₂] affect water-limited potential cocoa yield 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? To answer this question, we used the potential yields under water-limited conditions. An additional question was 3) how much cocoa could be produced under future climatic conditions without expansion of the land area under cocoa cultivation? To answer this question, we considered the water-limited potential yield with the following yield gap assumptions: (1) the existing yield gap (low-input scenario), and (2) a reduced yield gap (high-input scenario).

To address the three 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 [CO₂] 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 West and Central Africa.

2. Materials & methods

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

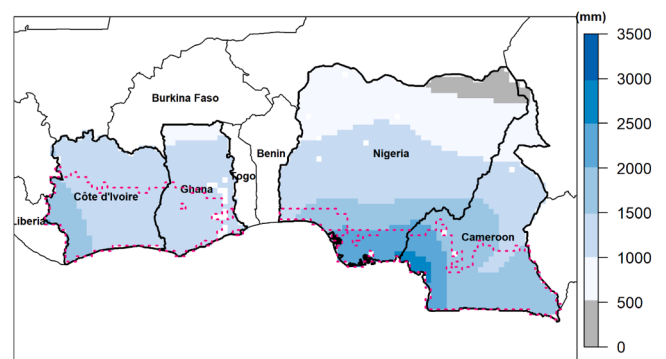


Fig. 1. Mean annual precipitation (in mm) distribution across West Africa; Côte d'Ivoire, Ghana, Nigeria and Cameroon, based on the Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling (Sheffield et al., 2006). Precipitation values are calculated means of 1980–2010 on a 25-km resolution. 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 to 2010.

Cameroon (Fig. 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 ~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 and 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 (Asante et al., 2021; Wessel and Quist-Wessel, 2015). Precipitation within these countries is characterized by decreasing precipitation along a South-North gradient (Fig. 1) with generally high temperatures (mean temperature above 18 °C) throughout the year.

2.2. CASEJ model description

CASEJ is an adaptation of the CASE2 physiological model (Zuidema et al., 2005), with the key modification being that in CASEJ photosynthesis is calculated following the Farquhar–von Caemmerer–Berry (FvCB) biochemical model (Farquhar et al., 1980). This modification addresses a major limitation of the CASE2 model, where photosynthesis is calculated based on light response curves (Tosto et al., 2023), an approach that does not allow for assessing the effects of changing atmospheric [CO₂] levels or its interaction with temperature and water use on photosynthesis. This limitation makes CASE2 poorly suitable for modelling the effects of climate change. By incorporating a simplified version of the FvCB model, CASEJ allows for simulating effects of warming and elevated [CO₂] levels on cocoa growth and yield under changing climate conditions.

With FvCB model in CASEJ, photosynthesis is computed as limited by electron transport and Rubisco kinetics without including any form of acclimation to elevated [CO₂] (i.e., the negative feedback that can arise where e.g., Rubisco is somewhat down regulated) and assuming no mesophyll resistance and a fixed ratio between intercellular and air [CO₂] of 0.7. These last two assumptions allow simplifying the calculations of CO₂ 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 [CO₂] mechanistically included). The effect of temperature on light-saturated photosynthesis was modelled the same way as in CASE2.

To ensure consistency of CASEJ with the original CASE2 model, CASEJ's parameter values were adjusted to approximate the same photosynthetic rates as those generated by CASE2 under ambient CO₂ conditions. Consequently, model outputs from CASEJ, such as annual bean yield and photosynthesis (total gross assimilation), closely align with those of CASE2 under current climatic conditions, showing strong correlations ($R^2 > 90$ %, Fig. S1). Since CASEJ retains all core physiological processes from CASE2, the validation performed for CASE2 under ambient CO₂ levels remains applicable to CASEJ. The primary modification, (i.e., incorporation of the FvCB model to simulate photosynthesis) extends CASEJ's capacity to simulate elevated CO₂ effects and their interactions with temperature and water, without altering the model's foundational structure or parameterization. However, under elevated CO₂ conditions, CASEJ's performance can only be evaluated using data from high CO₂ and Temperature experiments, which are currently unavailable for mature trees under field conditions.

CASEJ is implemented in the Julia programming language (Bezanson et al., 2017) with an interface that allows it to be run from within the R programming language (R Core Team, 2021). It requires input information on atmospheric [CO₂] 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. 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 with the CASEJ model at a grid-level (25 km spatial resolution) within the four cocoa producing countries in West and Central Africa. 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.

2.3. Historical & future weather, atmospheric [CO₂] 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 (Sheffield et al., 2006). Saturated vapor pressure (e^0 , kPa) was derived from minimum temperature and calculated as

$$e^0 = 0.6108 \exp \left[\frac{17.27 T_{min}}{T_{min} + 237.3} \right] \quad (1)$$

where T_{min} is the minimum temperature (°C).

Future weather data from the high-spatial resolution (0.25°), downscaled and bias-corrected climate-change projections data from the National Aeronautics Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset were obtained for the period of 2030 to 2060 (Thrasher et al., 2022). This dataset consists of climate scenarios based on Shared Socio-economic Pathways (SSPs), derived from the General Circulation Model (GCM), runs under the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). For this study, we included GCMs under the SSP 5–8.5 (high greenhouse gas emissions) scenario. While we acknowledge that SSP 5–8.5 is an extreme scenario with a low likelihood for end-of-century projections and may be considered less useful for policy planning (Hausfather and Peters, 2020), this objection primarily applies to projections beyond 2060. Up to 2060, differences in climate change projections between high and mid-emission scenarios remain relatively minor (IPCC, 2023), justifying the inclusion of GCMs under SSP 5–8.5 for this time period.

Global monthly records of atmospheric [CO₂] from 1980 to 2010 were obtained from the Mauna Loa Observatory database (Thoning et al., 1989). For the future period, atmospheric [CO₂] for CMIP6 under SSP585 was obtained from Cheng et al. (2022). To ensure consistency, historical and future [CO₂] records from one location (19.5° N, 155.6° W) were used.

Soil texture data classified based on the USDA system were obtained from the ISRIC database (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 of Asante et al. (2022), to be able to retrieve the standard values of soil water content at saturation, field capacity, and wilting point, which are defined in CASEJ based on the soil texture classes in the Driessen system (Driessen, 1986).

