Chapter 10

The impacts of climate change on crop yields in West Africa

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Introduction

Climate has a very strong influence on farming, which is considered to be the human activity that is most dependent on climate variations (Oram, 1989; Hansen, 2002). The impacts of climate on agriculture vary from one part of the world to another, with particularly marked socioeconomic consequences in developing countries in the tropics. Indeed, these countries experience great climatic variability, such as the monsoon regime in India and West Africa and the influence on the American continent of El Niño events (Challinor *et al*., 2003). In many cases endemic poverty increases the risk and seriousness of natural catastrophes (UNPD, 2004).

The rural populations of sub-Saharan Africa are particularly exposed to climatic events as they are closely dependent on rainfed agriculture, practiced on nearly 93% of cultivated land. It is reminded that 80% of the cereals eaten in sub-Saharan Africa are produced by this traditional farming and that the farming sector employs 70% of the total force (FAO, 2003) and forms 15 to 20% of GDP. In addition to this dependence, the rapid growth of the population and its poverty prevents access to technological adaptation (mechanisation, fertilisers, irrigation) and are factors that aggravate the socioeconomic effects of the climate (UNDP, 2004). Indeed, the limited means of rainfed agriculture for anticipating and correcting the effects of climate fluctuations is illustrated clearly by the strong correlation between agricultural productivity and rainfall, with consequences for food security. Since the 1970s, the most serious famines that required international food aid (1974, 1984-1985, 1992 and 2002) were caused entirely or partly by climate variations (Dilley *et al*., 2005).

This being so, *being able have better understanding and anticipation of climate fluctuations and their consequences for agriculture* is a major issue for development and food security in sub-Saharan Africa.

If sub-Saharan Africa frequently faces food insecurity today, what is going to happen in the future? A retrospective look at the movement in recent years gives a fairly pessimistic view of the future. Indeed, in spite of an increase in food production, very strong population growth has caused an increase in the poverty rate and malnutrition in Africa that is faster than anywhere else in the world, with a lower index of agricultural production per person than in other continents. According to COLLOMB (1999), taking into account requirement projections for 2050, when the United Nations considers that the world population will peak, extremely great efforts must be made to increase food production: that in Africa should increase more than fivefold between 2000 and 2050! The future of this region thus depends on the ability of the farming sector to meet the challenge of feeding a rapidly growing population. Succeeding this will be all the more difficult as climate change is now an ongoing phenomenon and will certainly have consequences for agriculture in Africa as elsewhere. The fourth and fifth Assessment Reports (AR4 and AR5) of the IPCC (Intergovernmental Panel on Climate Change) published in 2007 and 2014 respectively, have alerted the international community about an increase in temperature everywhere in the world and a probably increase in the frequency and intensity of major meteorological events such as droughts, with Africa mentioned as being the continent most vulnerable to changes in climate (IPCC, 2014). There is no doubt that a change in rainfall intensity and/or regime will affect the crop farming and pastoral systems in sub-Saharan Africa (CGIAR, 2009). Irrigated farming, like rice growing which plays an important role in feeding the urban population in Africa, will also be affected—not only because of a possible change in the availability of water but because of the rise in temperature that can lead to substantial decreases in yields (DINGKUHN, 1995; DINGKUHN and MIEZAN, 1995; DINGKUHN *et al*., 1995). It therefore seems crucial to be able *to provide a more accurate image of the expected evolution of agricultural production potential in sub-Saharan Africa in the context of warming of the climate.* However, the task is still difficult because of the strong uncertainty in regional climate change projections, in the response of plants to environmental changes (rainfall, temperature, atmospheric CO_2 concentration), in the linking of agronomic and climatic models and in the way farming systems will adapt gradually to environmental changes (CHALLINOR *et al*., 2007). The aim here is 1) to draw up an objective appraisal of the literature on the effects of climate change on agriculture in West African and 2) to understand the determinants of this response.

Drafting future yield scenarios

The literature on the impacts of climate change on agriculture in Africa and elsewhere in the world displays characteristic methodology described in Figure 1.

