Chapter

Climate Variability and Outlook of Cocoa Production in Côte D'ivoire under Future Climate

Antoine Alban Kacou M'bo, Mamadou Cherif, Kouakou Kouadio, Mahyao Germain Adolphe, Adama Bamba, Evelyne N'Datchoh Toure, Alla Kouadio Okou, Renée Brunelle, Yanick Rouseau and Daouda Koné

Abstract

Cocoa supports about 3.5 million people. Farmers produce each year 1.5 million ton. This performance hides production constraints, the most is climate variability. The climatic variables, temperature, precipitation, and 16 climatic indices were identified to assess the potential impacts on cacao in the past year, currently and under future climate. The climate data in the southern and central cocoa production zone were analysed for periods of 2021–2050 and 2041–2070. The climate reference period is 1981–2010. The climate projections are from the CORDEX RCP 4.5 and 8.5. The results suggest an increase in daily temperature of 1.0–2.1°C in the central region and 0.9–2.0°C in the southern region by 2041–2070. Cocoa could be affected by the projected changes, especially in the central region where the maximum daily temperature at which production is reduced (33°C) would be exceeded between 92 and 142 days per year by this time horizon. The direction of changes in precipitation cannot be established due to a lack of consensus between the climate models analysed. However, the little rainy season would start slightly earlier, potentially reducing the duration of the little dry season between the rainy seasons. The climate scenarios enhanced deterioration of growing environment conditions. It is necessary to take adaptation measures to mitigate climate impacts.

Keywords: climate, cacao, production, sustainability, Côte d'Ivoire

1. Introduction

Cocoa is one of Côte d'Ivoire's main sources of foreign currency and the driving force behind its economic growth. It alone accounts for 15% of GDP. With an annual production of more than one million five hundred thousand tons since 2015 [1], this performance is due not only to the valuable results of agronomic research but also to the favourable ecological conditions in the southern half of the country. However, this spectacular overall result, which has made Côte d'Ivoire the world's leading producer, is based on a rapid and poorly controlled increase in the area under cultivation, leading to extensive deforestation. Furthermore, the ageing of cocoa trees and the lack of appropriate maintenance have led to a drop in the productivity of orchards, resulting in the impoverishment of communities [2].

Cocoa production is subject to significant inter-annual variability, accentuated by the action of soil and climate hazards, strong parasitic pressure from insects, and diseases such as *Swollen shoot* [3, 4] and the brown rot disease caused by *Phytophtora sp*., [5]. The greatest production constraint since 2010 has been climatic variability [6–8]. This can be seen in the significant reduction in the total leaf area of cocoa trees, and in the fall of flowers and young fruit [9–11], leading to a drastic drop in yield and the failure to rehabilitate and replant cocoa orchards. The effects of climate variability can also be seen in the interruption of young fruit growth, the reduction in bean and pod size, and the deterioration in bean quality [12–14].

Cocoa production areas experience significant inter-annual variability [15]. Climate is one of the main factors explaining this variability. It is important to note that rainfall is the most significant factor in cocoa growing, as a prolonged lack of water during the flowering phase can lead to a drop in production. Other climatic (temperature, humidity, solar radiation), ecological, biological, and physical factors can also have a significant influence on the phenology of the cocoa tree and its yields. The cocoa tree, an ombrophilous plant, requires specific climatic conditions for its development [16], annual rainfall of between 1300 and 2000 mm with a limited number of dry days (less than 3 months), an average daily temperature of between 24°C and 28°C, relative humidity of between 80% and 90%, daily sunshine of more than four hours, and deep, well-aerated soil rich in clay and humus. To develop and improve cocoa-growing conditions in Côte d'Ivoire, agrometeorological studies would contribute to a better understanding of the climatic factors likely to influence the plant's environment. This could not only help to improve farming practices, but also assess certain risks to the cocoa tree due to irregular rainfall, extreme temperatures and humidity, and low insolation. The effects of climate shock are expected to vary from one region to another, implying a need for adaptation or mitigation by context [8, 17]. Communities dependent on cocoa production are increasingly vulnerable to the impacts of climate change. These impacts stem from an increase in temperature and a change in rainfall patterns.

To better assess the impact of the climate, climate scenarios are an important step in assessing the vulnerabilities and impacts of climate change, and in identifying adaptation strategies capable of sustaining cocoa production over the coming decades. A climate scenario is a plausible description of the future state of the climate [18]. According to the Ouranos report [19], climate scenarios are produced by combining in-situ observations used as a reference dataset and climate projections for a given climate variable. This combination results in a climate scenario or a sequence of values associated with this variable for a period extending over several decades and for a given frequency. Climate models refer to greenhouse gas (GHG) emission scenarios as Representative Concentration Pathways (RCPs) to represent future radiative forcing. There are several groups of RCP models, but the most widely used are RCP 4.5 and RCP 8.5, which correspond respectively to a decrease in GHG emissions (optimistic scenario) and a constant increase in emissions throughout the century (pessimistic scenario). These models are part of the CORDEX (COordinated Regional Climate Downscaling EXperiment) – Africa domain [20–22]. In the present analysis, the RCP 4.5 and RCP 8.5 models were used to develop climate scenarios for the cocoa-growing area in Côte d'Ivoire. The projections are likely values that lie within a confidence interval. 16 climatic indices were defined according to the requirements of the cocoa tree, and calculations were then made taking into account the uncertainty associated with the inter-model differences between the RCP 4.5 and RCP 8.5 greenhouse gas (GHG) emission scenarios. These calculations were used to develop climate scenarios for the cocoa-growing zone in Côte d'Ivoire, to interpret the impact of fluctuations in climatic variables on the cocoa tree in future decades, and to identify endogenous adaptation practices to cope with the future climate.

2. Zones and time horizons

The cocoa production zone in Côte d'Ivoire is divided into two climatic regions. The central region (between 5.5° and 8° north latitude) and the southern region (below 5.5° north latitude) (**Figure 1**). In each of the two climate regions, the projected climate parameters are temperature and rainfall over two (2) time horizons (2021 to 2050 and 2041 to 2070) compared with the reference period 1981–2010. The study began in 2019, and as the data for the 2011–2020 decade is not complete, the 1991–2020 normal has not been used as a reference. The length of the time horizons of thirty (30) years follows the normal standard in climatology [23, 24]. This duration is generally long enough to obtain representative climate statistics, except for extreme and scarcer events [19]. A total of 16 climate indices were identified and calculated to assess the impact of climate change on cocoa production. The parameters and thresholds associated with these indices are based on information presented in scientific articles and on WASCAL-CEA-CCBAD experts' knowledge of cocoa physiology and climate. These indices depend on two climatic variables, either temperature, rainfall, or both. The interpretation of the results is grouped by climatic variable.

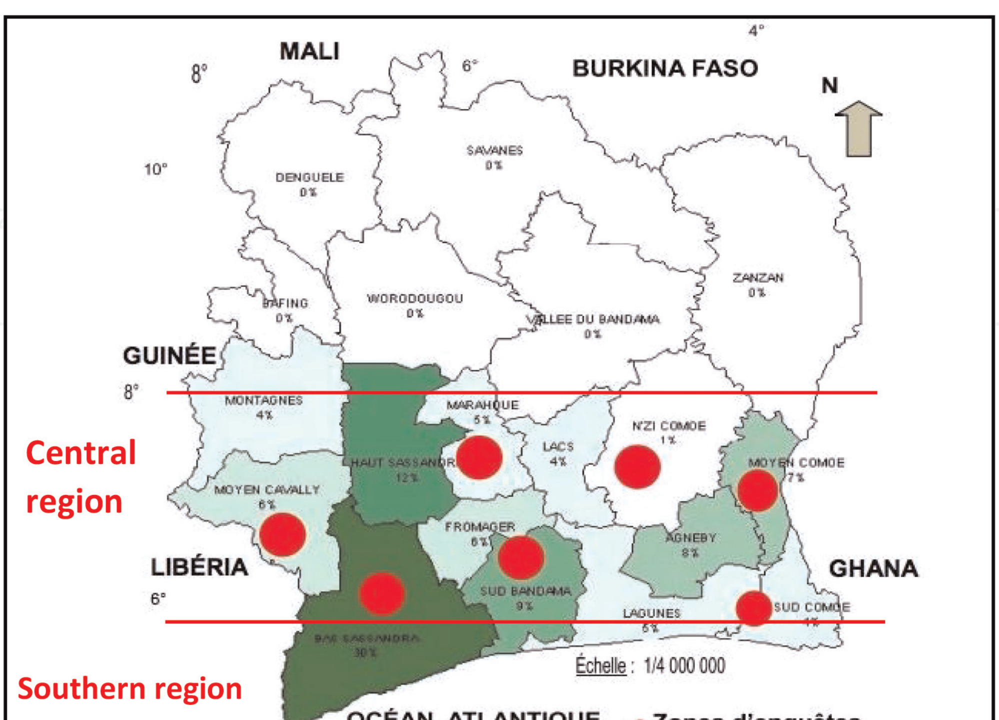

Figure 1.
Ivorian cocoa production area is divided into climatic regions.