2.4. GCM model selection

A total of 31 GCMs with complete information on required weather input for CASEJ 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. S2) (Ruane and 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. S2). 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. S2, Table S2).

2.5. Estimating climate change effects on mean cocoa yields

To understand how projected changes in climate and elevated [CO₂] levels influence cocoa yields, we first used the CASEJ model to simulate water-limited potential cocoa yield (Yw) based on historical climate and [CO₂] data. We identified suitable cocoa-growing areas as areas where the model predicted successful cocoa growth and yield. That is, areas where environmental conditions allow trees to thrive, maintain a positive carbon balance, and produce a yield above zero (yield threshold > 0).

To determine to what extent atmospheric [CO₂] levels could affect cocoa production in the future, we conducted simulations of Yw based on future climate data under two CO₂ scenarios: i) simulated Yw with effects of elevated [CO₂] (assuming no acclimation to elevated [CO₂]); and ii) simulated Yw without elevated [CO₂] effects (by setting [CO₂] at 363 ppm, corresponding to the average concentration of the historical period 1980–2010). These simulations were performed for each of the five selected representative GCMs (warm/wet, warm/dry, hot/wet, hot/dry and mid). For simulations with effects of elevated [CO₂], we allowed both projected future atmospheric [CO₂] levels and climate variables (temperature, precipitation) to change during the simulations. For the simulation without elevated [CO₂] effects, we kept the [CO₂] level constant at 363 ppm, while climate variables changed according to the GCM projections. We calculated the mean annual historical (1980–2010) and future Yw (2030–2060) (for each of the selected GCMs under the two [CO₂] scenarios) and calculated the relative change (in percentage) between the historical (Yw_H) and the future (Yw_F) values of Yw, that is

$$Yw (\%) = \left(\frac{Yw_F}{Yw_H} - 1 \right) \times 100 \quad (2)$$

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 precipitation; areas with more than three consecutive dry months 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 R² were calculated to evaluate the variation explained by fixed effects only, and the variation explained when including both fixed and random effects, respectively (Nakagawa and Schielzeth, 2010). All analyses were conducted with the R programming language (R Core Team, 2021).

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 within the detrend function in the dplR library in R (Bunn, 2008). 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 [CO₂] 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

$$Ywv (\%) = \left(\frac{Ywv_F}{Ywv_H} - 1 \right) \times 100 \quad (3)$$

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 R² for each model.

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 plantation area in the future, assuming that there will be no expansion. To do this, we calculated current and future cocoa production (i.e., cocoa area × yield) for Côte d'Ivoire and Ghana with and without [CO₂] effects, based on the mid GCM only. The total cocoa plantation area per 0.25° grid cell (Fig. S3) 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, 2022). We estimated total cocoa production based on two yield-gap scenarios: low-input scenario, where the (relative) cocoa yield gap is assumed to stay the same as current (a yield gap of 86 % of Yw) 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 which is a realistic yield target for farmers (Asante et al., 2022).

3. Results

3.1. Projected changes in climate in West and Central Africa

Relative to the historical period (1980–2010, Fig. S4), changes in

precipitation patterns over space and time and increases in temperature are projected for the four major cocoa producing countries in West (Côte d'Ivoire, Ghana, Nigeria) and Central (Cameroon) Africa by mid-century (2060) under the high emission scenario (SSP585) (Fig. S5–S6).

GCMs exhibited varying agreement in their projections for annual and wet season precipitation (Fig. S5, Fig. 2A–B). The wetter GCMs (warm/wet, hot/wet) predicted relatively larger increases in annual precipitation reaching a maximum average increase of ~ 800 mm per year (Fig. 2A). Additionally, they projected up to ~ 250 mm increases in wet season precipitation over most areas, with a few regions experiencing minor reductions (~ 50 mm) (Fig. 2B). In contrast, the mid and dry GCMs (warm/dry, hot/dry) predicted smaller annual precipitation increases, up to ~ 200 mm in some areas, but substantial reductions of up to ~ 400 mm in most parts of the region. They also projected slight increases in wet season precipitation, up to ~ 100 mm, but substantial reductions (~ 250 mm) over most remaining areas.

Regarding the dry season, all five GCMs, projected slight increases in precipitation, up to ~ 200 mm along the coastal areas (Fig. 2C) where cocoa is grown but more strongly towards the East. Conversely, decreases of up to ~ 100 mm were expected towards the northern parts of the region beyond the cocoa belt. The observed trend aligns with the findings of the IPCC interactive atlas, indicating a rise in dry season precipitation towards the East (Nigeria and Cameroon) but a comparatively minor increase in the West (Côte d'Ivoire) based on 28 models (IPCC, 2023). Thus, despite the mid and dry GCMs projecting an overall reduction in annual and wet season precipitation over most cocoa-growing areas, slight increases in precipitation were expected in the dry season across the cocoa belt. Furthermore, all GCMs predicted a reduction in the number of consecutive dry months, leading to a shorter dry season of up to 2 months over most of the region (Fig. 2D). Thus, while uncertainties persisted in annual and wet season precipitation projections, a consensus emerged for changes in dry season precipitation and dry season length. The relative uncertainty in precipitation

projections has been reported by several authors (e.g. Kent et al., 2015).

For temperature, there was more consensus among the five GCMs with future annual and seasonal minimum, maximum and average temperature (Fig. S6) projected to increase in the four cocoa producing countries by 2060 (Fig. S4e–S4 m). Projected increases in annual and seasonal minimum temperature were stronger (annual: 1°C to 5°C , dry season: 1°C to 7°C , wet season: 1°C to 5°C) than the projected increases in annual and seasonal maximum temperature (annual: 1°C to 3°C , dry season: 1°C to 5°C , wet season: 1°C to 3°C) across the four countries (Fig. S7).

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 (Y_{WF} ; 2030–2060) were higher than predicted yields for the historical period (Y_{WH} ; 1980–2010) for both with and without CO_2 scenarios for all five GCMs (Fig. S8).

