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Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation

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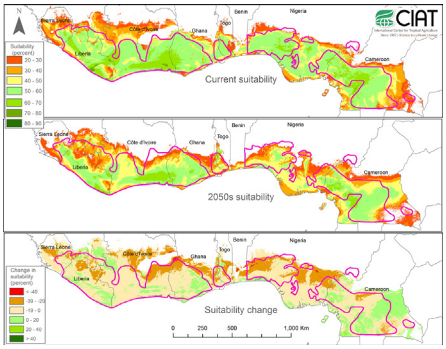
HIGHLIGHTS

- Comprehensive analysis of the climate change vulnerability of cocoa in West Africa
- Maximum dry season temperatures are projected to become limiting for cocoa
- Systematic use of shade trees in cocoa farms is needed, reversing current trends
- There is a strong differentiation of climate vulnerability within the cocoa belt
- Spatial differentiation of climate vulnerability may lead to future shifts in cocoa production

GRAPHICAL ABSTRACT



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ABSTRACT

The West African cocoa belt, reaching from Sierra Leone to southern Cameroon, is the origin of about 70% of the world's cocoa (*Theobroma cacao*), which in turn is the basis of the livelihoods of about two million farmers. We analyze cocoa's vulnerability to climate change in the West African cocoa belt, based on climate projections for the 2050s of 19 Global Circulation Models under the Intergovernmental Panel on Climate Change intermediate emissions scenario RCP 6.0. We use a combination of a statistical model of climatic suitability (Maxent) and the analysis of individual, potentially limiting climate variables. We find that: 1) contrary to expectation, maximum dry season temperatures are projected to become as or more limiting for cocoa as dry season water availability; 2) to reduce the vulnerability of cocoa to excessive dry season temperatures, the systematic use of adaptation strategies like shade trees in cocoa farms will be necessary, in reversal of the current trend of shade reduction; 3) there is a strong differentiation of climate vulnerability within the cocoa belt, with the most vulnerable areas near the forest-savanna transition in Nigeria and eastern Côte d'Ivoire, and the least vulnerable areas in the southern parts of Cameroon, Ghana, Côte d'Ivoire and Liberia; 4) this spatial differentiation of climate vulnerability may lead to future shifts in cocoa production within the region, with the opportunity of partially

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compensating losses and gains, but also the risk of local production expansion leading to new deforestation. We conclude that adaptation strategies for cocoa in West Africa need to focus at several levels, from the consideration of tolerance to high temperatures in cocoa breeding programs, the promotion of shade trees in cocoa farms, to policies incentivizing the intensification of cocoa production on existing farms where future climate conditions permit and the establishment of new farms in already deforested areas.

1. Introduction

Roughly 70% of the world's cocoa (*Theobroma cacao*) production originate from the coastal areas of the Gulf of Guinea in West Africa, reaching from Sierra Leone, Guinea and Liberia along the West African coast to southern Cameroon (http://faostat3.fao.org; ECOWAS, 2007). Along the Guinea coast, the only country not producing cocoa is Benin, located in the Dahomey gap in the forest belt where the savanna reaches down to the sea and the seasonal dryness of the climate precludes the planting of drought-sensitive crops like cocoa (ECOWAS, 2007). This area is known as the West African (WA) cocoa belt (International Trade Centre, 2001). It was once covered by the Guinean lowland forests in the west and the Nigerian lowland forests transitioning through Cameroon into the Congo basin in the east (Burgess et al., 2004), although much of these forests have now been converted for agriculture, including cocoa farms (Norris et al., 2010; Gockowski and Sonwa, 2011). Some cocoa is also produced in Africa further to the east of the Congo basin (e.g. Tanzania and Democratic Republic of Congo), but the quantities are minor in comparison. Currently, the world's cocoa industry depends largely on the WA cocoa belt for its most important raw material, not only because of the sheer volume of cocoa grown there, but also because it is the most important origin of high-quality bulk cocoa (as opposed to specialty cocoa) that cannot be readily replaced by other cocoa origins. Ghanaian cocoa is generally considered the “gold standard” of bulk cocoa on the global market (International Trade Centre, 2001).

Cocoa farming in this region is similarly important to the largely developed-country based global cocoa industry and to the economies of the producing countries. In 2011, cocoa beans were the most important agricultural export by value for Côte d'Ivoire, Ghana, Nigeria, Cameroon and Sierra Leone, the second most important for Guinea and Liberia, and the third most important for Togo (http://faostat3.fao.org). Since the introduction of the cocoa tree from Brazil and its spreading in West Africa in the 19th and early 20th century, it has been grown mostly by smallholder farmers and is today considered an archetypical smallholder crop in Africa, differently from Latin America where large cocoa estates are also common (Clarence-Smith and Ruf, 1996; International Trade Centre, 2001). Currently, about 2 million smallholder farmers in West Africa depend on cocoa for their livelihoods (http://www.cargill.com/connections/more-stories/help-for-westafrica-cocoa-farmers/index.jsp).

Cocoa production in this region faces a number of challenges. These include the low productivity of the mostly over-aged trees and small farms that do not provide an attractive income to current and future cocoa farmers; the variability and, until the recent price increases, low level of farm gate prices making it difficult to afford costly inputs such as mineral fertilizers; the insufficiency and often complete absence of technical assistance to cocoa farmers in most countries; and the prospect of climate change (Läderach et al., 2013). Most parts of the WA cocoa belt have a relatively long dry season compared to other major global cocoa producing regions (Wood and Lass, 2001). During the second half of the 20th century, West Africa has experienced a further drying of the climate, leading to decreases in annual rainfall by 30% in the West African savanna (Kotir, 2011), and also affecting the forest zone (Léonard and Oswald, 1996; Ruf et al., 2015). As a result, some important cocoa producing areas in the eastern forest belt of Côte d'Ivoire in the 1960s had essentially become unsuitable for growing and especially for replanting cocoa by the 1990s (Kassin et al., 2008; Ruf et al., 2015). This trend of rapid deterioration of the climate has halted and perhaps even seen a reversal during the last decade (Niang et al., 2014; Ruf et al., 2015). However, there is a concern that the projected global temperature increase and concomitant increase in potential evapotranspiration (ETP) and plant water demand may result in increased drought stress during the dry season and a further deterioration of the climatic conditions for cocoa (Läderach et al., 2013). Based on climate models recognized by the Intergovernmental Panel on Climate Change (IPCC), these authors predicted spatially differentiated climate impacts for cocoa in Côte d'Ivoire and Ghana, with losses of climatic suitability especially near the forest-savanna transition, and smaller negative or positive changes in other areas. Overall, they predicted a decrease in climatic suitability for cocoa in these two key cocoa producing countries that, if not addressed, could impact future world cocoa supplies (Läderach et al., 2013). This modeling approach has been further developed and applied to Liberia (Schroth et al., 2015c) and then expanded to all of West Africa, with focus on developing a regional approach to adaptation planning for cocoa in this region (Schroth et al., 2016).

In the present study, we analyze the drivers of current and future climate vulnerability[1] of cocoa in West Africa by identifying those climate factors that could potentially become limiting for cocoa in parts of the region and therefore need to be given particular attention in developing adaptation strategies. We also suggest adaptation measures to reduce the vulnerability of cocoa to the projected changes. We further show which countries in the cocoa belt are likely to be more or less affected by future climate change and discuss opportunities and possible risks of cocoa expansion into climatically less vulnerable areas.