2.1 Temperature

The ideal conditions to grow cocoa are when the annual average daily maximum temperature is between 30°C and 32°C and the annual average daily minimum temperature is between 18°C and 21°C [12]. These conditions are associated with maximum photosynthesis. A monthly average daily minimum of at least 15°C is necessary for plant health. A reduction in the growth and development of cocoa trees can occur if the number of days with a maximum temperature of over 33°C is too great [25, 26]. Taking into account this information on temperature-related aspects from the literature review, the following climatic variables were selected: average daily temperature (tas, °C), minimum daily temperature (tasmin, °C), and maximum daily temperature (tasmax, °C). These were used to calculate the following climatic indices:

- Average daily minimum temperature (TNg, °C),

- Mean maximum daily temperature (TXg, °C),

- Number of months per year with a low daily minimum temperature (TNgMonthsBelow) This is the number of months per year when the average value of the daily minimum temperatures (tasmin) is below a lower limit value for the cocoa tree. The threshold selected is 15°C.

- Number of days per year with a high daily maximum temperature (TXDaysAbove) This is the number of days per year when the daily maximum temperature (tasmax) is greater than or equal to 33°C.

2.2 Rainfall

Rainfall between 1500 and 2000 mm per year is generally considered to be the most favourable for cocoa farming. Too much rain can increase the occurrence of diseases and attract pests, thus increasing the mortality rate of cocoa trees. Less than 1200 mm/year can lead to reduced root growth, leaf drop, and reduced plant growth. Cocoa trees must receive at least 700 mm of rain during the rainy season. What's more, for cocoa to ripen properly, the rainy season must last 4 consecutive months, from the flowering phase to the end of the main harvesting season (March to November). In addition, dry periods of more than 14 days can lead to a drop in production, and a dry season of more than 3 months is not tolerated by cocoa trees. Taking into account the information on rainfall from the literature review, the Daily rainfall (pr, mm) climate variable was adopted. This variable was used to calculate the following climate indices:

- Number of rainy days per year (Rnnmm) This is the number of days per year on which the sum of daily rainfall is greater than or equal to 5 mm.

- Cumulative annual rainfall (PrcpTot; mm)

- Duration of dry spells, March-November (DryDurTot_1; days) This is the total duration of dry spells between 1 March (day 60) and 30 November (day 334). A dry spell is defined as a sequence of at least 14 days in which the cumulative daily rainfall is less than 1 mm.

- Duration of dry spells, November-March (DryDurTot_2; days): This is the total duration of dry spells, between 1st November (day 305) and 31st March (day 90). A dry period is defined as a period during which rainfall is less than 70 mm per period of 30 consecutive days. The pr variable was also used to calculate the climatic indices associated with the main (first) rainy season:

- Start of the main rainy season (RainStart_1; day of year) This is the day (value from 1 to 365) on which the main rainy season begins. This day normally occurs after 11 March. The algorithm identifies the first day after this date (day 71 of the year or more) on which a total of 20 mm of rain is received in two days without there being a dry period lasting 7 days in the 30 days following the first two rainy days. A dry day corresponds to a daily rainfall total of less than 1 mm.

- End of the main rainy season (RainEnd_1; day of the year) This is the day (value from 1 to 365) on which the main rainy season ends. This day normally occurs after 11 July. The algorithm identifies the first day after this date (day 193 of the year or more) on which daily rainfall is less than 10 mm/day for 10 consecutive days. The season cannot end before it has begun, so this index depends on RainStart_1. If no days are detected for a year, then that year is excluded from the calculation for the climate scenario being analysed. Also, the RainEnd_1 index depends on the RainStart_2 index, which means that the indices associated with the short rainy season are calculated before those for the long rainy season.

- Duration of the main rainy season (RainDur_1; days) This is the duration of the main rainy season, i.e., the number of days between the start and end of the rainy season, plus one day.

- Cumulative rainfall during the main rainy season (RainQty_1; mm) The pr variable was also used to calculate climate indices for the short (second) rainy season:

- Start of little rainy season (RainStart_2; day of year) This is the day (value from 1 to 365) on which the short rainy season begins. This day normally occurs after 11 August. The algorithm identifies the first day after this date (day 223 of the year or more) on which a total of 20 mm of rain is received in two days without there being a dry period lasting 7 days in the 30 days following the first two rainy days. A dry day corresponds to a daily rainfall total of less than 1 mm.

- End of short rainy season (RainEnd_2; days of the year) This is the day (value from 1 to 365) on which the short rainy season ends. This day normally occurs after 1st November. The algorithm tries to identify the first day after this date (day 306 of the year or more) on which daily rainfall is less than 10 mm/day for 10 consecutive days. The season cannot end before it has begun, so this index depends on RainStart_2. If no days are detected for a year, then that year is excluded from the calculation for the climate scenario being analysed.

- Duration of short rainy season (RainDur_2; days) This is the duration of the short rainy season, i.e., the number of days between the start and end of the rainy season, plus one day.

- Cumulative rainfall during the short rainy season (RainQty_2; mm).

3. Climate variability in the cocoa-growing zone

3.1 Current climate in the centre region

3.1.1 Temperature

Temperatures are high in February to March (**Figure 2**). During these months, the average temperature is 27.1°C, while the average maximum daily temperature is 32.6° C. The greatest inter-annual variation occurs between December and March. Temperatures are lowest in July and August. During these months, the average temperature is 24.1°C, while the average maximum daily temperature is 27.8°C. Temperatures rise slightly in October-November. The lowest temperatures are recorded in February–March (23.3°C) and October-November (22.1°C). In January, July, August, and December, the average daily minimum temperature is 21.7°C.

3.1.2 Precipitation

The sources of information available to assess the projected changes in these indices were: (1) rainfall climate scenarios, which were produced from reanalyses (the ERA5-Land ensemble) and climate projections (the CORDEX ensemble) using the

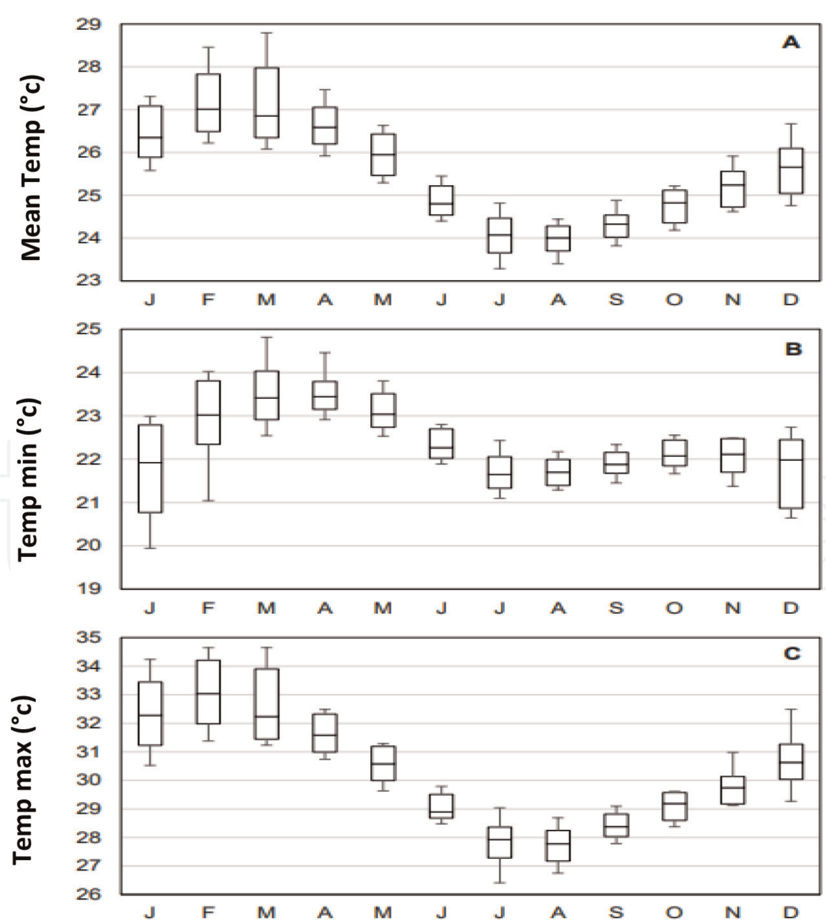

Figure 2.
Monthly climate normals for temperature, Central region. ERA5-Land reanalysis data for the period 1981–2010 were used. The diagrams are shown for: (A) mean temperature, (B) mean daily minimum temperature The vertical limits of the boxes correspond to the 10th, 50th, and 90th percentiles, while the ends of the error bars indicate the monthly minimum and maximum values.