Predicted changes in Y_w (future – historical) under the scenario with CO_2 effects were consistently more positive than predictions under the scenario without CO_2 effects for all GCMs (Fig. 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 Y_w were projected in Cameroon and Nigeria where larger increases in Y_w of up to $\sim 60\%$ and $\sim 39\%$ were expected with and without CO_2 effects, respectively (Figs. 3–4, S9). Yet, without CO_2 effects, reductions in Y_w (up to $\sim 2\%$ in Cameroon and $\sim 10\%$ 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 Y_w of $\sim 45\%$ and $\sim 30\%$ with and without CO_2 effects, respectively were expected. Under the scenario without CO_2 effects, larger reductions in Y_w of up to $\sim 12\%$ were expected for several areas in Côte d'Ivoire and Ghana particularly

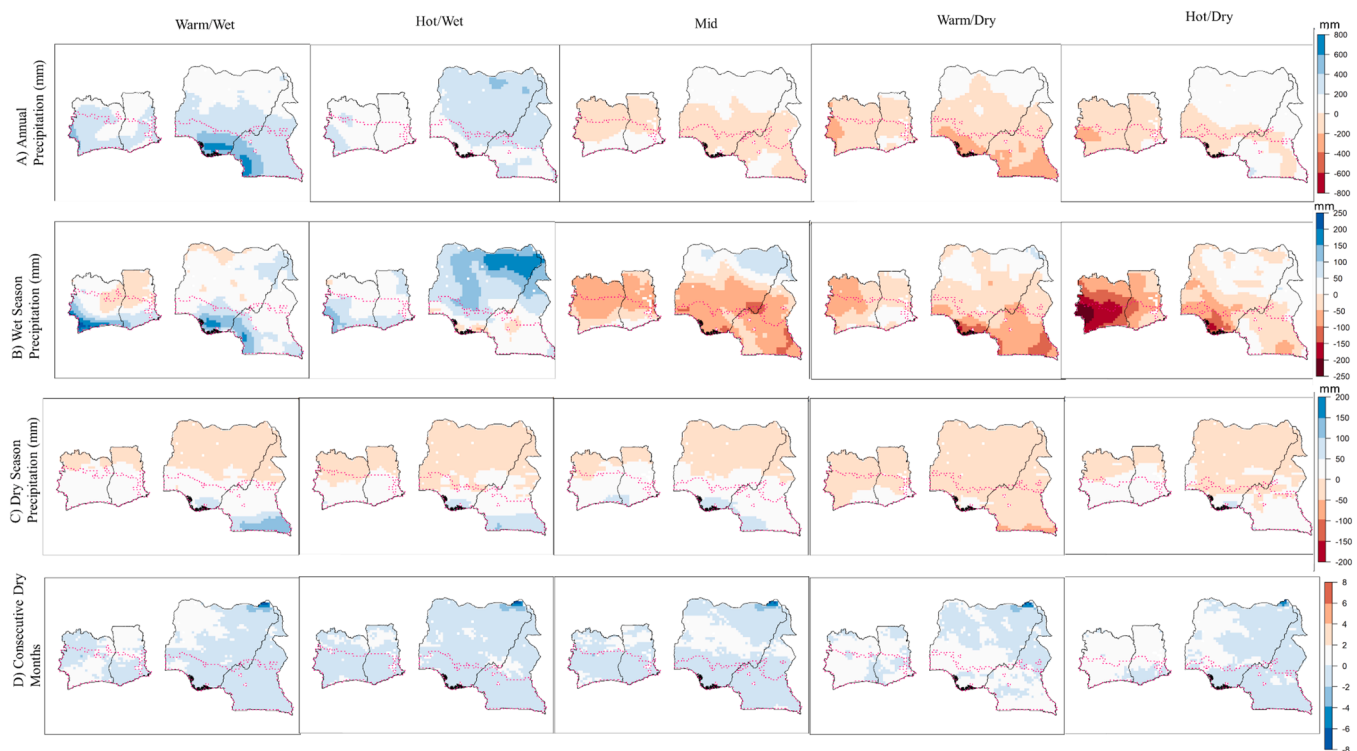


Fig. 2. Projected change between future (2030–2060) and historical (1980–2010) annual and seasonal precipitation across Côte d'Ivoire, Ghana and Cameroon based on five representative GCMs under the high emission scenario (SSP585). Shown are projected changes in annual (first row), wet season (second row), dry season (third row) precipitation (mm) and the number of consecutive months with precipitation <100 mm (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.