2. Methods

2.1. Characterizing the current and projected future climate of the WA cocoa belt

For characterizing the current and projected future climate of the WA cocoa belt, we followed the methodology described in Schroth et al. (2016). We created a map of the current extent of cocoa farming in the area and overlaid it with climate variables from the WorldClim database (www.worldclim.org; Hijmans et al., 2005). For the purpose of this study, we defined the WA cocoa belt as the cocoa producing areas between Sierra Leone in the west and Cameroon in the east (International Trade Centre, 2001). For the extent of cocoa farming in this area we used a map from the Atlas on Regional Integration in West Africa (ECOWAS, 2007) as a basis except for Nigeria where we used a map of cocoa producing districts from the 2007 national cocoa production survey (CRIN, 2008). We updated these maps with literature and field information. Specifically, we included all of Liberia as cocoa producing area because a recent report shows some cocoa production for essentially every part of the country (CAAS, 2007). We also included into the cocoa area the wet, southwestern parts of Côte d'Ivoire and Ghana where cocoa farming has expanded relatively recently (Ruf

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[1] The term vulnerability to climate change as used in this paper refers to the combination of exposure (the nature and extent of climate change) and sensitivity (the impact of this change on local systems, here cocoa).

et al., 2015). We then overlaid the entire cocoa production area with a 0.3 degree grid, generating 558 evenly spaced sampling points that were used as calibration points for the climate model as explained further below, as well as for the calculation of regional averages of climate variables. These points are shown in Figs. 1 to 5.

The WorldClim data are generated through interpolation of average monthly climate data from a global network of 47,554 meteorological stations on a 30 arc-second resolution grid, often referred to as 1 km resolution. Only stations for which there were more than 10 years of data were included, calculating means of the 1950–2000 period, referred to here as current or present climate. WorldClim includes data from 751 climate stations for the WA cocoa belt. Of these, 657 stations have precipitation data, 442 stations have mean temperature data, and 120 stations have data on temperature extremes. The database lists values for derived, bioclimatic variables that are often used in ecological niche modeling. These represent averages (e.g., mean annual temperature and precipitation), seasonality (e.g., annual range in temperature and precipitation) and extreme environmental factors (e.g., temperature of the coldest and warmest month, precipitation of the wettest and driest quarters). To these bioclimatic variables provided by WorldClim, we added a set of variables that were specifically intended to reflect the sensitivity of cocoa to drought (Wood and Lass, 2001; Carr and Lockwood, 2011). From the WorldClim information, we calculated for each location the number of consecutive months with < 100 mm of rainfall which is often used to characterize the length of the dry season for cocoa (Wood and Lass, 2001). Furthermore, following the approach taken by Läderach et al. (2013) for modeling climate vulnerability of cocoa in Côte d'Ivoire and Ghana, we added eight variables intended to reflect the response of potential evapotranspiration (ETP) to temperature variation. We estimated ETP with the Hargreaves equation (Hargreaves and Samani, 1985) as described by Läderach et al. (2013).

For the projected future climate, we included in our modeling all 19 global circulation models (GCMs) from the IPCC Fifth Assessment Report (2013) for which projected climate data for a 2050s time horizon had the necessary spatial resolution (see list of GCMs in Schroth et al., 2016). To increase the spatial resolution of the GCM results, we used a statistical downscaling method named the delta method, based on the sum of interpolated anomalies to high-resolution monthly climate surfaces from WorldClim (Hijmans et al., 2005; Ramirez-Villegas and Jarvis, 2010). We downloaded the data from the Climate Change and Food Security (CCAFS) Program's GCM portal (http://www.ccafs-climate.org/) and applied the downscaling method on the 19 GCMs for the intermediate emission scenario RCP 6.0 (Moss et al., 2010; Van Vuuren et al., 2011), and for the 30-year period 2040 to 2069, centered on 2055 and referred to in the following as "2050s".

2.2. Climate suitability prediction for cocoa production

To characterize the relative suitability for cocoa of the projected future climate distribution within the WA cocoa belt, we used two complementary approaches. Firstly, we mapped climate variables that, based on the eco-physiology and agronomy of cocoa in West Africa, are generally considered to be most critical to its climatic suitability (Wood and Lass, 2001; Almeida and Valle, 2007). These included the maximum temperature reached during the year and various variables describing the length and intensity of the dry season, specifically the total rainfall during the year, the number of consecutive months with < 100 mm of rainfall, and the difference between total rainfall and total ETP (indicative of the hydrological water balance) during the driest quarter of the year. We then analyzed where within the WA cocoa belt the respective variables were projected to become less favorable for cocoa in the future (2050s) climate, and whether in any location in

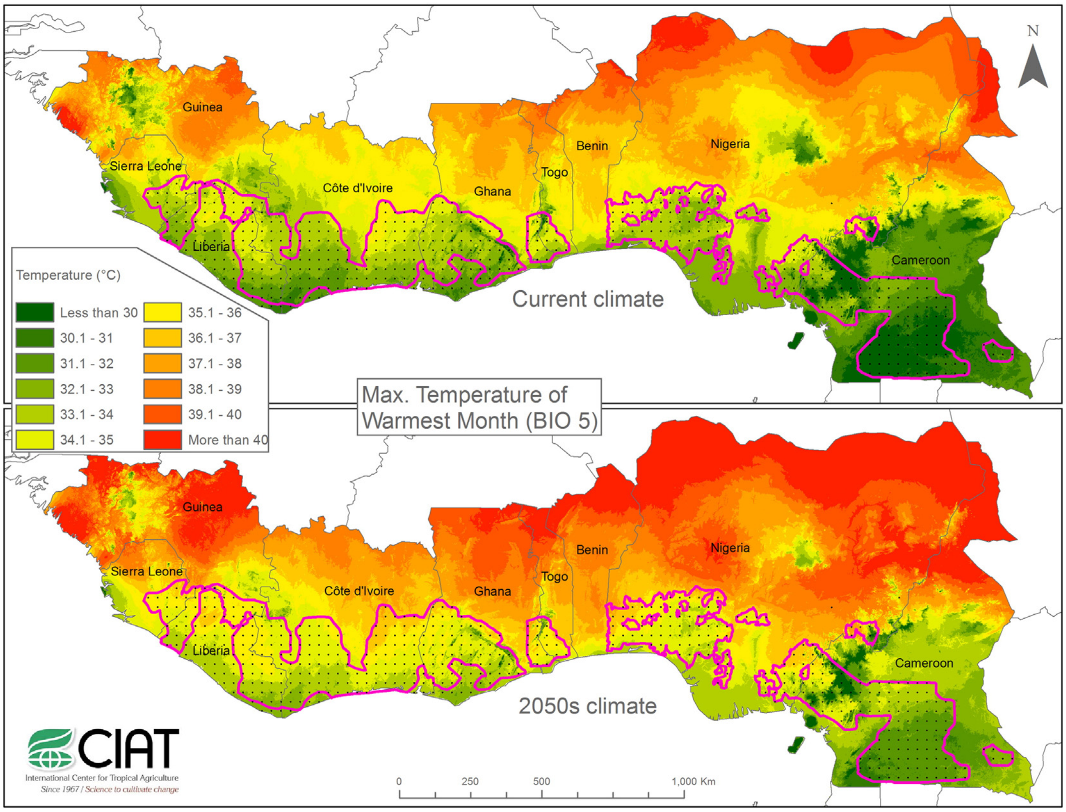

Fig. 1. Maximum temperature of the warmest month under current and projected 2050s climate conditions in the West African cocoa belt. The dotted area shows the extent of current cocoa production as used for model calibration. The red lines show areas of cocoa production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

