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Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire

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Abstract Ghana and Côte d'Ivoire are the world's leading cocoa (*Thebroma cacao*) producing countries; together they produce 53 % of the world's cocoa. Cocoa contributes 7.5 % of the Gross Domestic Product (GDP) of Côte d'Ivoire and 3.4 % of that of Ghana and is an important cash crop for the rural population in the forest zones of these countries. If progressive climate change affected the climatic suitability for cocoa in West Africa, this would have implications for global cocoa output as well as the national economies and farmer livelihoods, with potential repercussions for forests and natural habitat as cocoa growing regions expand, shrink or shift. The objective of this paper is to present future climate scenarios for the main cocoa growing regions of Ghana and Côte d'Ivoire and to predict their impact on the relative suitability of these regions for growing cocoa. These analyses are intended to support the respective countries and supply chain actors in developing strategies for reducing the vulnerability of the cocoa sector to climate change. Based on the current distribution of cocoa growing areas and climate change predictions from 19 Global Circulation Models, we predict changes in relative climatic suitability for cocoa for 2050 using an adapted MAXENT model. According to the model, some current cocoa producing areas will become unsuitable (Lagunes and Sud-Comoe in Côte d'Ivoire) requiring crop change, while other areas will require adaptations in agronomic management, and in yet others the climatic suitability for growing cocoa will increase (Kwahu Plateu in Ghana and southwestern Côte d'Ivoire). We recommend the development of site-specific strategies to reduce the vulnerability of cocoa farmers and the sector to future climate change.

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1 Introduction

In the year 2008/2009, world cocoa (*Theobroma cacao*) production was worth approximately nine billion U.S. dollars (ICCO 2008). Ghana and Côte d'Ivoire were the largest producer countries with together 53 % of world production (ICCO 2008). Cocoa contributed 7.5 % to the Gross Domestic Product (GDP) of Côte d'Ivoire and 3.4 % to that of Ghana (FAO 2008). Ghana, besides being the second largest cocoa producer, is also known as the world leader in premium quality volume (as opposed to specialty) cocoa. For Ghanaian cocoa farmers, cocoa contributes 70–100 % to their annual household income (Ntiamoah and Afrane 2008). Over the last 20 years, the poverty rate of cocoa farmers in Ghana declined from 60.1 % in 1991/92 to 23.9 %, or 112,000 households, in 2005/06 (Coulombe and Wodon 2007). Cocoa occupies 2.4 million hectares in Côte d'Ivoire and 1.5 million hectares in Ghana, more than in any other country in the world (Franzen and Borgerhoff 2007).

Cocoa has played a key role in the conservation of forests and their biodiversity in both countries, both negatively and positively. On one hand, cocoa has been an important factor in forest conversion for agriculture (Ruf and Schroth 2004; Asare 2006). On the other hand, shaded cocoa can provide valuable secondary habitat for forest fauna and flora in agricultural landscapes (Ruf and Schroth 2004; Schroth et al. 2011). It is estimated that 50 % of the cocoa farming area is under mild shade in both Ghana and Côte d'Ivoire, while about 10 % and 35 % is managed under no shade in Ghana and Côte d'Ivoire, respectively. Overall, the last decades have seen a decrease in the use of shade in cocoa in West Africa (Ruf and Schroth 2004; Ruf 2011).

Recent research has shown that crops in many parts of the world will be affected by progressive climate change, which will have impacts on food supply (Lobell et al. 2008; Läderach et al. 2010b) and ecosystems likewise (Schroth et al. 2009). Läderach et al. (2010a) have outlined the impact of progressive climate change on coffee (*Coffea* spp.) supply, farmer's livelihoods and environmental services provided by agroforestry systems, including carbon storage and watershed services. Like coffee, cocoa is a crop of major importance for smallholder livelihoods and ecosystems in many tropical countries and is a major export product and income generator for several West African countries. Cocoa is an understory rainforest tree and is known to be sensitive to drought, though quantitative information on crop water relations from mature field-grown plants is scarce (Carr and Lockwood 2011). Until recently, climatic predictions for the West African rainforest belt have been highly uncertain. Brown and Crawford (2009) showed that West Africa in general and the Sahelian region in particular are characterized by some of the most variable climates on the planet. Climate variability seems to have become particularly pronounced in the twentieth century. A period of unusually high rainfall from the 1930s to the 1950s was followed by extended drought for the next three decades (Brown and Crawford 2009). This decrease in average rainfall and their high variability has negatively impacted the region's climatic suitability for cocoa especially during the 1970s and 1980s (Leonard and Oswald 1996). However, the drying pattern has not been homogeneous throughout the region and data from Nigeria suggest that it was relatively more pronounced in the savannah than in the rainforest region where cocoa is grown (Oguntunde et al. 2011). Also (Sheffield et al. 2012) show that Africa and especially Sahelian countries have experienced the greatest increase in drought severity. In the light of global climate change and concerns about its potential impacts on the cocoa belt of West Africa, more detailed studies on future climatic predictions for the rainforest zone and their likely impacts on the cocoa crop are warranted.