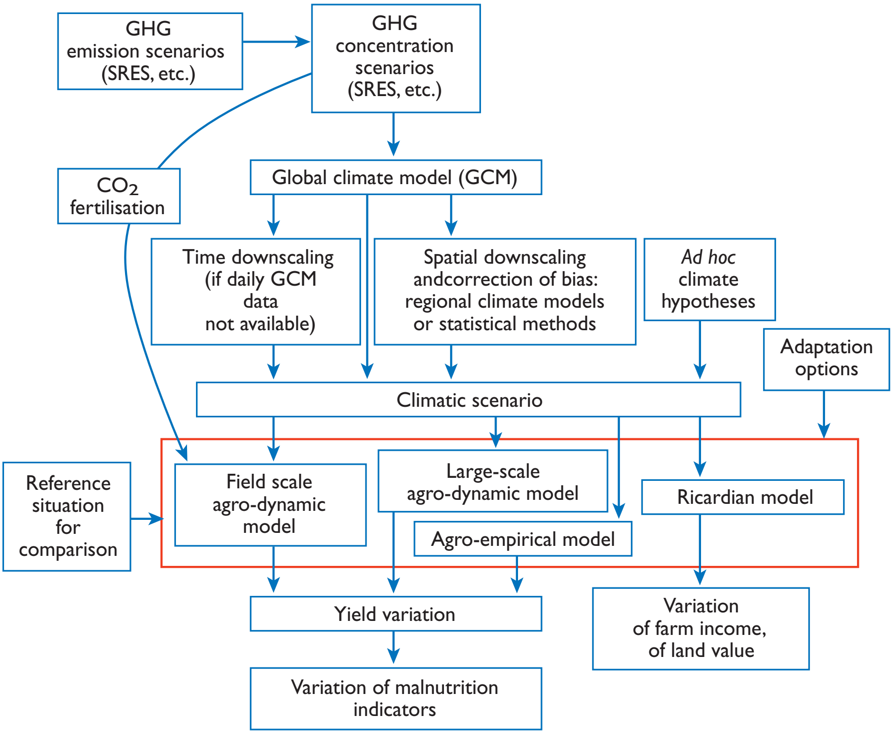

Figure 1.
Summary of the working method used in studies of impacts of climate change on yields.
Source: from ROUDIER *(2012).*

Thus, the following main stages are required in quantification of the variations in crop yields resulting from climate change.

Generating the future climate

Quantifying the impact of climate change on a given variable first requires the definition of the scenarios that describe the future evolution of the meteorological variables. The simplest method is to create a uniform scenario (e.g. + 10% rainfall, + 2°C in temperature) and to apply the change to observed climate data for the reference period (BEN MOHAMED *et al.*, 2002; SALACK, 2006; VANDUIVENBOODEN *et al.*, 2002). However, it is clear that although the method makes it possible to perform analyses whose sensitivity is interesting it is based on strong hypotheses as regards the future climate and does not necessarily maintain the coherence between climatic variables. An approach with more solid scientific bases exists, with the use of global climate models (GCM). As has been seen in Chapter 3, GCMs give a great variety of responses depending on the emission scenario or model used. Thus, in order to sample part of the uncertainty of climate projections, most of the studies published use several GCMs and/or scenarios (e.g. SCHLENKER and LOBELL, 2010).

Crop modelling

Constructing a model in which climatic information (temperature and/or precipitation for example) can be transcribed as agronomic variables (crop yields, biomass) is a prerequisite for the quantification of the links between climate and agriculture. This type of model is particularly useful for making a synthesis of existing knowledge on climate: plant relations, exploring hypotheses concerning climate change or farming practices, identifying key variables that should be pinpointed by researchers and drawing up scenarios for the future. Two separate approaches are generally used: the first is based on agronomic statistical models and the second on mechanistic models and both seek to estimate agricultural productivity in response to the climate. Empirical agricultural models are based on a statistical relation derived from observed data and that link agricultural yields at a given location with climatic variables. Although such relations are comparatively easy to set up, calibrating and validating a robust statistical model requires long data series (climate and yields). However, the relation has a particular advantage as it can be established directly at a large scale (national for example) using spatially aggregated climate data to predict yields in vast regions. The approach was used in particular by LOBELL *et al.* (2008) and by SCHLENKER and LOBELL (2010) who consider that it permits a simple evaluation of future climate impacts at a scale that is pertinent for informing decision makers.