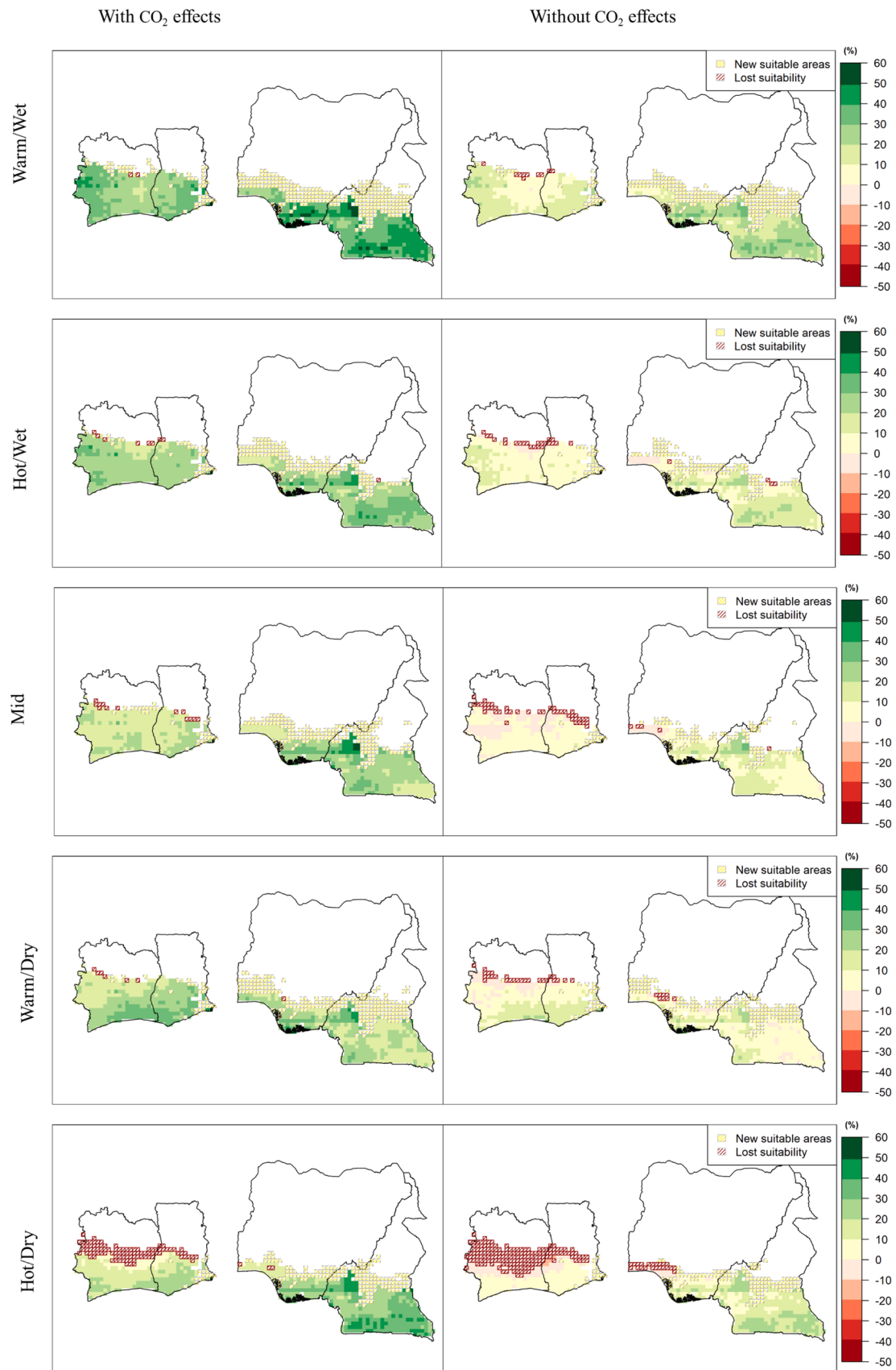


Fig. 3. Maps of predicted changes (future–historical in percentages) in simulated water-limited potential yield between the historical (1980–2010) and future (2030–2060) period, with and without CO₂ effects.

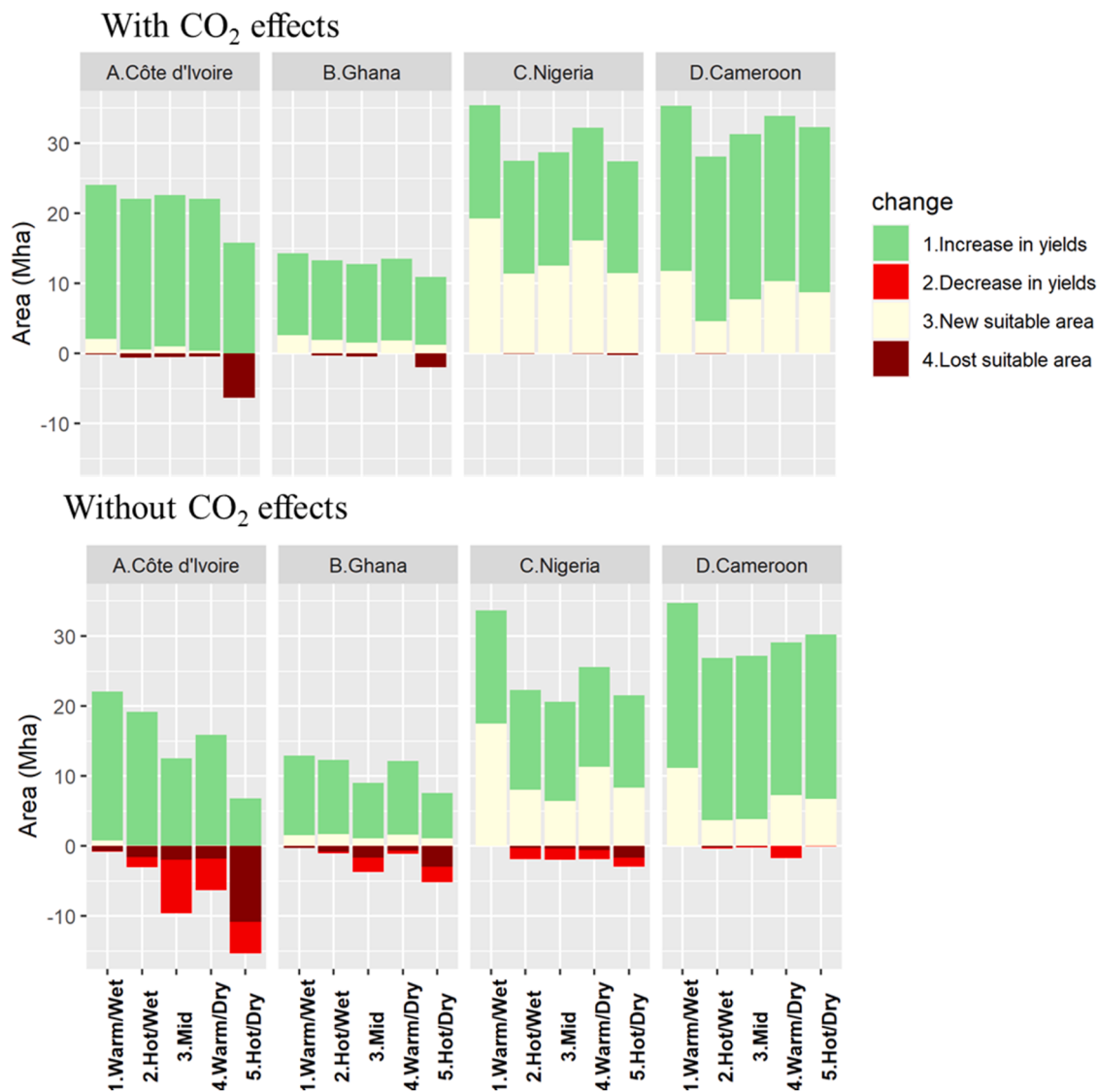


Fig. 4. Predicted changes in total area suitable for cocoa production in each country where simulated water-limited potential yield is expected to change, with and without CO₂ effects.

in the northern parts (Fig. 3). Predicted reductions in Y_w based on the drier GCMs were higher than those based on wetter models. Notably, under the hot/dry GCM (without CO₂ effects) scenario, almost no negative changes were predicted for Cameroon, while Côte d'Ivoire exhibited more areas with predicted negative change than areas with positive change (Fig. 4).