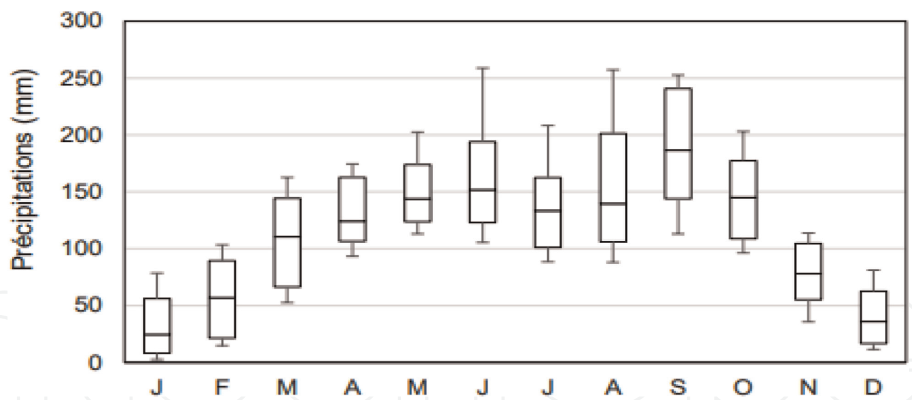

Figure 3.
Monthly climate normals for precipitation, Central region. ERA5-Land reanalysis data for the period 1981–2010 were used. The vertical limits of the boxes correspond to the 10th, 50th, and 90th percentiles, while the ends of the error bars indicate the minimum and maximum monthly values.

bias adjustment method, (2) rainy season detection parameters, and (3) the usual length of the break between rainy seasons in Côte d'Ivoire. An analysis of rainfall climate scenarios was completed to estimate monthly accumulations for the reference period and to visualize the characteristics of the two seasons, in terms of start, end, duration, and accumulation.

The data indicate more abundant rainfall between March and October inclusive, as well as the presence of two rainy seasons in the central region. Monthly rainfall is highest in September, followed by June, according to the median values (**Figure 3**). Interannual variability is greatest between June and September. The parameters initially chosen to detect the end of the rainy seasons during the reference period result in a long rainy season that ends 8 days before the start of the short season, on average (**Table 1**); this implies a quasi-unimodal distribution of rainfall. The period during which there is a decrease in rainfall between seasons seems too short considering the usual length of this period in Côte d'Ivoire (4–6 weeks) (**Figure 4**). Also, the timing of the break does not correspond to the decrease in rainfall between days ~200 and ~230 for the reference period.

Season	**Indice**	**Initial parameters (<5 mm/d × 20d)**		**Revised parameters (<10 mm/d × 10d)**	
Major rainy season	Start	07 April	Day 97	7 April	Day 97
	End	19 April	Day 231	31 July	Day 212
	Duration	135 Days		116 Days	
	Precipitations	606 mm (46% of total annual)		524 mm (39% of total annual)	
Short rainy season	Start	27 August	Day 239	27 August	Day 97
	End	04 December	Day 338	17 November	Day 212
	Duration	100 Days		83 Days	
	Precipitations	430 mm (32% of total annual)		392 mm (30% of total annual)	
Total	Duration	235 Days		200 Days	
	Precipitations	1036 mm (78% of total annual)		916 mm (69% of total annual)	

Table 1.
Characteristics of rainy seasons detected in the central region.

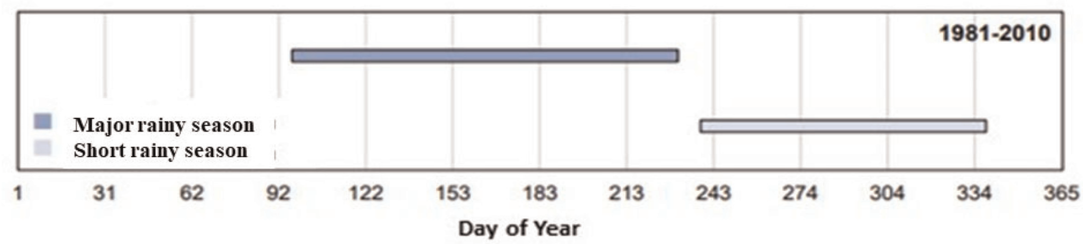

Figure 4.
Rainy seasons, based on initial definition of ONSET and cessation of rainy season for the central region.

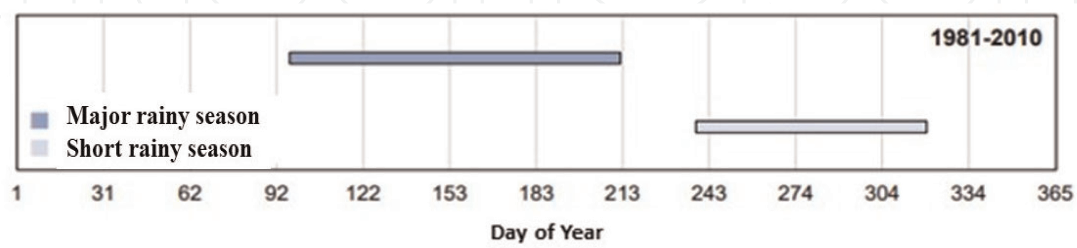

Figure 5.
Rainy seasons, based on revised definition of ONSET and cessation of rainy season for the central region.

These preoccupations prompted a sensitivity analysis of the parameters of the end-of-rainy-season indices. The formulation of these indices is that the season ends after the cumulative daily rainfall has been below a threshold P (mm/day) for a number of consecutive days t. A total of 25 combinations of thresholds P and t were tested with the reanalysis data for the reference period. For each of the combinations of these thresholds, the end dates of the rainy seasons were noted (averaged over the region). One of the combinations tested resulted in a dry period lasting 24 days (**Table 1**), which seems more compatible with reality (**Figure 5**). Using these rainy season detection parameters, the main rainy season extends from 7 April to 31 July, on average (**Table 1**). This corresponds to duration of 116 days. The short rainy season extends from 27 August to 17 November, lasting 83 days. Note that we now detect a dry season between the two rainy seasons with the revised parameters.

3.2 Current climate in the southern region

3.2.1 Temperature

The 30-year (1981–2010) monthly averages of mean, minimum, and maximum daily temperatures show important intra-annual variability. The high values of temperatures are recorded between February and April with average values about 23.6°C, 26.1°C and 30.2°C. The lower temperatures are observed in July and August during the little dry season. During these months, the average values are around 22.1°C for the minimum temperature, 23.9°C for the mean temperature and 26.7°C for the maximum temperature (**Figure 6**).

3.2.2 Precipitation

The projected changes in precipitation were assessed using (i) rainfall climate scenarios, which were produced from reanalyses (the ERA5-Land ensemble) and bias corrected climate projections (the CORDEX ensemble), (ii) existing definition of