The other approach is 'mechanistic' or 'dynamic' modelling based on equations representing the physiological processes of crop growth (uptake of carbon and nutrients, transpiration, etc.) and their development in response to the climate (e.g. the appearance of successive organs, vegetative phase, reproductive phase, etc.). As this approach can theoretically identify the intra-seasonal non-linear effects of climate on crops, most impact studies in agriculture use a mechanistic model (ROUDIER *et al.*, 2011). However, not all the models of this kind have the same physiological approach and do not attain the same degree of detail. In particular, the positive effect of a high atmospheric CO_2 concentration on photosynthesis (TUBIELLO *et al.*, 2007 a and 2007 b) is not taken into account in all mechanistic models (e.g. SALACK, 2006). Furthermore, these models require numerous parameters and are therefore used at field scale where these data are available and can be considered as homogeneous: they do not provide direct information on climate impacts at a larger scale.

It should be noted that a third approach, Ricardian analysis (MENDELSOHN *et al.*, 1994), is also used in estimating the impact of climate change on agriculture in West Africa (e.g. KURUKULASURIYA and MENDELSOHN, 2008; MOLUA, 2009). This approach is concentrated on the net income of farms rather than on yields and, unlike most impact studies, takes adaptation strategies into account. The Ricardian approach consists overall of several main stages: 1) the gathering of socioeconomic information about farms, 2) calculation of net farm return using this information, 3) establishing a regression between the calculated net return and different variables such as climate, soil and a set of economic variables, and 4) use of the link established between return and climate to project the impact of the future climate. It is noted that unlike empirical approaches, the regressions performed here are just for one year and so the method is a study of spatial variability.

Linking GCMs and cropping models

Combining a GCM and an agricultural model raises several problems. First, GCMs generally display significant bias in their climate simulations and especially in cumulated precipitation and regional distribution. The proportion of small rainfall events (< 10 mm/day) in cumulated total and frequency are over-estimated whereas the opposite occurs (under-estimation) for heavy rainfall (> 20 mm/day) (RANDALL *et al*., 2007; DAI, 2006). Thus certain impact studies that give local results generally require a certain correction of bias. The most simple correction method is the anomaly method. For a given GCM, an average annual anomaly calculated between the future and the current simulated climate is added to a current observed dataset (see for example MÜLLER *et al*., 2010). Secondly, the combining of a GCM and a deterministic model is more complex than the simple coupling of two models, because of the difference in the respective scales. Indeed, GCMs typically produce climatic projects for meshes with 2° side and although statistical models can be calibrated directly to use aggregated information of this type directly as input, mechanistic models require data at a finer scale. Downscaling must generally be performed from the overall GCM scale to the local scale of the agronomic model

Two types of downscaling are usually defined (and may sometimes be combined):

− statistical downscaling, in which empirical relations between atmospheric circulation at the meso-scale and the local climate are used to create realistic time series of local climatic variables. This method includes stochastic time generators, regressions (linear or not) and the weather type method. For example, ZORITA and VON STORCH (1999), MÜLLER *et al*. (2010) use a stochastic time generator to switch from monthly climatic variables to an hourly time step;

− dynamical downscaling uses models of the regional climate at a fine resolution (approximately 10-50 km) imbricated in the GCM (PAETH *et al*., 2011).

The need for agronomic modelling for studies on climate change has led recently to the development of mechanistic models at a global scale. These models are created and calibrated to function directly at a scale compatible with GCM output, making it possible to avoid the downscaling stage. Certain models have been developed to be independent of impact models while others are parts of models of overall vegetation where they are used for cultivated land (DE NOBLET-DUCOUDRÉ *et al*., 2004; BONDEAU *et al*., 2007; BERG *et al*., 2011). If necessary, they can thus be used for climate impact research.