There were also changes in areas suitable for cocoa (i.e., areas based on model simulations where cocoa can grow and produce) (Figs. 3–4). Relatively larger gains and smaller reductions in suitable areas for cocoa were predicted with CO₂ effects than without CO₂ effects for all the four countries. Amongst GCMs, the hot/dry model predicted larger reductions in areas suitable for cocoa under both CO₂ 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 CO₂ effects and up to ~6 Mha were predicted with CO₂ effects (Fig. 4). The largest gains in suitability, i.e., up to ~20 Mha (with CO₂ effects) and ~17 Mha (without CO₂ effects) with only small (~2 Mha without CO₂ effects) to no reduction in suitable area, were expected in Nigeria followed by Cameroon with gains of ~12 Mha and ~11 Mha with and without CO₂ effects, respectively. Smaller gains in suitability (up to ~2 Mha under both CO₂ scenarios) and losses (~2 Mha and ~2.5

Mha with and without CO₂ effects respectively) were expected in Ghana.

Results from the mixed-effects models indicated that effects of climate variables on both Y_{wH} and Y_{wF} (with and without CO₂ effects for all GCMs) were strong. For the historical period, climate variables (fixed effects) explained 56 % of the regional and temporal variation in Y_{wH} , as indicated by the marginal R^2 . By comparison, the explained variation in Y_{wF} for the future period was higher, with average marginal R^2 values of between 74 and 86 % under the scenario with CO₂ and 66–83 % without CO₂ effects (Table 1). For both Y_{wH} and Y_{wF} a large share of the total explained variance (when both fixed and random effects are considered) given by 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 Y_{wH} and Y_{wF} (for both CO₂ scenarios and across GCMs). Temperature effects were both positive and negative. Temperature had positive effects on Y_{wH} and Y_{wF} based on the warm/wet (under both CO₂ scenarios), warm/dry (under the scenario with CO₂) and mid (without CO₂ scenario) GCMs and negative effects on Y_{wF} based on the hot (hot/wet, hot/dry under both CO₂ scenarios), warm/dry (under the scenario without CO₂) and mid (under the scenario with CO₂) GCMs. Thus, except for the mid GCM, temperature effects became more negative or less positive when not accounting for CO₂ 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 climate variables. Yields are based on five GCMs with and without CO₂ 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 CO₂ scenario is indicated in bold.

Predictors	Estimates	Confidence Interval				Marginal R ² / Conditional R ²	
Historical							
Average temperature (dry season)	108		90 – 126		0.56 / 0.89		
Precipitation (dry season)	375		364 – 387				
Precipitation (wet season)	206		179 – 233				
Future							
	<i>With CO₂ effects</i>	<i>Without CO₂ effects</i>	<i>With CO₂ effects</i>	<i>Without CO₂ effects</i>	<i>With CO₂ effects</i>	<i>Without CO₂ effects</i>	
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	0.74 / 0.91	0.74 / 0.91	
Average temperature (dry season)	–26	–39	–46 – –6.1	–58 – –21			
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	0.86 / 0.92	0.83 / 0.94	
Average temperature (dry season)	22	–18	4.5 – 39	–32 – –2.9			
Precipitation (dry season)	720	594	707 – 732	584 – 605			
Hot/Dry							
Annual precipitation	177	191	136 – 217	145 – 236	0.79 / 0.91	0.74 / 0.92	
Precipitation (dry season)	684	573	669 – 699	559– 588			
Maximum temperature (wet season)	–68	–79	–100 – –36	–110 – –48			

3.3. Effects of climate change on inter-annual cocoa yield variability with and without CO₂ 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 (Figs. S8 & S10). Similar to Y_w, predicted changes in inter-annual yield variability were more positive (reduced variability) under the scenario with CO₂ effects than without CO₂. 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 (Figs. S11, 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 CO₂ scenarios (Figs. 5, S12). 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 %) (Figs. S11–S12).

Results from the mixed-effects models indicated that effects of climate variability on both Y_{wvH} and Y_{wvF} (with and without CO₂, 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 Y_{wvH} whilst the explained variation in Y_{wvF} ranged from 35 to 57 % under the scenario with CO₂ and from 22 to 54 % without CO₂ effects (Table S3). For most models, a large share of the total variance was explained by the fixed effects, except for Y_{wvF} based on the mid, warm/dry and hot/dry GCMs where fixed effects explained a smaller part of the total variance. Amongst the fixed effects, variability in the number of consecutive dry months consistently decreased Y_{wvH} and Y_{wvF} under both CO₂ scenarios across GCMs. Variability in precipitation and temperature had both positive and negative effects on yield variability depending on the climate scenario (Table S3).

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

Historical and future cocoa production in tonnes at country level based on the mid GCM only under both [CO₂] scenarios was estimated for Côte d'Ivoire and Ghana. Total cocoa production was calculated based on the current plantation area within each country (Fig. S3) and the estimated average cocoa yield (Fig. S13) based on current relative

yield gap (of 86 %, low-input scenario) and high-input scenario (relative yield gap of 73 %) (see Asante et al., 2022 for these definitions). Current cocoa plantation area (~3.69 Mha in Côte d'Ivoire and 2.15 Mha in Ghana; Fig. S3) and average predicted yields were larger in Côte d'Ivoire than in Ghana under both the low-input and high-input scenarios for both historical and future (both CO₂ scenarios) periods. Thus, total cocoa production in tonnes was higher in Côte d'Ivoire than in Ghana over both periods.

Under low-input scenario, total cocoa production in Côte d'Ivoire increased from the historical value of 2613,382 to 3130,895 tonnes (i.e., ~20 % increase) in the future scenario with CO₂ effects and to 2681,112 tonnes (~2.6 % increase) without CO₂ effects. Whilst in Ghana, production increased from a historical value of 1208,741 to 1566,026 tonnes (~30 %) in the future with CO₂ effects and to 1321,171 tonnes (9 %) without CO₂ effects (Fig. 6). Under the high-input scenario, total cocoa production was about twice that of the low-input scenario, with production increasing to 6038,154 tonnes in the future with CO₂ effects and to 5170,715 tonnes without CO₂ effects in Côte d'Ivoire. For Ghana, total production increased to 3020,194 tonnes with CO₂ effects and to 2547,973 tonnes without CO₂ 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 low-input and high-input scenarios.