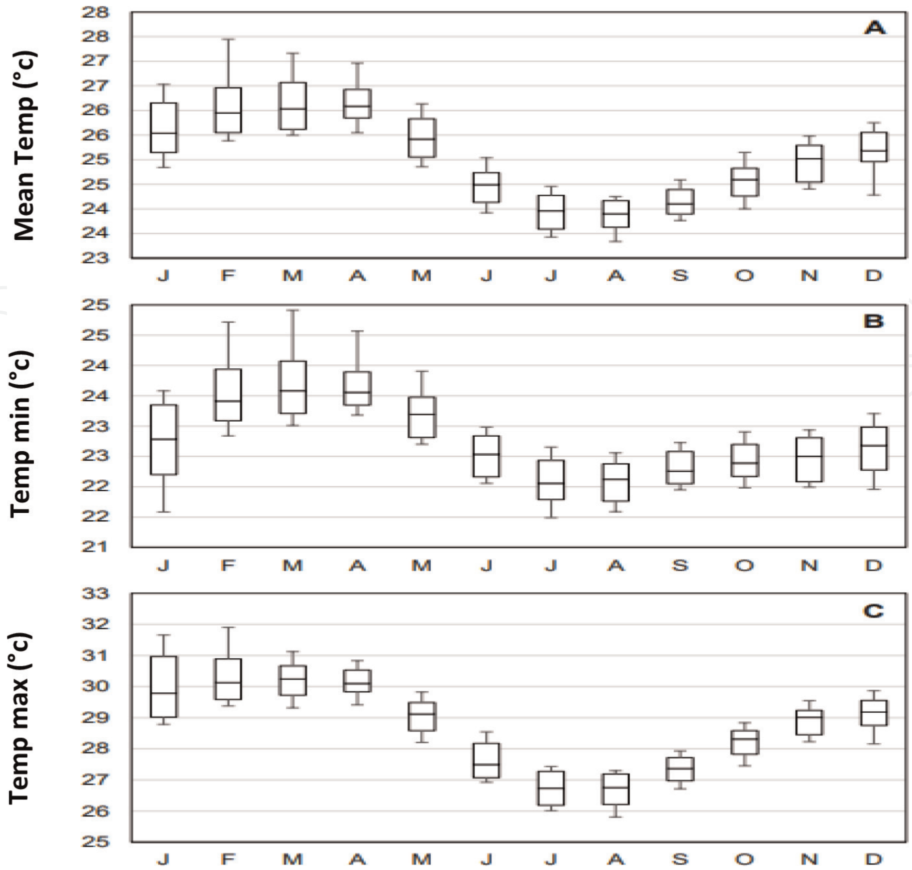

Figure 6.
Monthly climate normals for temperature, southern region ERA5-Land reanalysis data for the period 1981–2010 were used. The diagrams are shown for: (A) mean temperature, (B) minimum temperature, (C) and daily maximum temperature. The vertical limits of the boxes correspond to the 10th, 50th, and 90th percentiles, while the ends of the error bars indicate the minimum and maximum monthly values.

ONSET and cessation of rainy seasons, and (iii) usual duration of the little dry rainy season in the considered areas of Côte d'Ivoire. The seasonal analysis of the rainfall shows two rainy seasons in the southern region as well. Monthly rainfall is highest in May to June, followed by September-October, according to the median values (**Figure** 7). Interannual variability is greatest between June and August. The parameters initially chosen to detect the end of the rainy seasons result in a long

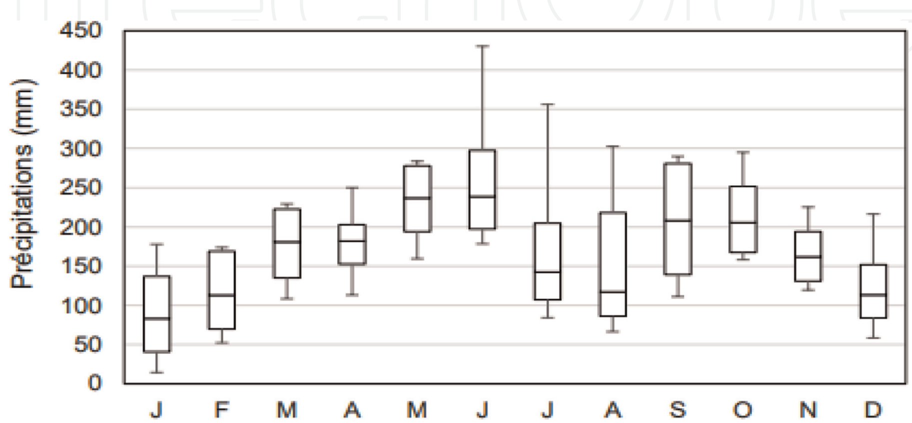

Figure 7.
Monthly climate normals for precipitation, southern region. ERA5-Land reanalysis data for the period 1981–2010 were used. The vertical limits of the boxes correspond to the 10th, 50th, and 90th percentiles, while the ends of the error bars indicate the minimum and maximum monthly values.

rainy season that ends 16 days before the start of the short season, on average (**Table 2**); as was the case in the central region, this implies a quasi-unimodal distribution of rainfall. The period during which there is a decrease in rainfall between seasons seems short, considering the usual length of this period in Côte d'Ivoire (4–6 weeks) (**Figure 8**). Also, the timing of the break does not correspond to the decrease in rainfall between days ~195 and ~235 for the reference period (**Figure 9**).

A sensitivity analysis was also carried out for the southern region. One of the combinations tested (10 mm/day for 10 days) resulted in a dry period lasting 31 days (**Table 2**) between the two rainy seasons, which seems more compatible with the reality in Côte d'Ivoire (**Figure 10**).

Season	Indice	Initial parameters (<5 mm/d × 20d)		Revised parameters (<10 mm/d × 10d)	
Major rainy season	Start	28 March	Day 87	28 March	Day 87
	End	15 August	Day 227	31 July	Day 212
	Duration	141 Days		126 Days	
	Precipitations	866 mm (46% of total annual)		805 mm (43% of total annual)	
Short rainy season	Start	31 August	Day 243	31 August	Day 243
	End	28 November	Day 332	19 November	Day 323
	Duration	90 Days		81 Days	
	Precipitations	542 mm (29% of total annual)		486 mm (26% of total annual)	
Total	Duration	231 Days		207 hours	
	Precipitations	1408 mm (75% of total annual)		1291 mm (69% of total annual)	

Table 2.
Characteristics of rainy seasons of the southern region.

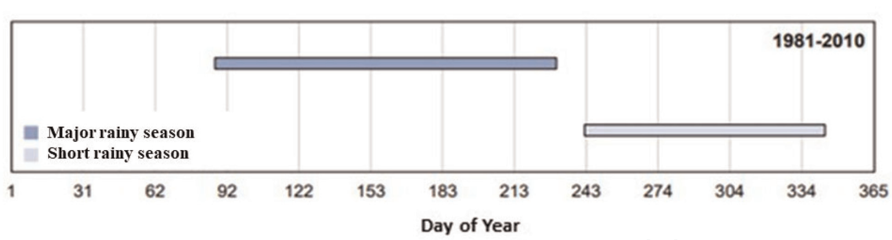

Figure 8.
Rainy season, based on initial definition of ONSET and cessation of rainy season for the southern region.

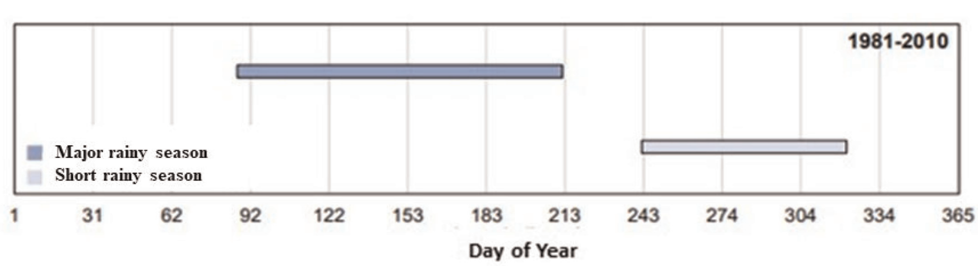

Figure 9.
Rainy seasons, based on revised definition of ONSET and cessation of rainy season for the southern region.

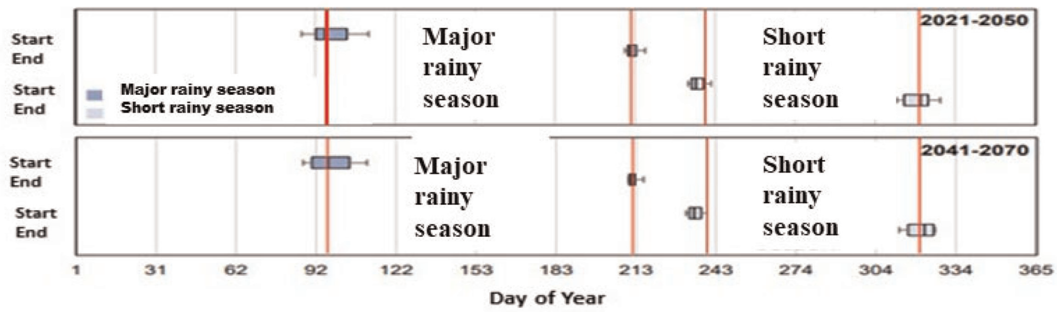

Figure 10.
Rainy seasons, based on revised parameters for the central region The vertical limits of the boxes correspond to the 10th, 50th, and 90th percentiles, while the ends of the horizontal bars indicate the minimum and maximum values for each of the climate indices associated with the rainy seasons. The vertical red lines correspond to the days of the year for the reference period, i.e. 97 (7 April), 212 (31 July), 239 (27 August), and 321 (17 November).

Using these rainy season detection parameters, the main rainy season extends from 28 March to 31 July, on average (**Table 2**). This corresponds to duration of 126 days. The short season runs from 31 August to 19 November, lasting 81 days. Note that there is a dry season between the two rainy seasons with the revised parameters.