The objective of this paper is to present future climate scenarios for the forest zone, the current cocoa belt Läderachof West Africa and to predict resulting changes in the relative climatic suitability of the main cocoa growing regions of Ghana and Côte d'Ivoire. These analyses aim to support farmers and governments in the producer countries as well as the cocoa sector and its supply chain actors more generally in their future strategic decisions. We first present the predicted change in climate for 2050 and then quantify changes in the spatial suitability for cocoa production for Ghana and Côte d'Ivoire using a niche model (MAXENT). We also identify the climatic factors that drive these changes in cocoa suitability. The paper concludes with a brief discussion of options for reducing the vulnerability of the West African cocoa sector to climate change.

2 Methods

2.1 Characterizing the current climate of the cocoa region

As current climate (baseline) we used historical climate data from the WorldClim database (www.worldclim.org; Hijmans et al. 2005). The WorldClim data are generated through interpolation of average monthly climate data from weather stations on a 30 arc-second resolution grid; this is often referred to as "1 km" resolution. The database includes data from 47,554 meteorological stations. The climate data for Ghana are based on 107 stations with precipitation data, 84 stations with mean temperature, and 20 stations with minimum and maximum temperatures. Those for Côte d'Ivoire are from 113 stations with precipitation data, 30 stations with mean temperature and 12 stations with minimum and maximum temperatures. The WorldClim database includes bioclimatic variables that were derived from the monthly temperature and rainfall values to generate more biologically meaningful variables. These are often used in ecological niche modeling (e.g., BIOCLIM, GARP; Hijmans et al. 2005). The bioclimatic variables represent annual averages (e.g., mean annual temperature and precipitation), seasonality (e.g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, precipitation of the wettest and driest quarters[1]). The complete list of derived bioclimatic variables and the minimum, maximum and mean of the two hundred and ninety four evidence locations for each variable used are given in Table S1.

2.2 Characterizing future climate of the cocoa region

A global circulation model (GCM) is a computer-based model that calculates and predicts how climate patterns will be in the future. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) was based on the results of 19 GCMs, data for which are available through an IPCC interface, or directly from the institutions that developed each individual model. The spatial resolution of the GCM results is inappropriate for analyzing the impacts on agriculture as in almost all cases the grid cells measure more than 100 km × 100 km. This is especially a problem in heterogeneous landscapes such as mountain areas and areas with forest-savanna boundaries or mosaics. Downscaling is therefore needed to provide higher-resolution surfaces of expected future climates if the likely impacts of climate change on agriculture and their spatial patterns are to be more accurately predicted.

We used a downscaling method (named delta method), based on the sum of interpolated anomalies to high-resolution monthly climate surfaces from WorldClim (Hijmans, et al. 2005). The method produces a smoothed (interpolated) surface of changes in climates (deltas or anomalies) and then applies this interpolated surface to the baseline climate (from

[1] A quarter is a period of 3 months (1/4 of the year).

WorldClim), taking into account the possible bias due to the difference in baselines. The method assumes that changes in climates are only relevant at coarse scales, and that relationships among variables are maintained towards the future (Ramirez and Jarvis 2010). We downloaded the data from the Earth System Grid (ESG) data portal and applied the downscaling method on 19 GCMs from IPCC (2007) for the emission scenario SRES-A2 (the business as usual scenario of the Special Report on Emission Scenarios) and for a 30 mean centered in 2055. The dataset (SRES scenario – GCM – time slice) comprises four variables at a monthly time-step (mean, maximum, minimum temperature, and total precipitation), on a spatial resolution of 30 arc-seconds (Ramirez and Jarvis 2010) from which the 19 bioclimatic variables (Table S1) were derived.