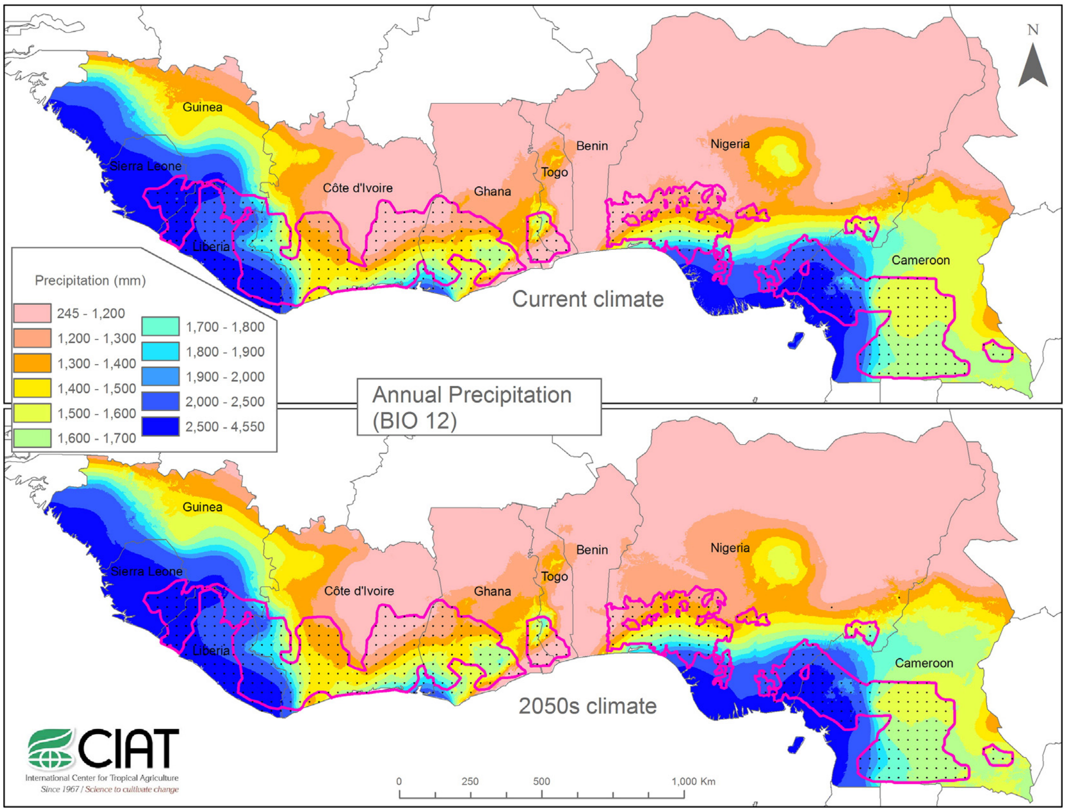

Fig. 2. Total annual precipitation under current and projected 2050s climate conditions in the West African cocoa belt. The dotted area shows the extent of current cocoa production as used for model calibration. The red lines show areas of cocoa production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the cocoa belt the respective variable was projected to reach values that are not currently found anywhere in the cocoa belt and that approached values considered critical for cocoa in the literature (Table 1; FAO, 2007).

This approach of looking at individual, potentially limiting variables might miss interactions among different climate variables (such as temperature and rainfall) that could influence the suitability of a future climate for cocoa. Therefore, in the second approach, we used a spatial, statistical niche model of current and future climatic suitability for cocoa in the WA cocoa belt that integrates a large number of climate variables, as described by Schroth et al. (2016). This model, Maximum entropy (Maxent), incorporates crop-environment interactions through a machine learning approach based on the current climatic conditions in cocoa growing areas (Phillips et al., 2006). The model builds on earlier modeling work on cocoa in West Africa (Läderach et al., 2013) and on other tree crops including coffee elsewhere (Schroth et al., 2009; Bunn et al., 2015; Schroth et al., 2015b). Climatic suitability for cocoa in the context of this analysis refers to the probability (in percent) that cocoa can be successfully farmed at a site, judged from the combined presence of climatic conditions that characterize other known sites of current cocoa cultivation. Not all areas identified by Maxent as climatically suitable actually grow cocoa since some may have unsuitable soil or be occupied by human settlements, protected areas or different crops. For calibrating the climate model, we used the 558 sampling points that had been generated by systematically sampling the cocoa production areas in the WA cocoa belt at a 0.3 degree grid, as explained before. In addition, a random background ("pseudo absence") sample at a 5:1 ratio of background to calibration points was drawn from the area of the countries of the cocoa belt excluding points of known cocoa presence. The climatic conditions at the calibration points of known occurrence and random pseudo absence of cocoa according to the climate surfaces created from the WorldClim data were used to train the Maxent algorithm and estimate the spatial distribution of relative climatic suitability for cocoa.

Similar to the approach based on individual climate variables mentioned before, we analyzed whether anywhere in the cocoa belt projected climatic suitability levels were lower than suitabilities experienced by cocoa in the region now, considering that if this were the case, then these areas would deserve particular attention in terms of adaptation measures or, failing these, might become unsuitable for cocoa. Three measures of model performance and uncertainty of predicted crop suitability were computed: (1) the area under the receiver operating characteristic curve (AUC) as a measure of model skill (Peterson et al., 2008); (2) the coefficient of variation (CV) among the 19 GCMs and (3) the measure of agreement (MA) which is the percentage of the 19 models predicting changes in the same direction as the average of all models at a given location.

3. Results

3.1. Changes in maximum temperatures

In the WA cocoa belt, maximum temperatures during the dry season generally increase from the coastal areas to the interior and are lower in the highlands (Togo, Cameroon) and at the border of the Congo basin (Cameroon) compared to lowland West Africa (Fig. 1, upper part). Most of the cocoa belt has maximum temperatures during the dry season <35 °C with values 35–36 °C at its northern edge near the forest-savanna transition zone. In average years, maximum temperatures >36 °C are restricted to the savanna zone outside the cocoa belt. As a result of the projected global temperature increase, the situation is expected to change substantially by the 2050s (Fig. 1, lower part). With the exception of the few highlands, maximum temperatures in the lower 30s are projected to become restricted to coastal areas as well