3.3 Future climate in the centre regions

3.3.1 Temperature

The following trends can be observed:

- Average temperature: The average value for the period 1981–2010 is 25.7°C. It is expected to reach between [26.3; 26.9] °C by 2021–2050 and between [26.6; 27.7] °C by 2041–2070, representing potential increases of between [+0.6; +1.2] °C and between [+0.9; +2.0] °C, respectively.

- The average minimum daily temperature for the period 1981–2010 is 22.6°C. It is expected to rise to between [23.2; 23.9] °C by 2021–2050 and between [23.5; 24.8] °C by 2041–2070, representing potential increases of between [+0.6; +1.3] °C and between [+0.9; +2.2] °C, respectively.

- Average daily maximum temperature: The average value for the period 1981–2010 is 30.3°C. It is expected to reach between [31.0; 31.6] °C by 2021–2050 and between [31.3; 32.4] °C by 2041–2070, representing potential increases of between [+0.7; +1.3] °C and between [+1.0; +2.1] °C, respectively.

- Number of months per year with an average low daily minimum temperature (below 15°C): The average value for the period 1981–2010 is zero months/year. It would still be zero months/year by 2021–2050 and 2041–2070.

- Number of days per year with a high average daily maximum temperature (greater than or equal to 33°C): The average value for the period 1981–2010 is 51 days. This would rise to between [77; 106] days/year by 2021–2050 and between [92; 142] days/year by 2041–2070, representing potential increases of between [+26; +55] days/year and between [+41; +91] days/year, respectively.

All the scenarios and climate indices suggest warming over the next few decades. This warming would be greater for the RCP 8.5 scenario group than for the RCP 4.5 group. Also, the difference between the RCP groups would be greater for the most distant period. The most favourable temperature for growing cocoa is between 18 and 32°C. The analyses show that the number of months with an average minimum daily temperature below 15°C is zero. It is more the average maximum daily temperature that is likely to be problematic for cocoa growing. It could reach this threshold by 2021–2050 and even exceed it by 2041–2070. In addition, the number of days with an average daily maximum temperature of over 33°C could double or even triple by 2041–2070. The spatial distribution of temperatures and indices is similar.

3.3.2 Precipitation

The following trends can be observed:

- Cumulative annual precipitation: the average value for the period 1981–2010 is 1328 mm. It would be between [1317; 1491] mm by 2021–2050 and between [1315; 1533] mm by 2041–2070, representing potential changes of between [−11; +163] mm and between [−13; +205] mm, respectively.

- The number of rainy days (≥5 mm) per year; the average value for the 1981–2010 period is 89 days. It would be between [83; 99] days by 2021–2050 and between [81; 100] days by 2041–2070, representing potential changes of between [−6; +10] days and between [−8; +11] days, respectively.

- The duration of dry periods between March and November; the average value for the 1981–2010 period is 3 days. It would be between [1; 5] days by 2021–2050 and between [1; 4] days by 2041–2070, representing potential changes of between [−2; +2] days and between [−2; +1] days, respectively.

- Duration of dry spells between November and March: The average value for the 1981–2010 period is 129 days. It would be between [123; 138] days by 2021–2050 and between [123; 139] days by 2041–2070, representing potential changes of between [−6; +9] days and between [−6; +10] days, respectively.

3.3.3 Major rainy season

The following trends can be observed:

- Start of season: The season generally begins on day 97 of the year during the 1981–2010 period. It would begin between days [92; 104] of the year by 2021–2050 and between days [90; 105] of the year by 2041–2070, representing potential changes between [−5; +7] days and between [−7; +8] days. respectively.

- End of season: The season ends on day 212 of the year over the period 1981–2010. It would end between days [210; 213] of the year by 2021–2050 and between days [210; 213] of the year by 2041–2070, representing potential changes between [−2; +1] days and [−2; +1] days, respectively.

- Season length: The season lasts an average of 116 days over the 1981–2010 period. It would last between [107; 120] days by 2021–2050 and between [108; 121] days by 2041–2070, representing potential changes of between [−9; +4] days and between [−8; +5] days, respectively.

- Seasonal cumulative precipitation: Cumulative precipitation averaged 524 mm over the period 1981–2010. It would change to a value between [481; 639] mm by 2021–2050 and to a value between [483; 664] mm by 2041–2070, representing potential changes between [−43; +115] mm and between [−41; +140] mm, respectively.

3.3.4 Short rainy season

The following trends were observed:

- Start of season: The season starts on day 239 of the year over the period 1981–2010. It would begin between days [234; 239] of the year by 2021–2050 and between days [233; 238] of the year by 2041–2070, representing potential changes between [−5; 0] days and between [−6; −1] days, respectively.

- End of season: The season ends on average day 321 of the year over the period 1981–2010. It would end between days [315; 324] of the year by 2021–2050 and between days [316; 326] of the year by 2041–2070, representing potential changes between [−6; +3] days and between [−5; +5] days, respectively.

- Season length: The average season lasts 82 days over the period 1981–2010. It would last between [79; 89] days by 2021–2050 and between [79; 91] days by 2041–2070, representing potential changes of between [−3; +7] days and between [−3; +9] days, respectively.

- Seasonal cumulative precipitation: Cumulative precipitation averaged 392 mm over the period 1981–2010. It would change to between [347; 497] mm by 2021–2050 and to between [353; 504] mm by 2041–2070, representing potential changes of between [−45; +105] mm and between [−39; +112] mm, respectively.

3.3.5 Little dry season

The rainy seasons are shown in **Figure 10**. The average duration of the break between rainy seasons or little dry season is around 8 days over the 1981–2010 period, based on thresholds of 5 mm/day for 20 days. The break would last between [3; 10] days for the 2021–2050 and 2041–2070 horizons, representing potential changes between [−5; +2] days. The length of the break between rainy seasons averaged 27 days over the 1981–2010 period, based on thresholds of 10 mm/day for 10 days. The break would last between [20; 27] days by 2021–2050 and between [21; 27] days by 2041–2070, representing potential changes between [−7; 0] and between [−6; 0] days, respectively. The pause would therefore be shorter than in the present climate.

3.4 Future climate in the south region of Côte d'Ivoire

3.4.1 Temperature

The following trends were observed:

- Average temperature: The average value for the period 1981–2010 is 25.2°C. It is expected to reach between [25.8; 26.4] °C by 2021–2050 and between [26.1; 27.2] °C by 2041–2070, representing potential increases between [+0.6; +1.2] °C and between [+0.9; +2.0] °C, respectively.

- Mean minimum daily temperature: The mean value for the period 1981–2010 is 23.0°C. It is expected to reach between [23.6; 24.2] °C by 2021–2050 and between [23.9; 25.0] °C by 2041–2070, representing potential increases between [+0.6; +1.2] °C and between [+0.9; +2.0] °C, respectively.

- Mean maximum daily temperature: The mean value for the period 1981–2010 is 28.8°C. It is expected to reach between [29.4; 30.0] °C by 2021–2050 and between [29.7; 30.8] °C by 2041–2070, representing potential increases of between [+0.6; +1.2] °C and between [+0.9; +2.0] °C, respectively.

- Number of months per year with a low average daily minimum temperature (below 15°C): The average value for the period 1981–2010 is zero months/year. It would still be zero months/year by 2021–2050 and 2041–2070. Number of days per year with a high average daily maximum temperature (greater than or equal to 33°C): The average value for the period 1981–2010 is 2 days. It would rise to between [7; 17] days/year by 2021–2050 and between [12; 47] days/year by 2041–2070, representing potential increases of between [+5; +15] days/year and between [+10; +45] days/year, respectively.

All the scenarios and climate indices suggest warming over the next few decades. This warming would be greater for the RCP 8.5 scenario group than for the RCP 4.5 group. Also, the difference between the RCP groups would be greater for the most distant period. As previously mentioned, the most favourable temperature for cocoa cultivation is between 18 and 32°C. The results indicate that the number of months with an average daily minimum temperature below 15°C is zero. Concerning the upper limit of 32°C associated with cocoa cultivation, the results indicate that the average maximum daily temperature (between [29.4; 30.8]°C) would not exceed this threshold in the climatic horizons considered in this study. However, this does not mean that, in some years, the annual average would not exceed this threshold. In addition, the number of days with an average daily maximum temperature of over 33° C, which was only 2 days for the 1981–2010 period, could increase significantly. The cocoa tree's comfort limit would be exceeded more often by 2041–2070.

3.4.2 Precipitation

The following trends were observed:

- Cumulative annual precipitation: The average value for the period 1981–2010 is 1888 mm. This would rise to between [1800; 2115] mm by 2021–2050 and between [1812; 2164] mm by 2041–2070, representing potential changes of between [−88; +227] mm and between [−76; +276] mm, respectively.