2.3 Enhanced bioclimatic model including evapotranspiration

Over most of the study area, annual rainfall is predicted to change relatively little over the next several decades, while temperatures are predicted to increase throughout the area (see below). Since some cocoa growing areas, such as Malaysia, already have a warmer climate than West Africa without this having an apparent negative effect on cocoa (Wood and Lass, 2001), we assumed that the temperature increase will have a mostly indirect effect on cocoa by increasing potential evapotranspiration (ETP) and thus influencing water availability to the plants. For ETP to be better reflected in the climate model, we expanded the set of bioclimatic variables including nine additional variables that reflect changes in ETP as a result of the temperature increase (Table S1).

We estimated ETP with the Hargreaves equation (Hargreaves and Samani, 1985):

$$\mathrm{ETP} = 0.0023 \cdot \mathrm{Ra} \cdot (\mathrm{T} - \mathrm{t})^{0.5} \cdot (\mathrm{tm} + 17.8)\mathrm{mm/day}$$

ETP	evapotranspiration in mm/day
Ra	extraterrestrial solar radiation expressed in water equivalent (mm/day)
T-t	difference between monthly maximum and minimum mean temperature (°C)
tm	mean air temperature (°C)

The Hargreaves method has been used to estimate water requirements in crop modeling (Kra and Ofosu-Anim 2010). It requires less data than the well-known Penman-Monteith method (Allen et al. 1998) while the results of the two methods are closely correlated (Hargreaves and Allen 2003). A recent study in Ghana produced similar results with both methods (Asare et al. 2011).

To generate an ETP layer for the study area we computed the monthly difference between mean maximum and minimum temperature using the WorldClim bioclimatic variables. Solar radiation was estimated for each month using the “shortwavc.aml” algorithm (Kumar et al., 1997) which requires as input a Digital Elevation Model (DEM) (Reuter et al. 2007), the location and the period of time. The output is given in kJ m^{-2} $month^{-1}$, which we converted into water equivalents in mm day^{-1}, considering that 1 mm day^{-1}=2.45 MJ m^{-2} day^{-1} (Allen et al. 1998). We used the daily ETP values as input for the Hargreaves equation with a GIS script to obtain the monthly ETP for current and future climate conditions.

The monthly ETP averages were then used to calculate meaningful bioclimatic variables (Table S1). We applied the same concept of annual trends and extreme or limiting environmental factors as used for the temperature and precipitation related bioclimatic variables explained above (Hijmans et al. 2005). With the nine additional ETP variables we ended up with 28 variables for the crop suitability modeling.

2.4 Crop suitability prediction

Ideally, a physiological model of the cocoa tree that accurately predicts the tree's response to environmental change considering the complexity of its interactions with a highly variable amount and kind of shade trees that modify the crop's microclimate and soil water content would have been used to predict the future impacts of a changing climate on cocoa farming. Physiological models such as DSSAT (Jones et al. 2003) and CropSyst (Stöckle et al. 1992) are widely used in annual crops, and significant progress has been made with the development of a physiological model for coffee (CAF2007; Van Oijen et al. 2010) that however requires a large set of input data for its calibration. No suitable model of this kind is available for the cocoa tree. We therefore use a niche model, MAXENT, that incorporates crop-environment interactions through a multiple regression approach based on the current climatic conditions in cocoa growing areas, then changes the climatic conditions according to climate change predictions and calculates relative impacts on the crop in a spatially explicit manner. The model assumes that a certain future climate at a given site is as suitable or unsuitable for the crop as is the same climate at another site in the present. This assumption is reasonable as long as crop genetics and cropping systems do not significantly change. It thus predicts what will happen in terms of relative climatic suitability for a crop if these factors do not change and helps identify those sites where adaptations in crops and cropping systems are necessary in order to avoid the consequences of a predicted decline in climatic suitability. This approach has previously been used with other tree crops including coffee (Läderach et al. 2010a; Schroth et al. 2009).

Maximum entropy (MAXENT) is a general-purpose method for making predictions or inferences from incomplete information. Similar to logistic regression, MAXENT weighs each environmental variable by a constant. The probability distribution is the sum of each weighted variable divided by a scaling constant to ensure that the probability value ranges from 0 to 1. The algorithm starts with a uniform probability distribution and iteratively alters one weight at a time to maximize the likelihood of reaching the optimum probability distribution. MAXENT is generally considered to be among the most accurate models for this task (Elith and Graham 2009).