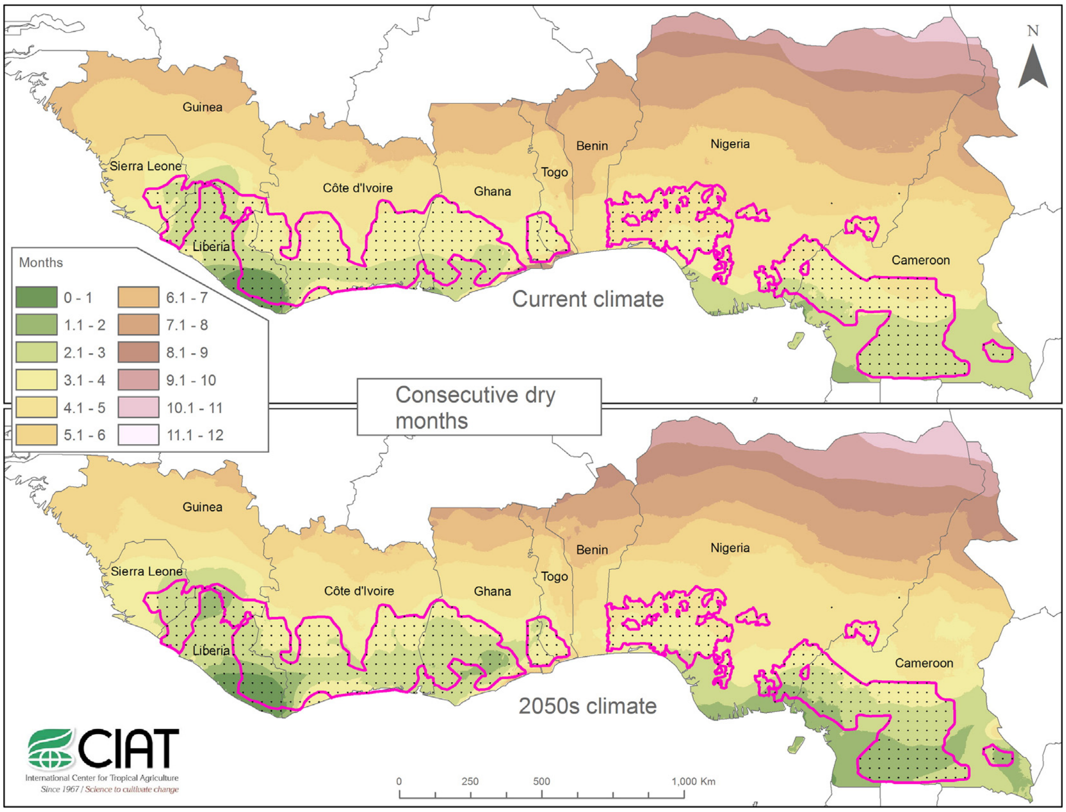

Fig. 3. Consecutive number of months with <100 mm rainfall ("dry months") under current and projected 2050s climate conditions in the West African cocoa belt. The dotted area shows the extent of current cocoa production as used for model calibration. The red lines show areas of cocoa production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

as Cameroon with its more equatorial location. Maximum temperatures in the 34–36 °C range that are typical for the forest-savanna transition zone in the current climate are projected to become common throughout the cocoa belt and in some areas almost reach the coast. Temperatures above 36 °C that are now confined to savanna climates are projected to affect the northern parts of the cocoa belt in Côte d'Ivoire, Togo and Nigeria. By the 2050s, temperatures above 38 °C, the limit tolerated by cocoa according to FAO (2007) (see Table 1), are not projected to be reached in average years within the cocoa belt proper, but very close to its present boundaries especially at the country triangle Guinea/Sierra Leone/Liberia that is influenced by the hot savanna of Guinea, as well as in Togo and Nigeria.

3.2. Changes in rainfall and evapotranspiration

In West Africa, cocoa is grown under a wide range of rainfall conditions. At the low end, with <1200 mm of average annual precipitation, are the northeastern cocoa areas in Côte d'Ivoire and adjacent parts of Ghana as well as areas on either side of the Dahomey gap (Togo and western Nigeria, respectively). At the high end, with >2500 mm of average annual rainfall, are areas around Mount Cameroon and the coastal parts of Liberia (Fig. 2, upper part). On average for the cocoa belt as a whole, the 19 GCMs projected very little change in annual rainfall (+40 mm per year), but with a tendency of increasing rainfall in the drier areas, benefiting the forest-savanna transition and the northern parts of the cocoa belt, and a slight decrease in rainfall in the wet coastal areas of Liberia and Côte d'Ivoire (Fig. 2, lower part).

More important than total annual rainfall for the climatic suitability for a perennial crop like cocoa is, however, rainfall distribution and specifically the length of the dry season (Wood and Lass, 2001). In West Africa, cocoa is now mostly grown in climates that have a maximum of four consecutive dry months, defined as months with <100 mm of rainfall (Fig. 3, upper part). Especially in Ghana and Côte d'Ivoire, the northern limit of the cocoa belt coincides roughly with the line of 4 months of dry season. In Liberia, along the coast, and in southern Cameroon the dry season is shorter with up to three months. The cocoa belt of Nigeria has the longest dry season with up to 5 consecutive dry months. In line with the projected increase in annual rainfall, the climate models project on average a shortening of the dry season by the 2050s in the WA cocoa belt (Fig. 3, lower part). Specifically, the area with up to 3 months of dry season is projected to expand northward in western Ghana, Cameroon and to a lesser extent in Côte d'Ivoire, while a large part of the western Nigerian cocoa belt is projected to acquire a dry season of <4 months in the 2050s (rather than up to 5 months now). Areas with <2 months of dry season, that are now very rare in West Africa except in the south of Liberia, are projected to appear in northern Liberia and southern Ghana and to expand significantly in southern Cameroon.

However, as a result of the overall increasing temperatures, ETP during the dry season is also projected to increase by the 2050s, especially in the increasingly hot savanna north of the cocoa belt, and this counteracts the beneficial effect of the shorter dry season on water availability during the driest months. The difference between rainfall and ETP during the driest quarter as indicator of the dry season water balance is projected to become more negative in the savanna in the 2050s compared to the present climate especially in Guinea, Ghana and Nigeria (Fig. 4). Changes in the cocoa belt itself are projected to be minor, suggesting that the projected increase in rainfall and the shorter dry season largely compensate for increasing dry season ETP. Deteriorations of the dry season water balance are, however, projected for the areas just north of the cocoa belt in Nigeria, Cameroon and eastern Côte d'Ivoire, already the driest parts of the WA cocoa belt (Fig. 3). Here, the risk of

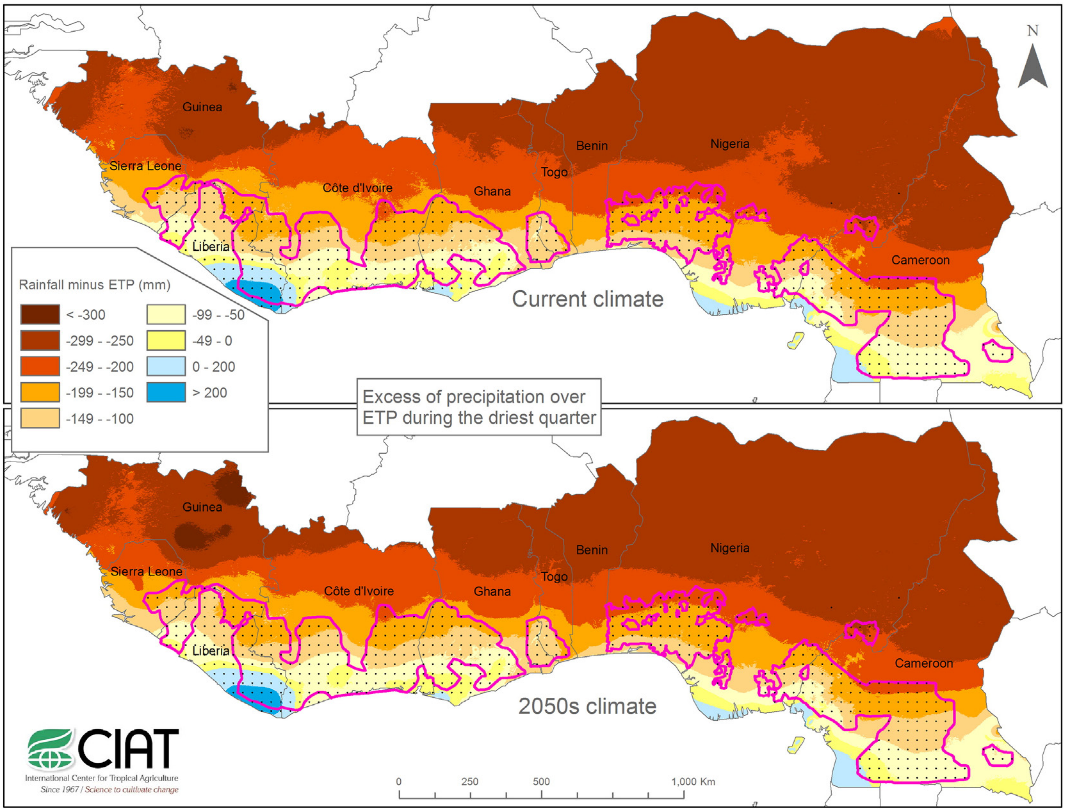

Fig. 4. Difference between total rainfall and potential evapotranspiration (ETP) during the driest quarter of the year under current and projected 2050s climate conditions in the West African cocoa belt. The dotted area shows the extent of current cocoa production as used for model calibration. The red lines show areas of cocoa production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

drought stress is likely to further increase especially in dry years when the belt of savanna climate moves further south into the forest zone.