- Number of rainy days (≥5 mm) per year: The average value for the 1981–2010 period is between 130 days. This would rise to between [115; 152] days by 2021–2050 and between [112; 154] days by 2041–2070, representing potential changes of between [−15; +22] days and between [−18; +24] days, respectively.

- Duration of dry periods between March and November: The average value for the 1981–2010 period is 0 days. It would still be zero months/year by 2021–2050 and 2041–2070.

- Duration of dry periods between November and March: The average value for the 1981–2010 period is 87 days. It would reach between [54; 112] days by 2021–2050 and between [55; 115] days by 2041–2070, representing potential changes of between [−33; +25] days and between [−32; +28] days, respectively.

3.4.3 Major rainy season

The following trends were observed:

- Start of season: The season starts on day 87 of the year over the period 1981–2010. It would begin between days [84; 93] of the year by 2021–2050 and between days [85; 96] of the year by 2041–2070, representing potential changes between [−3; +6] days and between [−2; +9] days, respectively.

- End of season: The season ends on day 212 of the year for the period 1981–2010. It would end between days [209; 216] of the year by 2021–2050 and between days [209; 214] of the year by 2041–2070, representing potential changes between [−3; +4] days and between [−3; +2] days, respectively.

- Season length: The season lasts an average of 125 days over the 1981–2010 period. It would last between [116; 131] days by 2021–2050 and between [115; 128] days by 2041–2070, representing potential changes of between [−9; +6] days and between [−10; +3] days, respectively.

- Seasonal cumulative precipitation: Cumulative precipitation averaged 805 mm over the period 1981–2010. It would change to a value between [768; 979] mm by 2021–2050 and to a value between [772; 1024] mm by 2041–2070, representing potential changes between [−37; +174] mm and between [−33; +219] mm, respectively.

3.4.4 Little rainy season

The following trends are observed:

- Start of season: The season begins on day 243 of the year during the 1981–2010 period. It would begin between days [237; 245] of the year by 2021–2050 and between days [235; 244] of the year by 2041–2070, representing potential changes between [−6; +2] days and between [−8; +1] days, respectively.

- End of season: The season ends on average on day 323 of the year over the period 1981–2010. It would end between days [317; 326] of the year by 2021–2050 and between days [318; 327] of the year by 2041–2070, representing potential changes between [−6; +3] days and between [−5; +4] days, respectively.

- Season length: The season lasts an average of 79 days over the 1981–2010 period. It would last between [75; 88] days by 2021–2050 and between [78; 89] days by 2041–2070, representing potential changes between [−4; +9] days and between [−1; +10] days, respectively.

- Seasonal cumulative precipitation: Cumulative precipitation averaged 486 mm over the period 1981–2010. It would change to between [384; 622] mm by 2021–2050 and to between [398; 650] mm by 2041–2070, representing potential changes of between [−102; +136] mm and between [−88; +164] mm, respectively.

3.4.5 Little dry season

The rainy seasons are shown in **Figure 10**. The average duration of the little dry season the break between rainy seasons is around 16 days over the period 1981–2010, based on thresholds of 5 mm/day for 20 days. The break would last between [6; 21] days by 2021–2050 and between [6; 20] days by 2041–2070, representing potential changes between [−10.0; +5.0] and between [−10.0; +4.0] days, respectively. The length of the break between rainy seasons averages 31 days over the 1981–2010 period, based on thresholds of 10 mm/day for 10 days. The break would last between [19; 35] days by 2021–2050 and between [21; 35] days by 2041–2070, representing potential changes between [−12; +4] and between [−10; +4] days, respectively (**Figure 11**).

4. Influence of climatic variables on cocoa tree physiology and post-harvest aspects

The aim was to establish the link between the fluctuation of climatic variables during the periods 2021 to 2050 and 2041 to 2070, on the establishment of orchards, the survival of cocoa trees after planting, the growth and development of cocoa trees, flowering, fruiting, drying and the technological quality of merchantable beans and cocoa pests and diseases. About cocoa diseases, the influence of climatic variables was

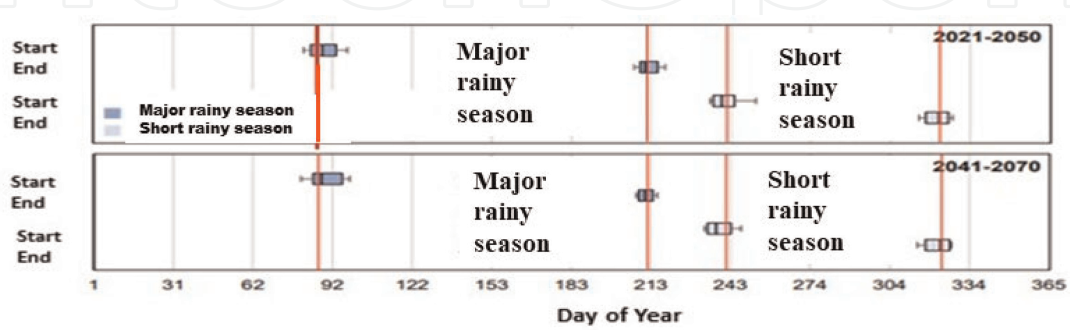

Figure 11.
Rainy seasons, based on revised parameters for the southern region. The vertical limits of the boxes correspond to the 10th, 50th and 90th percentiles, while the ends of the error bars indicate the minimum and maximum values for each of the climate indices associated with the rainy seasons. The vertical red lines correspond to the days of the year for the reference period, i.e., 87 (28 March), 212 (31 July), 243 (31 August) and 323 (19 November).

analysed on the development of brown rot and swollen shoot. Concerning pests, the analysis focused on mirids, stem borers, mealybugs, psyllids, and defoliating caterpillars. The immediate and lasting repercussions of climate change on diseases and pests are among the major concerns of scientists and policy-makers around the world. Rainfall and temperature are the most important factors in the development of diseases and pests.

Tables 3–10 summarise the results of the climate scenarios and their influence on cocoa production in the Central and Southern zones of Côte d'Ivoire.

5. Identification of climate smart practices for adaptation to climate variability in cocoa production

Generally, the adoption of climate-smart practices by cocoa farmers remains limited for a variety of reasons. Surveys carried out in Abengourou, Gagnoa, Vavoua, and Soubré to collect and analyse adaptation practices in cocoa farming enabled a range of agroecological practices covering all stages of cultivation to be inventoried (**Table 11**). The most promising practices for coping with the effects of climate change in cocoa farming were identified using multiple criteria (economic, social, and gender equality, environmental, and efficiency). This multi-criteria analysis shows that the most promising practices relate to tree planting, for shade purposes and other benefits provided by trees and agroforestry [27, 28]. These practices deserve to be included in the training curricula of professionals who work with cocoa farmers, just as these practices deserve to be widely disseminated and promoted among cocoa farmers. Cocoa cooperatives also play a role in disseminating these messages and in meeting the needs of their members, both men and women. These organizations benefit from taking climate change into account in the products and services they offer so that they can make informed and strategic decisions.

6. Conclusions

The analysis of the climate scenarios for the next 50 years for the central and southern zones of Côte d'Ivoire concerning cocoa farming provides an understanding of the projected impact of future climate on cocoa trees and the surrounding environment. In general, the various climate scenarios showed that there would be an increase in the average maximum temperature (up to 1.3°C higher by 2021–2050 and 2.2°C higher by 2041–2070) and an increase in the number of hot days (≥33°C) in both zones (Centre and South), although these changes would be more marked in the Centre zone. No consensus has been reached between the climate model projections for rainfall, except that the short rainy season could start earlier than in the present climate. These predictions could have impacts on cocoa cultivation. With respect to physiology, rainfall forecasts are favourable to the establishment, growth, flowering, and fruiting of cocoa trees. On the other hand, an increase in the number of hot days would be harmful to the cocoa tree. Concerning cocoa diseases (CSSVD and brown rot), increases in temperature and the number of hot days would help slow their progress in the orchards. About the main pests, increases in temperature and rainfall would not alter their dynamics, but only the delay in the start of the main rainy season could reduce the outbreak of defoliating caterpillars. For soil on

Central zone: period from 2021 to 2050					Cocoa physiology and post-harvest aspects						
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**
Temperature											
Average temperature (°C)	25.7 °C	25–26 °C	[26.3; 26.9]	[+0.6; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	22.6 °C	18 °C	[23.2; 23.9]	[+0.6; +1.3]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	30.3 °C	32 °C	[31.0; 31.6]	[+0.7; +1.3]	Favourable	Favourable	Favourable	Favourable	Favourable	Little favourable	Favourable
Number of warm days (≥ 33 °C)	51 Day/ year	51 Days/ Year	[77; 106]	[+26; +55]	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Little favourable	Favourable
Precipitation											
Rainfall (total annual, (mm)	1328 mm	[1200; 2000]	[1317; 1491]	[−11; +163]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	89 Days	89 Days	[83; 99]	[−6; +10] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	3 Days	3 Days	[1; 5] days	[−2; +2] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	07-Apr	15-May	[02 Apr; 14 Apr]	[−5; +7] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of major rainy season (<10 mm over 10 days)	31-Jul	15-Jul	[29 July; 1er Aug]	[−2; +1] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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Central zone: period from 2021 to 2050					Cocoa physiology and post-harvest aspects						
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**
Duration of major rainy season	116 Days	122 Days (700 mm)	[107 Days; 120 days]	[−9; +4] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	26-Aug	15-Sept	[22 to 27 Aug]	[−4; +1] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	17-Nov	11-Nov	[11–20 Nov]	[−6; +3] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	82 Days	65 Days (70 mm)	[79 to 89 Days]	[−3; +7] days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 3.
Interpretation of the influence of climatic variables for the period 2021–2050 on cocoa physiology and post-harvest aspects in the central zone.