4. Discussion

4.1. Elevated atmospheric [CO₂] could potentially offset the negative effects of warming on future cocoa production

Unsurprisingly, 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 CO₂ effects with no acclimation. This suggests that the rise in atmospheric [CO₂] by mid-century (454–650 ppm between 2030 and 2060) could potentially offset the negative effects of warming on cocoa production in West and Central Africa under the assumption of full and unconstrained CO₂ effects. For instance, in our simulation, we found large yield increases (~15 to ~21 %) due to elevated CO₂ across climate scenarios.

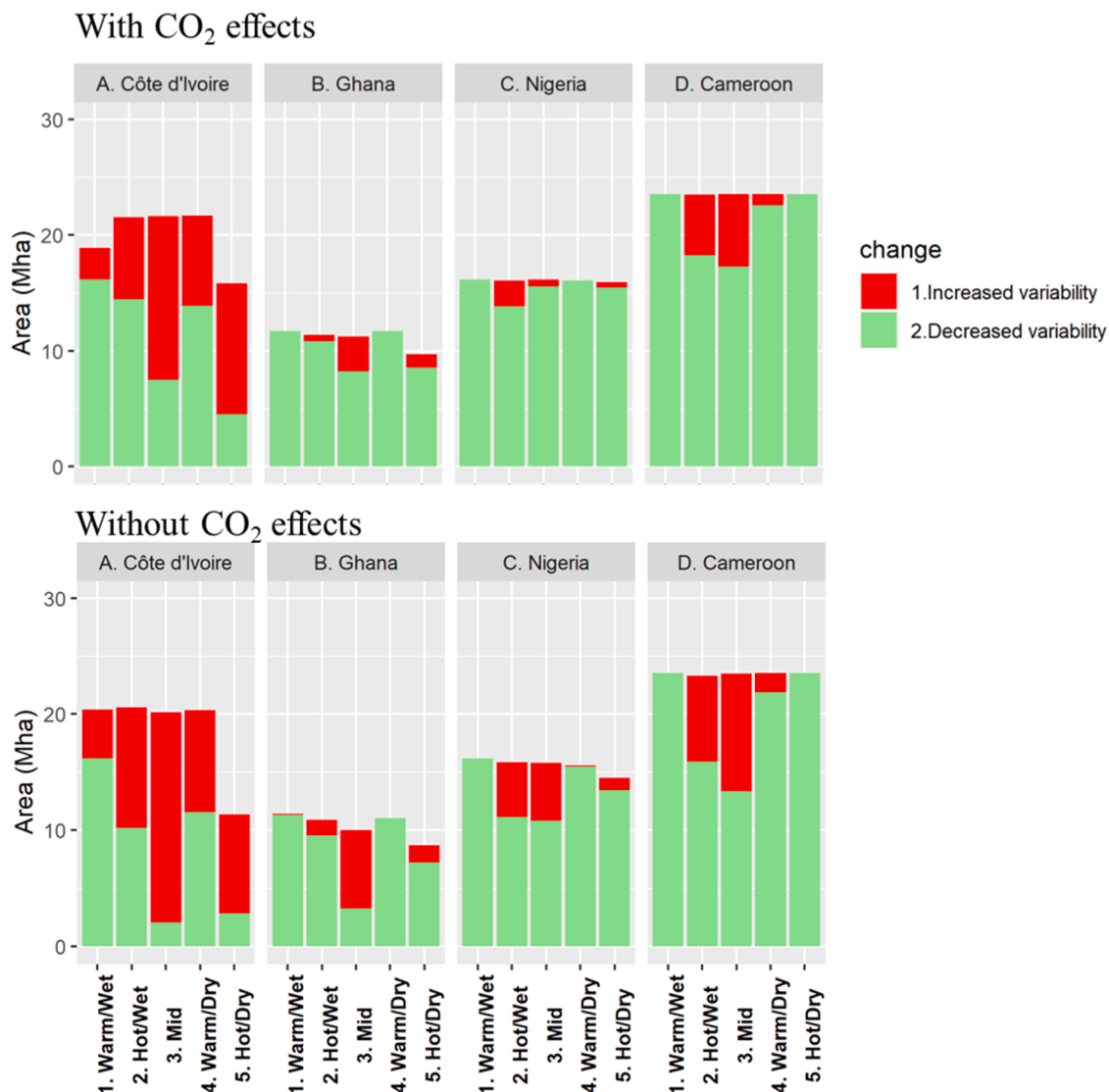


Fig. 5. Expected shifts in cocoa yield variability under climate change. Shown is the area under current cocoa production where variability in yield is expected to increase or decrease, for simulations with and without CO₂ effects.

Positive effects of increases in CO₂ and effects of adaptation (i.e., changes in agronomic management) on average yields of several C3 crops were found to be large enough to offset negative effects of temperature increases even at +4 °C (Makowski et al., 2020). Nevertheless, some studies have reported that the negative interaction between temperature and CO₂ offsets the positive effects of elevated CO₂ on wheat and rice yields (C3 crops) (Cai et al., 2016; Makowski et al., 2020; Tubiello et al., 2000). In free-air CO₂ concentration enrichment (FACE) experiments, C3 crop responses to increased atmospheric [CO₂] were found to be more strongly positive in tree crops (like cocoa), than in annual crops (Ainsworth and Long, 2005). The stronger response in tree crops to elevated CO₂ may be due to, e.g., length of exposure (longer lifespan), sink size and activity (related to the generally indeterminate growth habit of trees), which allows more use of extra photosynthate available in higher CO₂ environments when other resources are not limited (Lee and Jarvis, 1995). In coffee for instance, growth-chamber (without restrictions to root growth) (Rodrigues et al., 2016) and FACE trials (in Brazil, Ghini et al., 2015) showed that elevated [CO₂] 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 and 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 [CO₂] than annual crops like wheat and rice. FACE experiments for productive cocoa trees are currently unavailable. Juvenile cocoa trees grown under elevated [CO₂] (700 ppm) 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 [CO₂] 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 [CO₂] may require increases in soil nitrogen supply as effects of elevated [CO₂] tend to weaken under nutrient limitation (particularly nitrogen; Ainsworth and 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 and Giller, 2017). Integrated soil fertility management in combination with good agricultural practices is therefore an