3.3. Overall climatic suitability

The Maxent model converted the climate data for the WA cocoa belt, calibrated on the climates of current cocoa producing areas, into a mosaic of climatic suitabilities that largely matches the current location of the cocoa belt (Fig. 5, upper part). The modeled cocoa belt appears correctly as two stretches of (former) forest land, a western one reaching from Sierra Leone through Liberia, Côte d'Ivoire and Ghana into western Togo, and an eastern one from western Nigeria to southern Cameroon. Relative climatic suitabilities within the cocoa producing areas are mostly 50% or higher, falling off to lower values as the limits of the current producing areas are passed, e.g. at the transition to the savanna to the north or at the eastern and western margins of the Dahomey gap. Climatic suitability levels of <50% within the cocoa growing areas occur near these transitions but also where the climate is unusually wet for cocoa, such as in southern and coastal Liberia, the southwestern corners of Côte d'Ivoire and Ghana, and southeast Cameroon. These areas produce either small amounts of cocoa or have been included in the cocoa producing area relatively recently (CAAS, 2007; Ruf et al., 2015). Some areas are shown as climatically suitable but not growing cocoa, reflecting unsuitable soils or the prevalence of other crops and land uses.

For the 2050s, the model projects a much stronger separation of the western and eastern sections of the cocoa belt (Fig. 5, middle part). The Dahomey gap centered on Benin of climate conditions not or marginally suitable for cocoa is projected to expand in east-west extension and would reach from eastern Ghana deep into Nigeria, with the climatically suitable part of Togo becoming confined to a small stretch of highland area. Climatic suitability in western Nigeria is also projected to become mostly low, with the hottest and driest northern parts of the current cocoa belt becoming unsuitable for growing cocoa. The southward retraction of the climatically suitable area for cocoa from an increasingly hot savanna is also seen in Côte d'Ivoire, most notably in the east as well as adjacent parts of Ghana. In contrast, the southern part of the cocoa belt of Côte d'Ivoire and most of the Ghanaian cocoa belt are projected to remain highly suitable for cocoa. In the northern part of Liberia, where cocoa and coffee production of that country are concentrated, as well as adjacent parts of Guinea and Sierra Leone, climatic suitability is projected to decline markedly in line with the increase in maximum temperatures, while the more coastal parts of Liberia and Sierra Leone are projected to remain climatically highly suitable. The cocoa belt of Cameroon reaching westward into Nigeria is projected to decrease in suitability in the north in line with the increasing maximum temperatures and deterioration of dry season water balance, but otherwise is projected to maintain mostly high levels of climatic suitability.

As a result of these shifts in climatic suitability, areas of very low climatic suitability (<20%) were projected to increase in all countries of the cocoa belt with the exception of Cameroon, with largest relative increases in Sierra Leone and Togo (Table 2). Areas of intermediate climatic suitability (20–50%) were also projected to increase in all countries, while areas with high climatic suitability (>50%) were projected to decrease in all countries, with the most pronounced decreases in Guinea, Nigeria and Togo. For the WA cocoa belt as a whole, areas with climatic suitability levels >50% were projected to decrease by about half between the present and 2050s climates (Table 2).

Performance of the Maxent model was high, with an AUC value of 0.976 on average of 20 model runs on a scale from 0.5 for a chance model to 1 for a perfect model (Peterson et al., 2008). The coefficient of variation of model predictions was reasonably low with 0.39 on average and almost always below 0.5, with lower values in areas of high suitability and higher values in areas of marginal suitability, especially

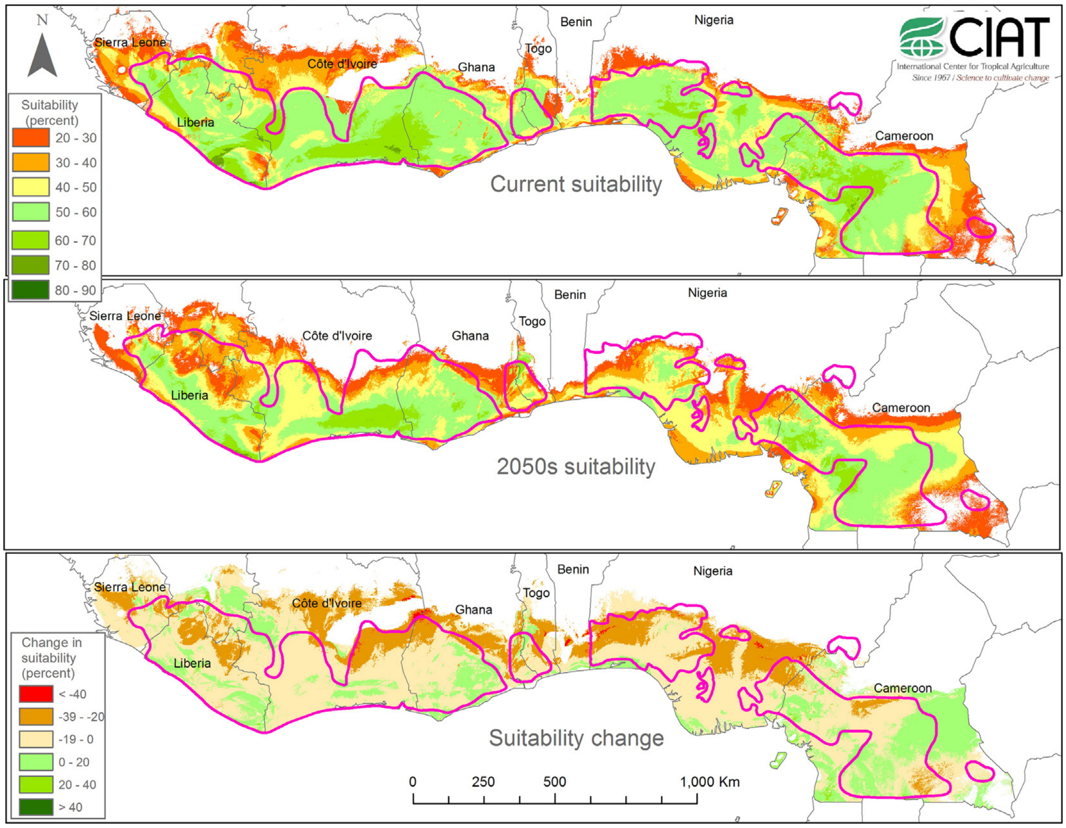

Fig. 5. Relative climatic suitability (in percent) for cocoa of the West Africa cocoa belt under current and projected 2050s climate conditions, as well as suitability change, according to a Maxent model based on 24 climate variables (see Schroth et al., 2016). The red lines show areas of cocoa production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at the northern limits to the savanna (Fig. 6, upper part). On the other hand, the agreement among models with regard to the direction of change in climatic suitability was highest towards the margins of the suitable area (where most or all models predicted negative suitability changes) and lowest in those core areas of current cocoa production where projected suitability changes were small and GCMs differed between slightly negative and slightly positive changes (Fig. 6, lower part).