Central zone: period from 2041 to 2050					Cocoa physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
Temperature												
Average temperature (°C)	25.7 °C	25–26 °C	[26.6; 27.7]	[+0.9; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	22.6 °C	18 °C	[23.5 ; 24.8]	[+0.9 ; +2.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	30.3 °C	32 °C	[31.3 ; 32.4]	[+1.0 ; +2.1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	51 days/ year	51 days/ year	[92 ; 142]	[+41 ; +91]	Favourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable
Precipitation												
Rainfall (total annual, (mm)	1328 mm	[1200 ; 2000]	[1315 ; 1533]	[−13 ; +205]	Favourable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable
Number of rainy days/year (≥5 mm/ day)	89 Days	89 Days	[81 ; 100]	[−8 ; +11]	Favourable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable
Number of dry days (<1 mm/day over 14 days)	3 Days	3 Days	[1 ; 4]	[−2 ; +1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	07-Apr	15-Mar	[31 Mar ; 15 April]	[−7 ; +8]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of major rainy season	31-Jul	15-Jul	[29 Jul; 1er Aug]	[−2 ; +1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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Central zone: period from 2041 to 2050					Cocoa physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
(<10 mm over 10 days)												
Duration of major rainy season	116 Days	122 days (700 mm)	[108; 121] Days	[−8 ; +1] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	26-Aug	15 Sept.	[21–26 Aug]	[−5; +0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	17-Nov	11-Nov	[12–22 Nov]	[−5; +5]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	82 Days	65 Days (70 mm mm)	[79; 83] Days	[−3 ; +1] Days	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable

Table 4.
Interpretation of the influence of climatic variables for the period 2041–2070 on cocoa physiology and post-harvest aspects in the central zone.

	Central zone: period from 2021 to 2050				**Diseases and pests of the cacao**						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Change from 2021 to 2050/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Temperature											
Average temperature (° C)	25.7 °C	25–26 °C	[26.3; 26.9]	25.7 °C	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (° C)	22.6 °C	18 °C	[23.2; 23.9]	22.6 °C	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (° C)	30.3 °C	32 °C	[31.0; 31.6]	30.3 °C	Favourable	Little favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	51 Days/ year	51 Days/ year	[77 ; 106]	51 days/year	Unfavourable	Unfavourable	Little favourable	Little favourable	Little favourable	Little favourable	Little favourable
Precipitation											
Rainfall (total annual, (mm)	1328 mm	[1200 ; 2000]	[1317 ; 1491]	1328 mm	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	89 Days	89 Days	[83 ; 99] Days	89 Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/ day over 14 days)	3 Days	3 Days	[1; 5] Days	[−2; +2]	Favourable	Little favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	07-Avr	15-Mar	[02–14 April]	[−5; +7] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Little favourable

Central zone: period from 2021 to 2050					Diseases and pests of the cacao						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Change from 2021 to 2050/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
End of major rainy season (<10 mm over 10 days)	31-Jul	15-Jul	[29 Jul; 1^{er} Aug]	[−2; +3] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of major rainy season	116 Days	122 Days	[107 – 120 Days]	[−9; +3] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	26-Aug	15-Sept	[22 to 27 Aug]	[−4; +1] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (< 10 mm over 10 days)	17-Nov	11-Nov	[11–20 Nov]	[−6; +3] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	82 Days	65 Days (70 mm)	[79 to 89 Days]	[−3; +7]Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 5.
Interpretation of the influence of climatic variables for the period 2021–2050 on cacao diseases and pests in the central zone.

Central zone: period from 2041 to 2070					Diseases and pests of the cacao						
Parameters	**Values for the reference period 1981–2010**	**Normal values for cacao**	**Projections 2041 –2070 (RCP 4.5 and RCP 8.5)**	**Change from 2041 to 2070/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Temperature											
Average temperature (°C)	25.7 °C	25–26 °C	[26.6; 27.7]	[+0.9; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	22.6 °C	18 °C	[23.5 ; 24.8]	[+0.9 ; +2.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	30.3 °C	32 °C	[31.3 ; 32.4]	[+1.0 ; +2.1]	Favourable	Little favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	51 Days/year	51 Days/ year	[92 ; 142]	[+41 ; +91]	unfavourable	unfavourable	Little favourable	Little favourable	Little favourable	Little favourable	Little favourable
Precipitation											
Rainfall (total annual, (mm)	1328 mm	[1200 ; 2000]	[1315 ; 1533]	[−13 ; +205]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	89 Days	89 Days	[81 ; 100]	[−8; +11]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	3 Days	3 Days	[1 ; 4]	[−2 ; +1]	Favourable	Little favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	06-Apr	15-Mar	(30 Mar ; 14 Apr)	[−7 ; +8]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Little favourable
End of major rainy season (<10 mm over 10 days)	30-Jul	15-Jul	(28–31 Jul)	[−2 ; +1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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Central zone: period from 2041 to 2070					Diseases and pests of the cacao						
Parameters	**Values for the reference period 1981–2010**	**Normal values for cacao**	**Projections 2041 –2070 (RCP 4.5 and RCP 8.5)**	**Change from 2041 to 2070/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Duration of major rainy season	116 Days	122 Days (700 mm)	[108; 121] Days	[−8 ; +1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	26-Agus	15-Sept	[21 26 Aug]	[−5; +0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	17-Nov	11-Nov	[12 ; 22 Nov]	[−5; +5]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	82 Days	65 Days (70 mm)	[79; 83] Days	[−3 ; +1]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 6.
Interpretation of the influence of climatic variables for the period 2041–2070 on cocoa diseases and pests in the central zone.

	Southern zone: period 2021 à 2050				Cocoa physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
Temperature												
Average temperature (°C)	25.2 °C	25–26 °C	[25.8; 26.4]	[+0.6; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	23.0 °C	18 °C	[23.6 ; 24.2]	[+0.6 ; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	28.8 °C	32 °C	[29.4 ; 30.0]	[+0.6 ; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	2 Days/ year	2 Days/ year	[7 ; 17]	[+5 ; +15]	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable	unfavourable
Precipitation												
Rainfall (total annual, (mm)	1888 mm	[1200 ; 2000]	[1800 ; 2115]	[−88 ; +227]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	130	130 jours	[115 ; 152]	[−15 ; +22]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	0 day	0 day	[0 ; 0]	[0 ; 0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	27-Mar	15-Mar	[25 Mar ; 03 Apr]	[−2 ; +7] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of major rainy season (<10 mm over 10 days)	30-Jul	15-Jul	[28 Jul; 4 Aug]	[−2 ; +5] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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Southern zone: period 2021 à 2050					Cocoa physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
Duration of major rainy season	125 Days	122 Days (700 mm)	[116; 131] Days	[−9 ; +6] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	31-Aug	15-Sept	[23 Aug; 01 Sept]	[−8; +1] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	19-Nov	11-Nov	[14 to 23 Nov]	[−5; +4] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	79 Days	65 Days (70 mm)	[75; 88] Days	[−4; +9] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 7.
Interpretation of the influence of climatic variables for the period 2021–2050 on cocoa physiology and post-harvest aspects in the southern zone.