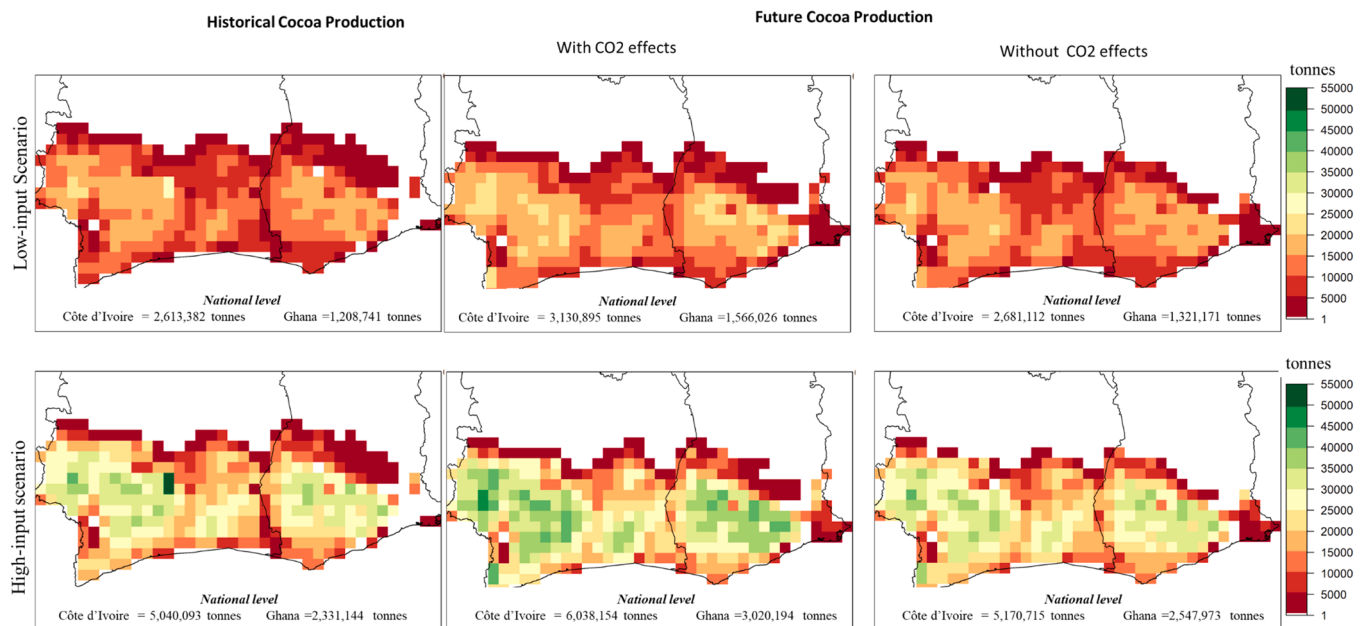


Fig. 6. Predicted historical and future cocoa production (tonnes) with and without CO₂ estimated based on the total cocoa plantation area and simulated annual cocoa yield based on the current relative yield gap (86 %) and attainable yield gap in high-input systems (73 %). Predictions are based on the mid GCM only.

important adaptation strategy (Asante et al., 2021). The positive effects of elevated [CO₂] on cocoa productivity supports our hypothesis.

4.2. 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 were expected under future climate, particularly when CO₂ effects are accounted for and under wetter climate-change scenarios. Across the four cocoa-producing countries, we identified a clear (south) east – west gradient with predictions being most positive for Cameroon in the east, followed by Nigeria (although largest increases in land area suitable for cocoa were identified here) and Ghana and least positive for Côte d'Ivoire in the west. Inter-annual yield variability was found 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. S11). 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 (suitable growing areas) 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. This shift in production could have significant consequences for countries like Cameroon, as potential increases in cocoa production in this region outside the current growing area could have serious consequences for forest areas. Cameroon is one of the African countries where most rain forest and associated biodiversity is still present (Sassen et al., 2022). Balancing the need to adapt cocoa production to climate change while preventing deforestation induced by cocoa expansion will be a significant challenge now and in the future. Market mechanisms such as the Regulation on deforestation-free products (europa.eu) which aims to prevent imports or trade of cocoa produced in recently deforested areas, could play a crucial role in reducing the expansion of cocoa at the expense of forests. Thus, a potential shift of

cocoa production to Cameroon, that one could deduce from our study as being a possible prospect, would come with serious complications.

The predicted geographic trend in climate suitability was comparable to previous predictions of climate change impacts based on SDMs (Läderach et al., 2013; Schroth et al., 2016, 2017) but our projections of the overall net effect of climate change on cocoa suitability are more positive except for under the hot/dry scenario. This difference can be explained by different climate data (both historical and future climate) and the use of different impact models. Regarding the impact model, unlike SDMs, we included effects of physiological acclimation of cocoa to changes in climate and CO₂ effects and quantified suitability changes in terms of yields. While our modelling approach intends to integrate current knowledge of cocoa growth and yield formation, including the elevated CO₂ effect, we do not consider that in some areas farmers may not grow cocoa because other crops are economically more advantageous. Yet, to our knowledge, our study is the first to quantify effects of climate change and elevated [CO₂] effects on cocoa yield using a process-based approach.

The outlook of climate change effects on cocoa production 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. 3). Analyses with a mixed-effects model showed that, together, climate factors explained 66–86 % of the variation in predicted yields (Table 1) and 22–57 % of the variation in inter-annual yield variability (Table S3) across sites and years. It also showed that increases in dry season precipitation had the strongest positive effect on yield whilst the reduction in the consecutive number of dry months (lower variability) decreased inter-annual yield variability. Increases in dry season precipitation were predicted by all GCMs for coastal zones where cocoa is grown, therefore allowing production to increase. However, it is important to note that more wet and humid conditions associated with increasing precipitation particularly in the dry season could increase incidence of diseases such as black pod which has considerable negative effects on cocoa yields (Cilas and 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.