Adaptation to climate change

Some studies on the impacts of climatic change take into account the adaptation of farming systems or populations. CHUKU and OKOYE (2009) held that there are four main categories of available options for adaptation in agriculture to face climate change: 1) income and asset management strategies, 2) government programmes and support 3) farm production practices and 4) technological developments. It is stressed in the same study that these categories are characterised by the scale (local, national) and the type of agents involved. Sahelian farmers already use numerous options for adaptation at the local scale. They generally involve production practices (e.g. water management, the use of certain varieties, fertilisation) and also income management techniques (e.g. the diversification of returns, migration). It is thus seen that it may be necessary to consider adaptation in this type of study in order to avoid over-estimating the impact of climate change on farm yields. However, adaptation is not taken into account explicitly in most studies on West Africa. In some studies, such as that of MÜLLER *et al*. (2010), sowing dates change each year but remain based overall on the same technique. This attitude is therefore more an adaptation to inter-annual climate variation than to climate change. TINGEM and RIVINGTON (2009) simulated the yields of certain crops with and without adaptation. They considered new sowing dates and hypothetical improved varieties. Future yield losses were thus clearly limited. Similarly, BUTT *et al*. (2005) set out their results both without adaptation and with a set of theoretical adaptation options: economic options, crop combinations and varieties resistant to high temperatures. Here again, these options clearly increase future yields. Finally, Ricardian studies examine total adaptation. However, it is not possible to give detail in the results about what options are used and the impact of climatic changes without adaptation. Furthermore, this method does not take the costs of transition into account and hence overestimates the profit drawn from the adaptation.

A decrease in agricultural yields under the effect of climate change

Numerous articles and reports describe projections of yields in sub-Saharan Africa in response to environmental changes (CHALLINOR *et al*., 2007). But all these documents are focused on a particular country or group of countries lay emphasis on a crop or a specific variety and use different methodologies (an empirical or mechanistic model to simulate yields, different regionalisation methods, different climatic models or scenarios, taking the effect of CO2 into account). It is therefore fairly difficult to have an idea of the overall impact of climate change on agriculture in Africa and above all of the uncertainties accompanying these projections. ROUDIER *et al*. (2011) performed a meta-analysis of the results in the literature, compiling the results given in 16 recent publications on the subject to form a yield database for the future. Figure 2a shows that the sign of the relative change in yield between the present and the future is negative in most cases, with a decrease in yield of some 10% in comparison with the present. However, this figure holds strong uncertainty as the distributions of the responses display considerable spread, varying from -40% to + 80% depending on the case. Taking into account atmospheric CO_2, which has a fertilising effects on plants although this is still not well known and is poorly represented in models (LONG *et al*., 2006; TUBIELLO *et al*., 2007 b; AINSWORTH *et al*., 2008), mitigates the negative effect of climate change although the combined impacts of the environmental changes (climate and CO_2) are negative overall.