For the future crop suitability predictions we required data for the current distribution of cocoa. These were compiled from existing databases, maps, expert knowledge and field missions where coordinates were gathered using a Global Positioning System (GPS). In addition, the literature was reviewed to identify main growing areas for cocoa. For some areas the collected data were insufficient to determine the spatial distribution of the growing areas and we used land cover and potential land use maps based on soil characteristics (Dabin et al. 1960) to identify current cocoa growing areas. Two hundred and thirty-five data points of cocoa farm locations were collected during a field mission using GPS. Fifty-nine additional points were identified from potential land use maps by overlaying the layers of land cover and potential land use including the indications of expert knowledge in the area. In total, two hundred and ninety-four data points were used for the analysis (Figure S1). Initial trial runs of the prediction of current cocoa extension were validated with experts and the model was rerun. The results were then discussed in a cocoa expert meeting in Accra, Ghana, with 14 representatives of the cocoa sector and supply chain. Feedback on current cocoa distribution was included in the final distribution maps.

Climatic suitability for cocoa in the context of this analysis refers to the probability (in percent) that cocoa grows well, judged from the combined presence of favorable climatic variables. Not all areas identified by MAXENT as climatically suitable actually grow cocoa since some may be occupied by human settlements, protected areas or different crops. Climate suitability is therefore the level of presence of certain climatic characteristics that permit successful cocoa growing, as deducted from the range of climatic conditions in those locations where cocoa is currently found in the countries under study. The climatic characteristics used here are the 19 bioclimatic variables listed in Table 1.

2.5 Environmental factors driving climatic suitability

To understand the relative influence of different climatic drivers on changes in relative climatic suitability for cocoa, we carried out a forward step-wise regression analysis with the suitability shift per data point as the dependent variable and the model-average changes in the bioclimatic variables between the present and future as the independent variables. The relative contribution of each variable to the total predicted suitability shift in terms of the proportion of R-square explained when adding each variable to the linear regression model was calculated. This analysis was carried out separately for the data points showing positive and negative shifts in suitability.

2.6 Uncertainty and model validation

Two measurements of uncertainty of predicted crop suitability were computed: (1) The coefficient of variation (CV) among GCM models and (2) the percentage of the 19 models predicting changes in the same direction as the average of all models at a given location. The agreement among models was also tested with Tukey's (1977) outlier test. These tests did not detect any strongly diverging GCM models, therefore all 19 models were included in the final analysis.

3 Results

3.1 Climate predictions

Under the IPCC's (2007) A2 (business as usual) scenario, the average rainfall in the cocoa belt of Ghana and Côte d'Ivoire is predicted to decrease only insignificantly from 1467 mm now to 1455 mm in 2050, with most of the change occurring after 2030 (Figure S1). In 2030

Table 1 Contribution of different bioclimatic variables to the predicted shift in suitability for cocoa in Ghana and Côte d'Ivoire

All Bios+ETP

Variable	Adjusted R2	R2 due to variable	% of total variability	Present mean	Change by 2050s
Locations with decreasing suitability (n=263, 89.5 % of all observations)					
ETP9=ETP of coldest quarter	0.13	0.13	41.1	256 mm	12 mm
Bio7=Temperature annual range (Bio5 – Bi06)	0.23	0.05	17.2	12.4 ° C	0.7 °C
Others			41.7		
Locations with increasing suitability (n=31, 10.5 % of all observations)					
Bio15=Precipitation seasonality (coefficient of variation)	0.5	0.5	89.3	55	1.9
Others			10.7		

(data not shown), the precipitation is predicted to decrease by a range of 7 – 20 mm in most parts of Côte d'Ivoire and to increase by a range of 5 –21 mm in southern Ghana (coastal regions). Thus, southern Ghana will initially become slightly wetter, before a weak drying tendency will prevail throughout most of the cocoa region (Figure S1). In 2050, the earliest and strongest decrease in precipitation will be seen in the west of the region, with decreases ranging from 20 mm to 39 mm in Bafing, Worodougou, Valle du Bandama and Zanzan in Côte d'Ivoire, then gradually expanding to Brong Ahafo in Ghana. In Ghana, the coastal region, outside of the core area of cocoa production, is predicted to experience an increase in precipitation by 20–30 mm. The maximum number of cumulative dry months, defined as the maximum number of months with less than 100 mm precipitation, is predicted to decrease from 4 months now to 3 months in 2050 (Figure S1).