For temperature, effects on yields were both positive and negative, which suggests that projected temperatures up to mid-century are close

to the optimal temperature for cocoa production. However, whether these temperatures 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., 2023). 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 CO₂ effect. However, a recent study examining the combined effects of elevated CO₂ and increased temperatures reported an improvement in growth in heat-tolerant cocoa genotypes, while mitigating some adverse temperature impacts on more sensitive genotypes (Mateus-Rodríguez et al., 2023). This highlights a need to explore potential improvements in cocoa germplasm through breeding to expand temperature tolerance, potentially enhancing cocoa production viability in warmer future climates. It also further underscores the need to update temperature relations in crop models to better include extreme warming and CO₂ interactions (Tao et al., 2020; Wang et al., 2017).

Overall, water availability during the dry season and the length of the dry season will play a key role in determining future yields and yield variability (Carr and Lockwood, 2011), as well as the extent to which the CO₂ effect will offset the negative impacts of warming. Nevertheless, further research endeavors are crucial to gain a deeper understanding of cocoa's response to water availability particularly under dry conditions, CO₂ effects and simultaneous interactions with temperature (Tosto et al., 2023).

4.3. 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 2613, 382 tonnes in Côte d'Ivoire which is slightly higher than the reported average of 2248,000 tonnes for the 2020/2021 season whilst our predicted average of 1208,741 tonnes in Ghana was also slightly higher than the 1047,000 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 CO₂ effects in Côte d'Ivoire and ~30 % and ~9 % in Ghana, respectively, following current management practices, i.e., the low-input scenario. Nonetheless, the yield gap under low-input scenario with-CO₂ effects may likely be higher in the future due to nutrient limitations on most cocoa farms (van Vliet and Giller, 2017). This suggests that under these modelling assumptions, current country-level production could be maintained with current plantation area in Côte d'Ivoire and Ghana by mid-century, assuming no change in management and constant yield gaps under the mid-climate scenario.

Nonetheless, as cocoa demand increases (currently growing at approximately 3 % per year (Beg et al., 2017)) beyond current levels, our results show the possibility of doubling country-level production on current plantations if yield gaps were reduced from 86 % (low-input scenario) to 73 % (high-input scenario) through improved management or recommended management practices (Asante et al., 2022). Investments in good management practices such as increasing cocoa planting density (Abdulai et al., 2020; Asante et al., 2022) in combination with pruning (Tosto et al., 2022), black pod control (Akrofi et al., 2015; Asitoakor et al., 2022) and adequate nutrient management (Hoffmann et al., 2020) offer opportunities to increase yields on current cocoa plantations. This may help reduce pressure on forests and thus reduce cocoa-related deforestation in major cocoa producing countries (Abu et al., 2021; Ruf et al., 2015; van Vliet and Giller, 2017).

4.4. Limitations

This study has a number of limitations which need to be taken into account when interpreting 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 and 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 changes 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 ensemble averages. But, given the pivotal role that changes in dry season precipitation, may have in determining future yields much more research on these changes is imperative.

Secondly, the validation of the cocoa simulation model should be considered. CASE2 (based on which CASEJ was developed) 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 CO₂ rise studies, as there are currently no FACE experiments and warming experiments for cocoa. Such experiments for productive cocoa trees are needed to validate modelling results in order to find out how far off CO₂ effects in our simulations are from reality. Furthermore, in our calculations we only included short-term effects of elevated [CO₂], but no long-term acclimation to [CO₂]. Crop responses to elevated [CO₂] in the field may be smaller than model predictions possibly because mitigating effects caused by, for example, nutrient limitations are not adequately accounted for in models (Ainsworth and Long, 2005, and see Section 4.3). Thus, our simulations with the full-CO₂ effects scenario may likely have overestimated CO₂ effects on cocoa productivity, and this is the reason we also included the no CO₂ effects scenario. FACE experiments would help to quantify overestimation of CO₂ effects in our simulations.

Nonetheless, as we still lack a complete understanding of cocoa responses to climate change which is also reflected in the CASEJ model. For example, as in CASE2, processes related to cocoa reproductive phenology, such as flowering (the model assumes a fixed conversion rate from flowers to fruits) and pod abortion (cherelle wilt) are not explicitly modelled (Tosto et al., 2023). These processes which can be influenced by changing climatic conditions are crucial for accurately predicting future cocoa production. Continued research efforts are therefore required to close these knowledge gaps to enhance accurate predictions of future cocoa production under climate change.

5. Conclusion

By mid-century, with notable exceptions, increases in potential water-limited cocoa yields and gains in the area suitable for production are expected, particularly under wetter climate-change scenarios and assuming full effects of elevated CO₂. 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 (although largest increases in land area suitable for cocoa were identified here), Ghana and the least positive for Côte d'Ivoire. In areas with increasing yields, inter-annual yield variability was identified 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 (the mid GCM) showed that current country-level production could be maintained within current cocoa growing areas of Côte d'Ivoire and Ghana by mid-century. Projected increases in dry season precipitation by GCMs were the most important factor explaining predicted increases in potential water-limited yields whilst projected shortening of the dry season reduced yield variability. Temperature effects were both positive and negative suggesting that temperature ranges are mostly close to optimal depending on the level of warming and water stress. These results indicate that, despite projected increases in temperature and changes in precipitation distribution by GCMs, projected increases in dry-season precipitation and shorter dry-season length could 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. Nonetheless, accurate projection of future cocoa production under climate change still requires better understanding of physiological responses of cocoa, particularly to elevated $[CO_2]$. Key gaps remain due to the lack of long-term field studies on mature trees, which are needed to quantify impacts on yield and to validate model predictions under future climate. Addressing these knowledge gaps through further research will enhance the accuracy of future cocoa production predictions.

CRedit authorship contribution statement

Paulina A. Asante: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Eric Rahn:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Niels P.R. Anten:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Pieter A. Zuidema:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Alejandro Morales:** Methodology, Software, Writing – review & editing. **Danaë M.A. Rozendaal:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.agrformet.2025.110393](https://doi.org/10.1016/j.agrformet.2025.110393).

Data availability

Data will be made available on request.

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