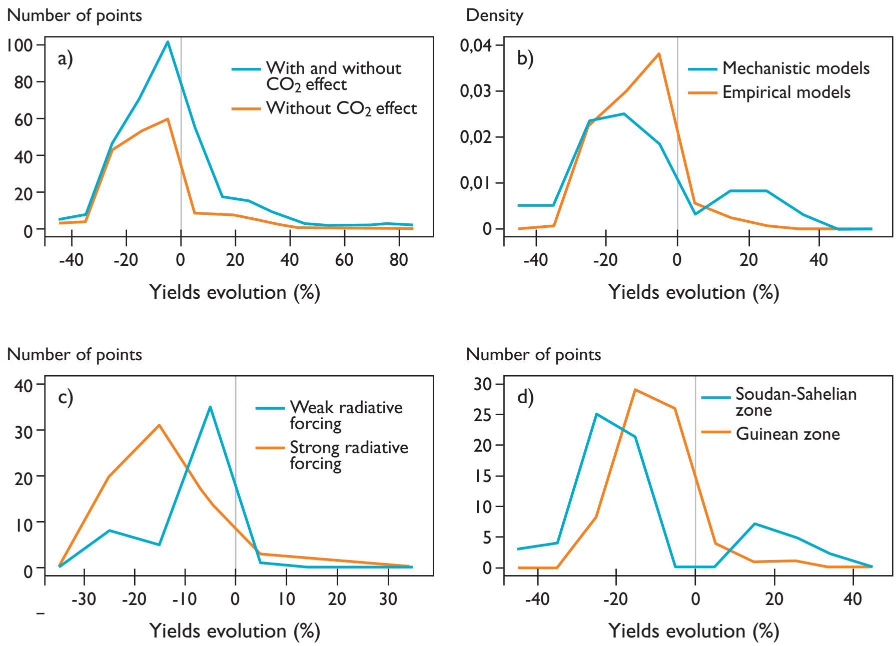

Figure 2.
(a) Distribution of relative changes in yield in West Africa between the present and the future in 16 recently published studies (in blue). The same distribution is shown in orange but only for the studies in which the effect of CO2 on plants is not considered.
(b) As in (a) but with distinction made between the results based on mechanistic models (in blue) and those based on empirical models (in orange).
(c) As in (a) but with distinction made between results for weak (blue) or strong radiative forcing (orange).
(d) As in (a), but comparing the results for the Sudan-Sahelian countries (in blue) with those for the Guinean countries (in orange).
Source: from Roudier *(2012).*

It is also interesting to see that even if the dispersion of the results from the use of mechanistic models is stronger (which is logical as these models are less constrained than statistical models), the sign of the change of yield that they predict is the same as that of empirical models (Fig. 2b). The amplitude of the impacts of climatic change on yields appears to be modulated by the intensity of radiative forcing. In other words, the higher the concentration of atmospheric CO_2 considered in these studies (distant time horizons, economic scenarios with high emission levels such as A2), the stronger the negative impact expected in yields (Fig. 2c). This observation highlights the importance of taking into account CO_2 emission reduction by mitigation measures that can limit the impacts on agriculture in West Africa. Finally, Figure 2d shows that climate change has a differential impact according to region in West Africa, with the Sahelian countries being harder hit than the Guinean countries. This meta-analysis was extended to a larger set of publications (52 articles) to show the expected impact of climate change on the yields of 8 major crops in Africa and Asia (KNOX *et al.*, 2012). The latter authors show an 8% decrease in agricultural yields by 2050 in both regions. In Africa wheat yields will fall by 17%, maize by 5%, sorghum by 15% and millet by 10%. Because of a limited number of studies and also contradictory results, KNOX *et al*. (2012) were unable to show results that were as clear-cut and robust for rice, cassava and sugar cane crops.

The respective influence of changes in temperatures and precipitation in yield scenarios

We can now examine the climatic variables that cause this negative impact in the existing studies and in particular the respective roles of temperature and precipitation. Changes in these features are both major determinants in the recent trends observed in agricultural production in sub-Saharan Africa. Both the increase in temperatures and above all the decrease in precipitation have led to production deficits since the 1970s (BARRIOS *et al*., 2008). Although the effects of precipitation have been dominant in recent history, as is shown by the strong link between rainfall and millet productivity in Niger, the situation might be completely different in the future. Indeed, SCHLENKER and LOBELL (2010) show that the increase in temperature forecast by models is much stronger than that of precipitation, which is generally smaller than the historical standard deviation. Furthermore, the authors use empirical modelling of the climate-yield relation to show that the marginal impact of the change in the standard deviation of rainfall is smaller than that of a change in the standard deviation of temperatures in the future. Even if rainfall were not to change in the future, yields would decrease by about 15% as a result of the increase in temperatures that would shorten cropping cycles and increase moisture stress as a result of increased evaporation. According to SCHLENKER and LOBELL (2010), changes in precipitation nonetheless have an impact, but smaller than that of temperature. Depending on whether rainfall increases or decreases in the future, the impact on yield could be amplified by a factor of two – respectively -10% and -21% if the median change is considered. This finding is coherent with that of SALACK (2006) who showed that warming (+1.5°C) would inevitably have negative effects on the yield of a millet variety, even if these effects may be mitigated by an increase in precipitation.