Mean annual temperature is predicted to increase by 2.1 °C on average by 2050 passing through a 1.2 °C increase in 2030 (Figure S1). The predicted increase in temperature by 2050 is between 1.7 and 2.1 °C for the southern (forest) regions and up to 2.5 °C for the northern (savanna) regions in both countries. The mean daily temperature range is predicted to remain almost constant with 9.1 °C now and 9 °C in 2050. The coefficient of variation among models is 3 % for temperature and 7.5 % for precipitation.

3.2 Crop suitability predictions

The performance of the MAXENT model was generally high, with AUC (kappa) values ranging between 0.990 (0.907) and 0.999 (0.979) for the test data (20 %), and almost no variation for the train data (80 %), resulting in relatively low levels of uncertainty for the spatial predictions (see Figures. S2 and S3 in the supplementary materials).

The MAXENT analysis shows a broad belt of suitable cocoa climates across the rainforest zone of Ghana and Côte d'Ivoire. This belt is bordered by zones of less suitable climates forming the transition to the savanna in the north of both countries and the coastal savanna in Ghana and an adjacent area in Côte d'Ivoire, that are currently marginally or not suitable for cocoa. According to the analysis, the climatically most suitable cocoa areas in Ghana are mainly in the Eastern, Central, Ashanti, Western and southern Brong Ahafo regions, while in Côte d'Ivoire they are mainly in Sud-Comoe, Agneby, Moyen Comoe, Sud-Bandama and Fromager regions (Fig. 1).

For 2050 the model predicts an overall decrease in the climatic suitability of the current growing regions. This would be expected considering the temperature mediated increase in evapotranspiration not compensated by increasing rainfall, increasing the risk of drought to which cocoa is very susceptible (Anim-Kwapong and Frimpong 2005). The coefficient of variance (CV) for the 2050 bioclimatic variables ranged from 0 to 25 % suggesting reasonable agreement among climate models (Fig. 1). Most affected by the suitability decrease are the southern Brong Ahafo and Volta Regions in Ghana, and Lagunes, Moyen Cavally, Marahoue and Haut Sassandra in Côte d'Ivoire (Fig. 1). Parts of these areas will become marginal or even unsuitable for cocoa, while other parts will remain suitable though less so than they are today (Fig. 1). The Western Region of Ghana, currently the country's most important cocoa producing region, is predicted to suffer a reduction in climatic suitability over most of its area and especially in the south, while the currently most important cocoa region of Côte d'Ivoire, Bas Sassandra, is predicted to become climatically more suitable over most of its area (Fig. 1). All other things being equal, this might lead to a shift in relative production between the two countries at the favor of Côte d'Ivoire, already the larger producer now.

Apart from the southern parts of Bas Sassandra in Côte d'Ivoire and some marginal areas in the southern part of the Western Region in Ghana, there are only few areas where the model