4. Discussion

4.1. Is heat or drought the greater threat to cocoa?

Under present climatic conditions, it is generally assumed that drought is the greater threat than high temperature to cocoa in West Africa (Carr and Lockwood, 2011). This is because cocoa is successfully grown in climates in southeast Asia (e.g. Malaysia) that are warmer than the West African cocoa belt (Wood and Lass, 2001). On the other hand, cocoa is considered drought sensitive (Carr and Lockwood, 2011) and West Africa has a relatively long dry season compared to other cocoa producing regions, e.g. in southeast Asia or southern Bahia, Brazil (Wood and Lass, 2001). Drought years regularly affect cocoa yields in West Africa and have particularly done so during severe El Niño years of the 1980s (Ruf et al., 2015). In the drier parts of the WA cocoa belt, mortality of cocoa seedlings during the dry season is common (Kassin et al., 2008). Since average temperatures in the cocoa belt, as elsewhere, are projected to increase through global climate change, ETP and thus plant water demand are expected to increase as well and this could lead to increased drought stress of cocoa trees especially during the dry season and in particularly dry (El Niño) years (Läderach et al., 2013). It is thus reasonable to assume that water availability during the dry season will play a key role in determining the future climatic suitability of the WA cocoa belt for cocoa farming (Carr and Lockwood, 2011).

Table 1
Environmental requirements and limits of cocoa (*Theobroma cacao*)[a].

Variable	Optimum or tolerance	Value
Annual mean temperature (°C)	Optimum	22–25
	Tolerance	20–27
Minimum-maximum temperature (°C)	Optimum	21–32
	Tolerance	10–38
Annual precipitation (mm)	Optimum	1200–3000
	Tolerance	900–7600
Number of dry months	Optimum	0
	Tolerance	1–3

[a] Based on FAO (2007).

Contrary to this scenario, we show here that prospects for the cocoa belt with regard to water availability during the dry season are relatively favorable. The expected increase in ETP and thus plant water demand is projected to be compensated for the most part by increased rainfall and a shorter dry season (Fig. 2, Fig. 3). As a result, we find little difference in the balance between rainfall and ETP of the driest quarter between the current and projected 2050s climate for the WA cocoa belt (Fig. 4). Our projection suggests that the length of the dry season and the rainfall-ETP balance during the driest quarter of the year as key indicators of the risk of drought stress will generally remain within the bounds of those values found in the cocoa belt now, with the exception of a certain deterioration of the dry season water balance at the northern edge of the cocoa belt of eastern Côte d'Ivoire, Nigeria and Cameroon. This does not mean that in the 2050s cocoa would not suffer

Table 2
Areas with different climatic suitability levels for cocoa (*Theobroma cacao*) in the current and projected 2050s climates per country in the West African cocoa belt.

	Present climate (in 1000 ha)			Projected 2050s climate (in 1000 ha)			Relative change in area (in percent of present area)		
Suitability	<20%	20–50%	>50%	<20%	20–50%	>50%	<20%	20–50%	>50%
Sierra Leone	0.5	670	846	336	744	437	+71,398	+11	−48
Guinea	32	712	547	79	1174	39	+144	+65	−93
Liberia	27	3080	7014	223	5713	4184	+726	+86	−40
Côte d'Ivoire	111	2425	11,638	994	8164	5016	+800	+237	−57
Ghana	20	1291	7755	192	4270	4604	+858	+231	−41
Togo	1.6	122	777	38	680	183	+2313	+458	−77
Nigeria	908	2045	8707	2422	8091	1147	+167	+296	−87
Cameroon	24	1993	11,111	24	5049	8055	−1	+153	−28
Total	1123	12,337	48,395	4307	33,885	23,664	+283	+175	−51

from seasonal and periodic drought stress in parts of the cocoa belt, but that according to our projection, the drought stress experienced by cocoa in the future climate will differ relatively little from conditions experienced in the cocoa belt now. This does not take the possibility into account that in the meantime more drought tolerant cocoa varieties may be selected and distributed to farmers, reducing the risk of drought stress, although we are not aware of drought tolerant cocoa varieties having yet been identified or created by research in the WA region where genetic diversity of cocoa is relatively small (Zhang and Motilal, 2016). Alternatively, drier-than-average years could become more frequent in West Africa than they are now, possibly increasing the drought risk (Abiodun et al., 2013), although there is currently little information about future changes in the frequency or intensity of extreme climatic events in West Africa (Niang et al., 2014).

On the other hand, we project a substantial increase in maximum temperatures during the dry season in the WA cocoa belt (Fig. 1). In large parts of the area, cocoa would experience maximum temperatures by the 2050s that are currently not experienced within the cocoa belt or only at its seasonally hottest, northern margins. This is especially true for the country triangle Guinea/Sierra Leone/Liberia, for the northeast of the Ivorian cocoa belt, and for parts of the current cocoa areas of Togo and Nigeria. In cocoa, photosynthetic rates decrease once optimum temperatures are exceeded, affecting growth and development (Almeida and Valle, 2007). Although the maximum temperature of 38 °C tolerated by cocoa according to FAO (2007) (see Table 1) is not projected to be reached within the cocoa belt by the 2050s, this applies to an average year and it is possible that temperatures could locally exceed this limit in particularly hot and dry (e.g. El Niño) years (Abiodun