South zone: period 2041 to 2070					Cacao physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
Temperature												
Average temperature (°C)	25.2 °C	25–26 °C	[26.1; 27.2]	[+0.9; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	23.0 °C	18 °C	[23.9 ; 25.0]	[+0.9 ; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	28.8 °C	32 °C	[29.7 ; 30.8]	[+0.9 ; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	2 Days/ year	2 Days/ year	[12 ; 47]	[+17 ; +45]	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable
Precipitation												
Rainfall (total annual, (mm)	1888 mm	[1200; 2000]	[1812; 2164]	[−76; +276]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	130	130 Days	[112; 154]	[−18; +24]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	0 Dry days	0 dry days	[0 ; 0]	[0 ; 0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	27-Mar	15-Mar	[25 Mar ; 5 Apr]	[−2 ; +9]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of major rainy season (<10 mm over 10 days)	30-Juil	15-Jul	[27 Jul; 1 Aug]	[−3 ; +2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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South zone: period 2041 to 2070					Cacao physiology and post-harvest aspects							
Parameters	**Reference period values 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 et RCP 8.5)**	**Changes from 2021 to 2050/ reference period**	**Establishment in the farm**	**Growth and development**	**Flowering**	**Fructification**	**Production**	**Quality (size) of beans**	**Drying**	**Storage**
Duration of major rainy season	125 Days	122 Days (700 mm)	[115; 128] Days	[−10 ; +3] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	31-Aug	15-Sept	[22–31 Aug]	[−9; +0] Days								
End of short rainy season (<10 mm over 10 days)	19-Nov	11-Nov	[14–23 Nov]	[−5; +4] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	79 Days	65 Days (70 mm)	[78; 89] Days	[−1; +10] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 8.
Interpretation of the influence of climatic variables for the period 2041–2070 on cacao physiology and post-harvest aspects in the southern zone.

South zone: period 2021 to 2050					Cacao diseases and pests						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Change from 2021 to 2050/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Temperature											
Average temperature (°C)	25.2 °C	25–26 °C	[25.8; 26.4]	[+0.6; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	23.0 °C	18 °C	[23.6 ; 24.2]	[+0.6 ; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	28.8 °C	32 °C	[29.4 ; 30.0]	[+0.6 ; +1.2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	2 Days/ year	2 Days/ year	[7 ; 17]	[+5 ; +15]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Precipitation											
Rainfall (total annual, (mm)	1888 mm	[1200 ; 2000]	[1800 ; 2115]	[−88 ; +227]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	130	130 Days	[115 ; 152]	[−15 ; +22]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	0 Dry day	0 dry day	[0 ; 0]	[0 ; 0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	27-Mar	15 Mar	[25 Mar; 03 Apr]	[−2 ; +7 Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of major rainy season (< 10 mm over 10 days)	30-Jul	15-Jul	[28 Jul; 4 Aug]	[−2 ; +5] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

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South zone: period 2021 to 2050					Cacao diseases and pests						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2021–2050 (RCP 4.5 and RCP 8.5)**	**Change from 2021 to 2050/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Duration of major rainy season	125 Days	122 Days (700 mm)	[116; 131] Days	[−9 ; +6] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	31-Aug	15-Sept	[23 Aug; 01 Sept]	[−8; +1] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	19-Nov	11-Nov	[14–23 Nov]	[−5; +4] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	79 Days	65 Days (70 mm)	[75; 88] Days	[−4 +9] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 9.
Interpretation of the influence of climatic variables for the period 2021–2050 on cocoa diseases and pests in the southern zone.

South zone: period 2041 to 2070					Cacao diseases and pests						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 and RCP 8.5)**	**Change from 2041 to 2070/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
Temperature											
Average temperature (°C)	25.2 °C	25–26 °C	[26.1; 27.2]	[+0.9; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Minimum temperature (°C)	23.0 °C	18 °C	[23.9 ; 25.0]	[+0.9 ; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Maximum temperature (°C)	28.8 °C	32 °C	[29.7 ; 30.8]	[+0.9 ; +2.0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of warm days (≥ 33 °C)	2 Days/ year	2 Dry/ year	[12 ; 47]	[+17 ; +45]	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Unfavourable	Favourable	Favourable
Precipitation											
Rainfall (total annual, (mm)	1888 mm	[1200 ; 2000]	[1812 ; 2164]	[−76 ; +276]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of rainy days/year (≥5 mm/day)	130 Days	130 days	[112 ; 154]	[−18 ; +24]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Number of dry days (<1 mm/day over 14 days)	0 Dry day	0 Dry day	[0 ; 0]	[0 ; 0]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of the major rainy season	27-Mar	15-Mar	[25 Mar ; 5 Apr]	[−2 ; +9]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Little favourable
End of major rainy season (<	30-Jul	15-Jul	[27 Jul; 1 Aug]	[−3 ; +2]	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

South zone: period 2041 to 2070					Cacao diseases and pests						
Parameters	**Reference period 1981–2010**	**Normal values for cacao**	**Projections 2041–2070 (RCP 4.5 and RCP 8.5)**	**Change from 2041 to 2070/ reference period**	**CSSVD**	**Black pod**	**Mirids**	**Stem borers**	**Mealybugs**	**Psylles**	**Defoliating caterpillars**
10 mm over 10 days)											
Duration of major rainy season	125 Days	122 days (700 mm)	[115; 128] Days	[−10 ; +3] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Start of short rainy season	31-Aug	15-Sept	[22–31 Aug]	[−9; +0] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
End of short rainy season (<10 mm over 10 days)	19-Nov	11-Nov	[14–23 Nov]	[−5; +4] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable
Duration of short rainy season	79 Days	65 Days (70 mm)	[78; 89] Day	[−1; +10] Days	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable	Favourable

Table 10.
Interpretation of the influence of climatic variables for the period 2041–2070 on cocoa diseases and pests in the southern zone.

Illustrations	Agroecological practices identified
Temporary shade plants	
	• Plantation of banana trees for temporary shade • Planting tree legumes (*Cajanus cajan*) for temporary shade and human consumption
Permanent shade trees	
	• Plantation of compatible fruit and forest species for shade purposes • Plantation of perennial legumes (e.g. *Acacia mangium* and Albizia)
Crop system management	
	• Association of cocoa with food crops (e.g. yam, tomato, okra ...) • Association of cocoa with edible cover crops (e.g. groundnuts, beans, soya, sweet potatoes)

Illustrations	Agroecological practices identified
Soil fertility management	
	• Production and use of compost made from cocoa residues • Mulching around cacao
Pruning cocoa trees	
	• Flowering pruning once a year in line with the start of the rainy season (after the first heavy rain) and cleaning of pruning equipment • Training pruning in the rainy season and cleaning of pruning equipment
Disease and pest management	
	• Use of vegetative barriers against swollen shoot and strong winds • Regular inspection of orchards for early detection of symptoms of disease and pests • Use of mechanical methods (pruning, plugging holes with stems, manual removal of insects, leaves, attacked fruit) to prevent the appearance of and/or control pests • Use of grass swaths to prevent attacks by harmful insects • Use of natural/biological repellents (neem, ginger, predatory insects) to prevent the appearance of and/or control pests
Post-harvest activities	

Illustrations	Agroecological practices identified
	• Storage of cocoa beans protected from bad weather

Table 11.
Identification of agroecological practices to adapt to climate change effect in cocoa farming.

which crop is grown, (cocoa trees, and associated crops) would also be affected by climate change, with an increase in the number of hot days (≥33°C). This would result in high evapotranspiration, low soil water retention, and rapid degradation of organic matter, leading to a decline in soil fertility. In addition, climate change could lead to lower yields and higher levels of poverty in rural areas. Given the impact that climate change would have on cocoa farming over the periods 2021–2050 and 2041–2070, strategies are proposed to improve the resilience of producers within cocoa cooperatives in Côte d'Ivoire. A set of agro-ecological practices have been identified that could counteract the adverse effects of climate change.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Antoine Alban Kacou M'bo[1*], Mamadou Cherif[1], Kouakou Kouadio[1,2], Mahyao Germain Adolphe[3], Adama Bamba[1,4], Evelyne N'Datchoh Toure[1,4], Alla Kouadio Okou[5], Renée Brunelle[6], Yanick Rouseau[7] and Daouda Koné[1]

1 African Center of Excellence on Climate Change, Biodiversity and Sustainable Agriculture (CEA-CCBAD/WASCAL), Université Félix Houphouet-Boigny (UFHB), Côte d'Ivoire

2 Geophysical Station of Lamto (GSL), N'Douci, Côte d'Ivoire

3 Centre National de Recherche Agronomique, Gagnoa Research station, Côte d'Ivoire

4 Laboratoire des Sciences de la Matière, de l'environnement et de l'Energie Solaire (LASMES), UFR-SSMT of Felix Houphouët Boigny University, Côte d'Ivoire

5 Agence National d'Appui au Developpement Rurale (ANADER), Côte d'Ivoire

6 SOCODEVI, International Cooperation Organization, Canada

7 OURANOS, Consortium on Regional Climatology and Adaptation to Climate Change Montréal, Québec, Canada

*Address all correspondence to: mbo.antoine@ufhb.edu.ci

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