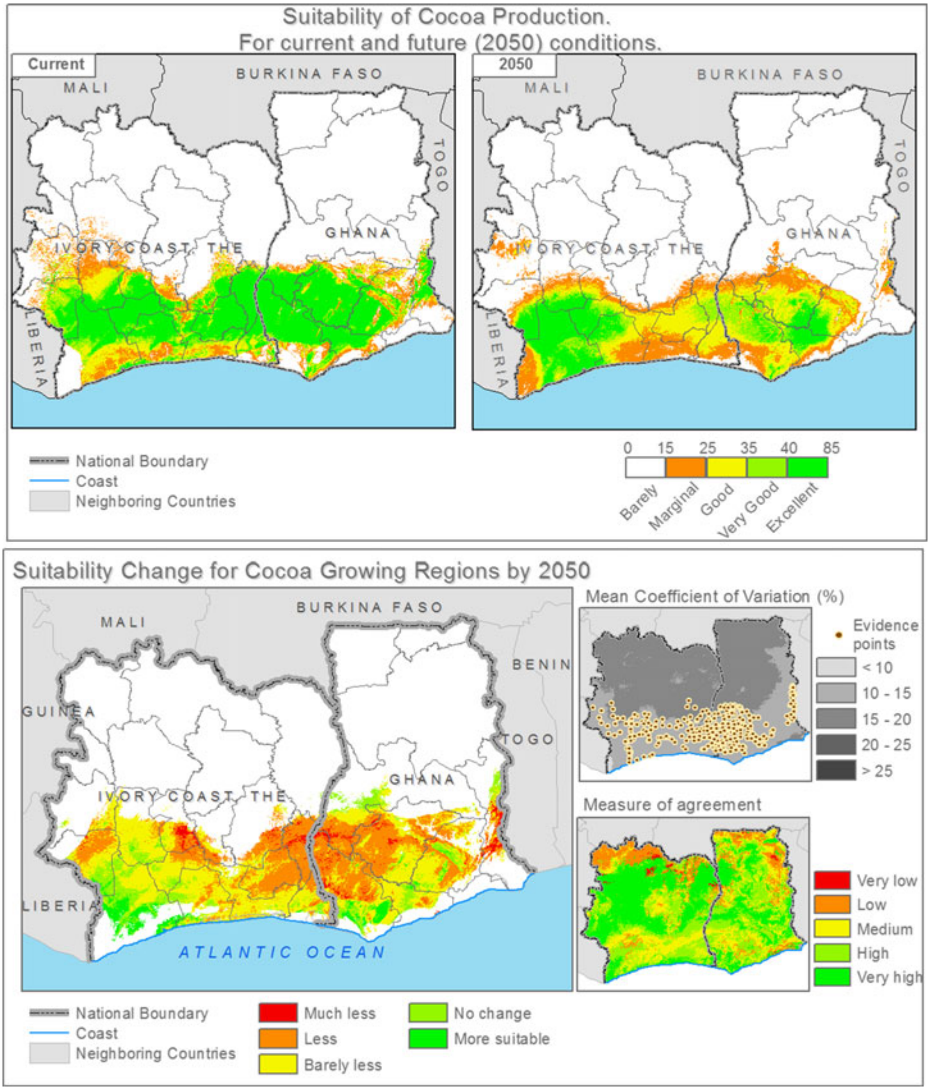

Fig. 1 Current and future climatic suitability for cocoa production within cocoa-growing regions of Ghana and Côte d'Ivoire. Suitability change for cocoa growing-regions by 2050 and measurements of agreement and Coefficient of Variation of results. The used evidence points are compared to the CV map

predicts improving climatic conditions for growing cocoa. These are generally in hilly terrain, such as the Mampongtin Range and Atewa Hills (also called the Kwahu Plateau) in Ghana, and hilly parts of Western Côte d'Ivoire and reflect the increase in average temperature by up to 2 °C (Figure S4). Cocoa cultivation has been introduced in the west part of the Kwahu Plateau, however the Atewa hills is a forest reserve where cocoa cultivation is not permitted.

Compared to now, areas at altitudes up to about 400 m above sea level (masl) will suffer a decrease in suitability as a result of the general temperature increase and consequent increase in evaporation (Figure S4). This includes the currently optimum growing areas at altitudes of 100–250 masl. Areas above 400–450 masl are predicted to benefit from the temperature increase and become more suitable for growing cocoa, but this applies to only very limited areas in the two countries and cannot compensate for the suitability decrease in the lowlands.

3.3 Climatic variables driving change in suitability

Of the 294 spatial data points used in the suitability model, 89.5 % showed decreasing and 10.5 % showed increasing climatic suitability for cocoa by 2050 (Table 1). Negative suitability changes were mostly driven by the increase in potential evapotranspiration (ETP), especially during July to September (the coldest quarter, which includes the short dry season), possibly because of the sensitivity of pod growth during this phase to drought. This was followed in statistical significance by a variable related to temperature increase, which is also the driver of increased ETP. For the relatively few data points that showed increasing climatic suitability, this increase was most highly correlated with an increase in the seasonality of the climate (measured as the coefficient of variation of monthly rainfall within a given year). These areas are mostly in the wettest, southwestern corners of the two countries were an increase in seasonality of rainfall may be beneficial for the cocoa crop (Table 1).

4 Discussion

4.1 Adaptation of the climate model to cocoa eco-physiology

An initial analysis of the impact of climate change on cocoa production in West Africa (Läderach et al. 2011) suggested a relatively drastic decrease of climatic suitability for cocoa of current growing areas. This was a consequence of the general increase in temperature that was "interpreted" by the statistical model as making the future climate more similar to the current climate of the (hotter and drier) savanna zone in the northern part of the two countries, where currently little or no cocoa is grown. The reason why cocoa is not usually grown in the savanna is mostly because it is drier, not because it is hotter than the rainforest zone; the rainforest zone of Malaysia, which is about 2 °C hotter than that of West Africa, is very suitable for growing cocoa (Wood and Lass, 2001). Similarly, the expected temperature increase of the next several decades, with little change in rainfall, will presumably affect cocoa not so much directly via heat stress as indirectly via the increase in ETP and thus decrease in water availability to the crop (Anim-Kwapong and Frimpong 2005; Carr and Lockwood 2011). In this sense cocoa is different, for example, from Arabica coffee where there is a direct temperature effect because coffee quality, and thus its price, is highly sensitive to ambient temperature (Läderach et al. 2010a, b).