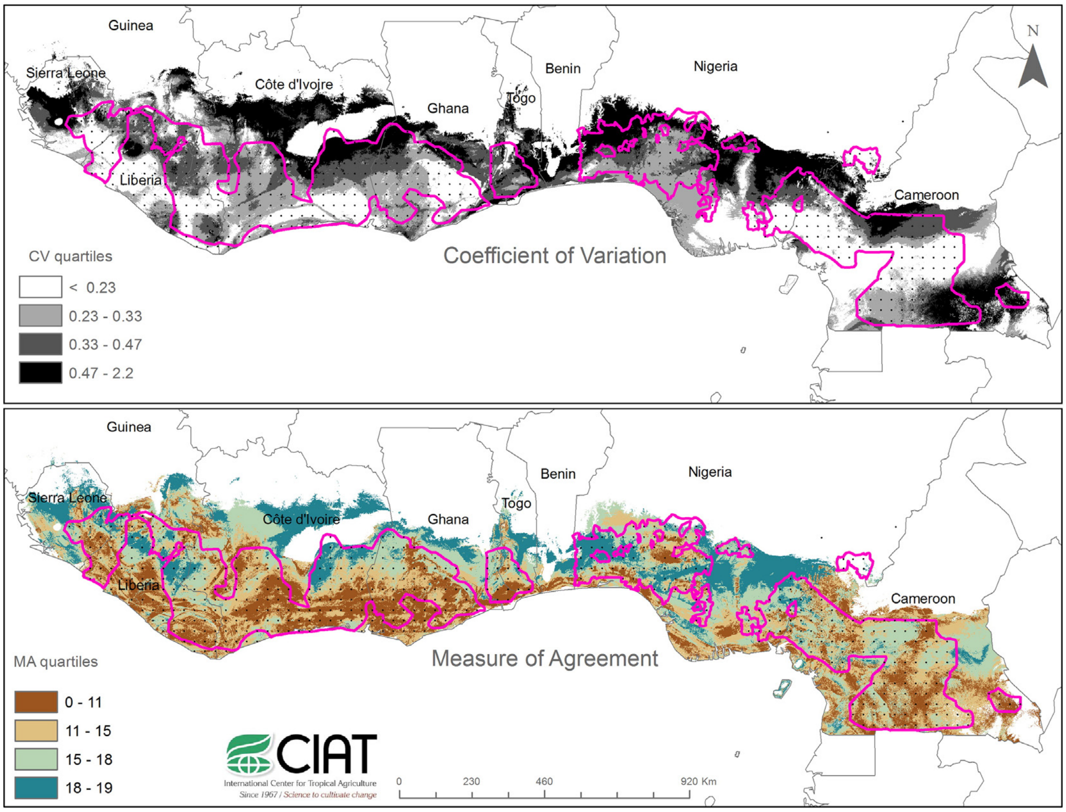

Fig. 6. Coefficient of variation of suitability prediction of the 19 Global Circulation Models (upper part) and measure of agreement expressed as the number of models that predict the same direction of change as the average of all models (lower part) for a Maxent model of relative climatic suitability for cocoa of the West Africa cocoa belt (see Fig. 5). The dotted area shows the extent of current cocoa production as used for model calibration. The red lines show areas of cocoa production.

et al., 2013). We therefore propose that maximum dry season temperatures might become as or more important than water availability for the future climatic suitability for cocoa in West Africa and need to be taken into account in the selection of planting material of cocoa (and eventually also of the shade trees) and the design of climate change resilient production systems.

4.2. Adaptation measures and limits to adaptation

The question whether maximum temperatures or water availability during the dry season will be more limiting to the survival, growth and yield of cocoa (and companion) trees in a future climate is particularly important for the design of climate resilient production systems because an efficient – and the only practical – way of protecting cocoa trees from high temperatures is through overhead shade from appropriately selected, spaced and managed companion trees and certain crops (especially bananas and plantains) in the cocoa farm (Willey, 1975; Lin, 2007). Shading can reduce leaf temperatures of cocoa by up to 4 °C (Almeida and Valle, 2007). Adequate ventilation is also important as a complementary measure, including for reducing fungal disease pressure in cocoa, and requires sufficient spacing and regular pruning of the cocoa trees (Zhang and Motilal, 2016). However, the possibilities for using wind exposure for cooling are limited by the sensitivity of cocoa leaves to wind (Alvim and Alvim, 1980), the fact that in West Africa dry season winds (the *harmattan*) tend to reach the cocoa belt from northeastern directions and are very dry, and also because the wind may not blow when the highest temperatures are reached in the dry season. The potential for normal agronomic practices (such as intercropping and pruning) to protect cocoa from increasing maximum temperatures seems therefore limited, while irrigation is rarely used and may remain too expensive for most cocoa farmers in West Africa (Carr and Lockwood, 2011). The expectation that in parts of the WA cocoa belt maximum temperatures might become a limiting factor for cocoa thus implies that the conventional opinion that cocoa can be grown without shade provided that water and nutrient supply and overall management are adequate (Almeida and Valle, 2007) may no longer hold in West Africa in the future. It leads us to recommend a comprehensive strategy aiming at the maintenance or increase of shade trees in cocoa farms, against the current trend for shade reduction in cocoa farms in several countries of West Africa and elsewhere (Ruf and Schroth, 2004; Ruf, 2011). This recommendation is particularly important for the hotter northern parts of the cocoa belt but also applies as a prophylactic measure and for exceptionally hot years to the coastal areas (Fig. 1). Beside the protection from high temperatures, shade trees in cocoa farms have of course numerous other uses, ranging from economic farm diversification with timber and non-timber products (Schroth and Ruf, 2014; Sonwa et al., 2014), to biological pest control (Schroth et al., 2000; Van Bael et al., 2008), possibly increased pollination of cocoa trees (Young, 1982; Groeneveld et al., 2010), to other local and global ecosystem services such as soil, water and biodiversity conservation and carbon storage (Schroth et al., 2004; Tscharntke et al., 2011; Schroth et al., 2015a).

An expectation of severe and growing water limitation during the dry season, on the other hand, may have led to a different recommendation, because under such conditions there could eventually not be enough water available for both cocoa and shade trees during the dry season and increased drought stress and mortality of the cocoa trees might result (Willey, 1975). For example, the prevalence of little shaded practices in cocoa farming in parts of Nigeria, as opposed to the traditional shade use in cocoa in eastern Ghana, eastern Côte d'Ivoire and especially southern Cameroon (Gockowski and Sonwa, 2011), has been explained with the relatively dry climate and long dry season of that region that discourages the use of shade trees (Wood and Lass, 2001). Willey (1975) also mentions that cocoa farmers in drought prone parts of Ghana do not use shade trees because they feel that these would compete with the cocoa for water during the dry season. Where microclimatic (e.g. wind) protection of tree crops is needed but conditions are too dry to use overhead shade, the use of shelterbelts of trees surrounding plots of tree crops has been recommended (Foster and Wood, 1963; Schroth, 1998), but these would not protect the cocoa trees from high maximum temperatures. The same applies to the use of deciduous shade trees that would drop their leaves during the dry season, at the time when protection against extreme temperatures is most needed. We propose that a point of climatic unsuitability for a tree crop like cocoa would be reached if increasing temperature maxima mandated the association with shade trees, but water scarcity during a long dry season made the use of shade trees unviable. Fortunately, our model data suggest that this situation will not be common in the WA cocoa belt by the 2050s, thanks to the projected local increase in rainfall and shorter duration of the dry season balancing the increase in water demand caused by the higher average temperatures (Fig.2, Fig. 3, Fig. 4).

Another key measure to reduce the vulnerability of farming systems to climate change is their diversification with crops and trees that differ somewhat in their environmental requirements and their sensitivity to environmental shocks (Schroth and Ruf, 2014). A number of studies has shown an ongoing trend towards diversification of tree crop based systems in the tropics including West Africa responding to market and environmental pressures (see volume edited by Ruf and Schroth, 2015). As a measure to reduce the vulnerability of cocoa production systems to climate change, diversification is particularly indicated in areas of decreasing climatic suitability for cocoa farming, notably in the northern parts of the current WA cocoa belt (Fig. 5). Depending on the future climatic trajectory, diversification may merely reduce the dependency of local communities on cocoa as their principal cash crop, or in the most negatively affected areas be a step in the progressive replacement of cocoa based systems by systems based on more heat and drought adapted crops and trees. Even in parts of the cocoa belt where future climate projections are favorable to cocoa growing, a degree of diversification of farming systems is desirable since it reduces the vulnerability of communities to market risks as well as environmental risks not readily captured by climate models, such as non-linear changes in pest and disease pressures (Schroth et al., 2000). Ways how governments and supply chain actors can support diversification decisions by tree crop farmers have been discussed by Schroth and Ruf (2014).