As explained in the Methods section, for the present study the effect of a temperature-mediated increase in ETP was included in the improved climate suitability model through nine additional bioclimatic variables (Table S1). Inclusion of temperature driven changes in ETP in the model "softens" this temperature effect (both the negative effect in the lowlands and the positive effect in the highlands) by placing greater emphasis on the water cycle and its impact on the cocoa plant (Fig. 1), which is more consistent with cocoa eco-physiology (Anim-Kwapong and Frimpong 2005). Test runs where the temperature related bioclimatic variables were removed and the model was run only with the precipitation and ETP related variables gave very similar results to the one with the temperature related variables included, which was retained for the final results (data not shown).

That a temperature driven increase in ETP reduces climatic suitability for a drought sensitive crop such as cocoa, especially in a region that is already relatively dry compared to other major cocoa growing areas of the world (Wood and Lass, 2001), is consistent with expectation. Some authors have reported that a temperature increase of 3 °C implies an increase of ETP by 17 % (Martin et al., 1989; Rosenberg et al., 1989). The effect of increased ETP on cocoa should be strongest in those areas that are already at the drier margins of the climatically suitable area, that is, in the transition zone to the savanna, while areas with a very wet climate, such as the southwest corner of Côte d'Ivoire, could actually benefit, which is what the model shows (Fig. 1).

4.2 Preparing for climate change

Although according to our analysis the climatic suitability of the West African rainforest belt, where most of the world's cocoa is now grown, for growing cocoa in the future will not decline as drastically as feared earlier (Läderach et al. 2011), predictions continue to suggest an overall drying of the climate through a temperature driven increase in evaporative demand that will not be compensated by a change in rainfall and not fully by a slightly more favorable rainfall distribution. Lowland areas at the margins of the current cocoa growing zone, including areas near the transition to the northern and coastal savannas, will be most affected by the drying, while only very limited areas at higher elevation will benefit from temperature increase and some areas in the very wet southwestern corner of Côte d'Ivoire will benefit from an increase in evaporation. Overall the area of favorable climatic conditions for growing cocoa in the two countries will likely shrink (Fig. 1).

These changes in climatic suitability are predicted to take place over a time period of almost 40 years, so they will mostly impact the next rather than the current generation of cocoa trees and farmers. In other words, there is time for adaptation. Decreasing climatic suitability will most likely be perceived by farmers as more frequent or severe drought years, possibly accompanied by bush fires as in the El Niño year 1983 (F. Ruf, personal communication), rather than as a gradual decline of average climate. Thus, adaptation demand may come in waves for which government and private stakeholders should be prepared. Failure to adapt in time to the risk of decreasing yields of the main crop and income earner of millions of farmers in the forest zone may lead to an increased exodus of rural populations overflowing the cities, and possibly increased conflicts over land in the southwest of Côte d'Ivoire, already a major cocoa producing area and one of the very few areas in the region where climatic conditions are predicted to become more suitable.

Among the priority measures to reduce the vulnerability of the West African cocoa sector to climate change is the initiation of breeding programs for greater drought resistance (Carr and Lockwood 2011). For being effective, these need to be combined with programs to put selected germplasm in the hands of the cocoa farmers, who still commonly use local seeds for planting. Such programs may initially focus on the northern and eastern fringes of the cocoa belt, where the demand for drought resistant varieties should already be greatest and increase fastest in the future (Fig. 1). Irrigation technology might be an option in some places, but considering its cost is unlikely to be adopted by large numbers of family farmers in West Africa (Carr and Lockwood 2011).

Especially where climatic conditions are predicted to become poor to marginal, but also throughout the rest of the cocoa region, farmers should be encouraged to diversify their farming systems to depend less exclusively on cocoa and have options ready to switch to if and when conditions become unfavorable for their traditional main crop. In many parts of the West African cocoa belt, there is already an active process of crop diversification where farmers complement (and in some cases replace) their traditional "pioneer crop", cocoa, that they often planted as first crop after forest clearing, with other tree crops such as rubber, oil palm or citrus (Ruf and Schroth 2013). This diversification can be seen as an adaptation to market and environmental conditions, including a certain environmental degradation that often goes along with the gradual change from a forest environment to the environment of established agricultural landscapes with their drier microclimate, more degraded soils, and higher weed, pest and disease pressure (Ruf and Schroth 2013). This diversification process is not necessarily a response to global climate change now, but it could easily be turned (or turn itself) into one in the future. As farmers cultivate a broader range of crops (say, cocoa and rubber rather than just cocoa), they will observe themselves which of these do better in more years and gradually shift their emphasis on those, without necessarily abandoning their old crops. This diversification process reduces market and environmental risks and empowers farmers to make their own adaptation decisions. It should be encouraged by providing access to planting material, finance and technical support (Anim-Kwapong and Frimpong 2005; Ruf and Schroth 2013), rather than be seen as a threat to the cocoa sector, focusing limited resources initially on those parts of the cocoa belt where climatic conditions will become marginal.

A third way for cocoa farmers to adapt to a drier climate is through a change in management practices. One possibility to do so would be to plant the cocoa trees at wider spacing to reduce their water needs per unit area, although this may also imply a greater effort for weed control as well as, initially, lower per-hectare yields. Furthermore, across West Africa, a significant number of farmers still grow cocoa under more or less dense shade of forest trees (Ruf and Schroth 2004), although many now prefer light or no shade for their cocoa plantations (Ruf 2011). While shading protects cocoa trees from direct sun light and increasing temperatures, the shade trees can also compete with understory trees for water. As the evaporative demand increases in a warmer environment, there will be less water available to support both cocoa and shade trees through the dry season. Where the hydrological conditions become increasingly marginal for cocoa, farmers may choose deciduous shade trees that consume less water (but also provide less protection) during the dry season, and replace large forest remnant trees with smaller, planted trees, including species that are locally known for low competitiveness. They may also choose to plant trees more in shelterbelts as a protection against drying winds rather than as overhead shade, as is common in dry environments. In general, however, it must be said that the interactions between shade and understory trees in water limited environments are still poorly understood and require more research under “real world” conditions, especially in mature plantations, to support farmer decisions (Carr and Lockwood 2011; Tscharntke et al. 2011).

5 Conclusions

According to Global Circulation Models accepted by the UNFCCC, the yearly and monthly minimum and maximum temperatures in the cocoa-growing regions of Ghana and Côte d’Ivoire will increase progressively through 2050 by up to 2.0 °C, while changes in yearly and monthly precipitation will be small. Increased temperature will drive an increase in potential evapotranspiration that is not compensated by a change in rainfall and only partly by a slightly more favorable rainfall distribution with a shorter dry season.

Our refined statistical crop suitability model predicts that, as a consequence of the drier climate, the overall climatic suitability of the current cocoa growing zone in the two countries will decrease, though not as drastically as predicted by an earlier model. Also, the suitable area will shrink, with especially areas bordering the savannas in the north and south of the current forest belt becoming marginal. Climatic suitability for cocoa will increase in some higher elevation areas, such as the Kwahu Plateau of Ghana, as a consequence of the temperature increase, but these areas are of very limited extent. More significantly, the climatic suitability is also predicted to increase in the southwest of Côte d'Ivoire, already a major producing area, where the predicted increase in evaporation would make a very wet climate more suitable for the crop and especially its post-harvest processing and conservation.

These changes will be gradual and leave time for adaptation, though not for complacency. Important measures to reduce the vulnerability of the West African cocoa sector to climate change include the breeding of more drought resistant cocoa varieties and their distribution to farmers; support to farmer strategies of crop diversification that are already ongoing in many parts of the cocoa belt; and applied research into management practices to make farms more resilient to increasingly severe and frequent dry spells that will accompany the general drying of the climate.

Our results do not show disaster in the making. There is no reason for farmers and governments of West African countries, that equally depend on cocoa income, to panic. Changes in the climatic suitability for growing cocoa will happen, but this will be a slow and gradual process, and it will not affect all parts of the cocoa belt equally. This is an important message to communicate to farmers and other stakeholders, many of whom have heard and are concerned about climate change. Perhaps our most important message is that climate change requires a spatially differentiated communication and engagement strategy. It is through this engagement with farmers and local stakeholders that priority adaptation measures will most clearly emerge.

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