4.3. Regional patterns of change in climatic suitability

Our climate projection for the 2050s suggests that the WA cocoa belt will be more clearly divided into a western and an eastern section, separated not only by the current, narrow Dahomey gap but also by substantial areas of marginal climatic suitability affecting Togo and western Nigeria (Fig. 5; Table 2). Western Nigeria is already among the driest and hottest parts of the WA cocoa belt now, and this situation is projected to further intensify by the 2050s despite the projected slight increase in annual rainfall. The risk of heat and drought stress here is further amplified by the projected very high maximum temperatures and deterioration of the dry season water balance in the savanna just to the north of the cocoa belt from where dry winds blow into the cocoa belt during the dry season (Fig. 1, Fig. 4). Cocoa is grown here traditionally with little shade (Wood and Lass, 2001), and whether farmers will be ready to adopt higher-shade practices in time to prepare for the increasing dry season temperatures is an open question. Among the major cocoa producing countries in West Africa, we consider Nigeria to be the one that is most at risk from climate change. In Togo, on the other hand, cocoa is already confined to a relatively small area of higher elevation in a country dominated by savanna, and with increasing temperatures in the lowlands the area with a suitable climate for cocoa is projected to markedly decrease (Fig. 5; Table 2). Overall, then, it is possible that cocoa production in Nigeria and Togo are going to severely decline over the coming decades.

For the western section of the cocoa belt, our model shows a mixed picture. Although large areas in Ghana and the southern part of the

Ivorian cocoa belt are projected to retain a suitable climate for cocoa farming, overall the suitable area is projected to decrease (Fig. 5; Table 2). This is especially a consequence of the projected decrease in climatic suitability of the northern parts of the cocoa belt in both countries, with the most severe impacts being projected for the northeastern cocoa areas of Côte d'Ivoire. This area, a major hub of cocoa production in the 1960s, has already become marginal for cocoa farming during the second half of the 20th century owing to the region-wide decrease in rainfall (Ruf et al., 2015) and may cease producing cocoa within the next generation of cocoa trees and farmers. Neighboring parts of Ghana and the northwest of the Ivorian cocoa belt are also projected to be affected by declining climatic suitability and their continued ability to produce cocoa may depend on the wide-spread adoption of adaptation measures.

Further to the west, the advance of the hot savanna temperatures towards the forest and cocoa belt is projected to seriously affect the main cocoa producing areas in northern Liberia as well as adjacent parts of Sierra Leone and Guinea, with prospects for the small cocoa area in the latter country looking particularly bleak (Fig. 5; Table 2). However, in view of the relatively high rainfalls and short dry season in this area, the conditions for managing the projected increase in maximum temperatures through the systematic use of shade are particularly good. Cocoa could be grown here in multi-strata agroforests under a canopy of useful trees creating their own microclimate (Schroth and da Mota, 2014), although the control of fungal diseases in the hot and humid microclimate will require particular attention. In addition, climatic conditions are projected to remain favorable for cocoa to expand into more coastal parts of Liberia, where production levels are currently very low (CAAS, 2007).

Overall, we thus predict that climate change will drive a shift of cocoa production within the WA cocoa belt from areas of declining climatic suitability to areas where climatic conditions are likely to remain favorable to cocoa farming through the coming decades and where there is a potential for cocoa farming to intensify and/or to expand. In the western branch of the cocoa belt, these latter areas are located mostly in southwestern Ghana, southern Côte d'Ivoire and Liberia, while in the eastern branch they are located mostly in Cameroon. The progressive shift of cocoa production towards areas of higher climatic suitability has already characterized the development of the Ghanaian and Ivorian cocoa sectors over the past half-century and was related to a large flow of national and international migrants establishing and working on the cocoa farms, and to massive deforestation (Gockowski and Sonwa, 2011; Ruf et al., 2015). With climatic suitability for cocoa projected to decline in various parts of the cocoa belt, a shift in production areas could put additional pressure on the remaining forest resources in areas suitable for production expansion, which might include Liberia and Cameroon with their still relatively large forest reserves. To prevent that cocoa becomes again a major driver of deforestation in the WA cocoa belt, it is therefore paramount that the intensification of existing cocoa farms in areas of continued climatic suitability and their adaptation to climate change is given priority over new planting, and that new cocoa farms are established on previously cleared land where they can contribute to landscape restoration, especially if shaded practices are used. An important question is also whether the projected decrease in suitable area for cocoa farming will be compensated in part by the expansion of cocoa farming further into the Congo basin despite significant political and logistical difficulties and with the risk of causing deforestation there. At the present state, this is difficult to predict and beyond the scope of our study, but is a question in need of research.

5. Conclusions

Previous research has shown that cocoa farming in the world's largest producer countries, Côte d'Ivoire and Ghana, is likely to be negatively affected by future climate change. It has also pointed out the spatially differentiated pattern of these impacts within each country, with the most negative effects to be expected near the forest-savanna transition zones and neutral or positive effects at higher elevation and in the most humid parts of these countries (Läderach et al., 2013). Schroth et al. (2016) expanded this analysis to the entire cocoa belt of West Africa. In the present study we attempt to identify those climate factors that are most likely to become limiting to cocoa farming and that need to be given particular attention when designing adaptation strategies. We suggest that the projected hydrological conditions in the future cocoa belt will not differ greatly from the conditions to which cocoa is subjected in its current production areas because the projected increase in water demand due to higher temperatures will be largely compensated by a shorter dry season. Seasonal drought stress is likely to remain an issue for cocoa farming in West Africa, but is not projected to become more severe a problem than it already is now, with the exception of the northern fringes of the cocoa belt at the transition to the savanna. On the other hand, maximum temperatures during the dry season in the future cocoa belt are projected to resemble those now found only in the savanna and to locally approach the limits of tolerance of cocoa reported in the literature. We suggest that especially in the drier and hotter parts of the cocoa belt, cocoa should be grown under increased shade cover as a protection against high dry season temperatures and that a certain area may become unsuitable for cocoa when high temperatures require the use of shade but a long and intensive dry season does not permit the association of cocoa with shade trees.

We show that the projected impacts of climate change on the cocoa belt will differ within and among countries. The most negative effects are projected for the countries on either side of the Dahomey gap (Togo and Nigeria, respectively) as well as Guinea and the northeastern part of the cocoa belt of Côte d'Ivoire, while changes in most of the cocoa belt of Cameroon and Ghana with the exception of their northern fringes, southern Côte d'Ivoire and Liberia with the exception of its northern counties are projected to be more modest and locally positive. In this lies an opportunity and a threat. The opportunity is to stabilize regional cocoa output as countries with more favorable climate trajectories could gradually take over market space as other countries may be forced to reduce production and switch to crops with different climatic requirements. Such less affected countries or regions which may include Liberia and Cameroon could become “relative winners” of climate change in terms of cocoa production (see Schroth et al., 2015b). The threat is that a shift in cocoa production towards the south, west and east of the current WA cocoa belt could cause a wave of deforestation specifically in Liberia, Cameroon and possibly the Congo basin, unless it is accompanied by effective agricultural and forest conservation policies emphasizing the intensification of existing cocoa farms and channeling future cocoa expansion on already deforested land. A key conclusion of our research is thus that adaptation measures for cocoa in the WA cocoa belt are needed at several levels: at the crop level by selecting cocoa varieties and companion trees and crops that are tolerant to high maximum temperatures in addition to drought and diseases; at the farm level by increasing shade to protect the sensitive cocoa trees against increasing dry season temperatures and to diversify farmers' incomes as a buffer against market and environmental risks; and at the national and regional policy level by implementing agricultural and forest policies that encourage the intensification of existing cocoa farms where climatic conditions permit and the siting of new cocoa plantings on previously deforested land, and that create incentives for farmers to retain and plant native trees in their farms.

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