Another way of addressing the respective effects of warming and variations in precipitation on agricultural yields was proposed by SULTAN *et al*. (2013). The authors performed a set of simulations using the SARRA-H model (DINGKUHN *et al*., 2003) for several millet and sorghum varieties at a set of 35 meteorological stations covering 9 countries in West Africa during the period 1971-1990. The authors then used the delta method to superimpose incrementally at local meteorological stations temperature anomalies of from 0°C to +6°C with 1°C steps and/or relative precipitation anomalies ranging from -20% to +20% with 10% steps. SARRA-H model simulations were performed to quantify the yield response to these temperature and/or precipitation anomalies (Fig. 3).

It is seen that the negative impact on simulated yields caused by a 2°C temperature increase in Africa can be compensated by a 20% increase in rainfall. In contrast, when warming exceeds 3°C, a deficit in simulated yield is seen, whatever the rainfall anomaly considered (within the interval of variation -20% to +20% that was considered to be realistic as we used the minimum and maximum projections of the models CMIP3 and CMIP5 for the region as a base). Projection of the temperature and precipitation response of all the CMIP3 and CMIP5 simulations (all the models and scenarios are merged in the figure) shows that these projections for 2030-2050

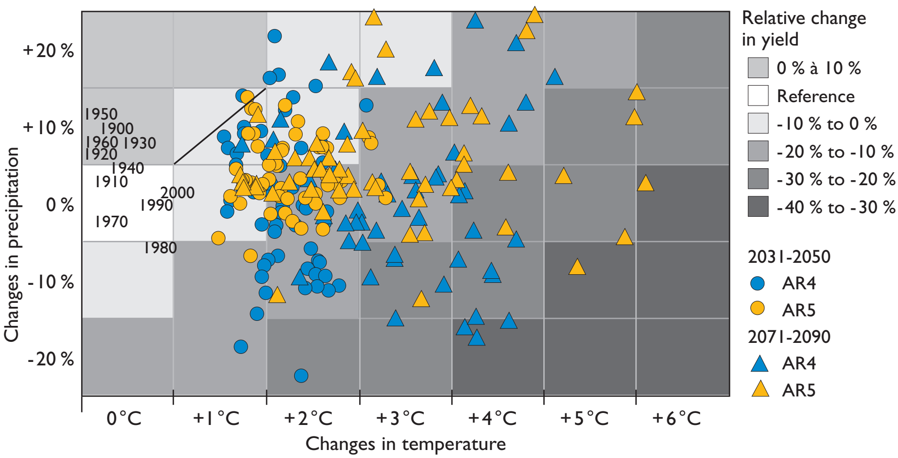

Figure 3.
The effect of changes in temperature and precipitation on average yield.
Relative change in yield (%) in comparison with the 1961-1990 reference period or 7 temperature scenarios (abscissae) and 5 rainfall scenarios (ordinates).
The results are shown as the means for 35 meteorological stations in West Africa and 6 sorghum and millet varieties.
The blue triangles and circles represent future changes projected by several GCMs of CMIP3 (AR4 in the figure) and three IPCC scenarios (B1, A1B, A2) respectively for the periods 2071-2090 and 2031-2050.
The projections of CMIP5 models (AR5 in the figure) and of RCP scenarios (4.5, 6.0 and 8.5) are represented by orange triangles and circles.
The temperature and precipitation anomalies observed since the beginning of the century using CRU data are also shown by decades ('1940' in the figure means the 1941-1950 anomaly in comparison with 1961-1990).
All the changes in yields are significant at a 5% confidence level except for those in the box marked with a diagonal line.
Source: IPCC (2014)

correspond to a yield response range varying from -10% to +10% with a majority of negative to nil impact (from -10% to 0). However, all the projections using the period 2070-2090, whatever the model and/or scenario, display a yield response range that decreases from slightly (between -10% and 0) to strongly (to -40%). The variations in yield response in the future are largely dominated by the effect of temperature, with warming of up to +4°C in the projects of models CMIP3 and CMIP5 in Africa, thus confirming the findings of BERG *et al*. (2013) and SCHLENKER and LOBELL (2010). It is interesting to observe that these temperature variations and precipitations projected by the models and their impact on yields are very different to those observed during the 20th century. It can be seen in Figure 4 that past climatic anomalies are distributed along a vertical axis (precipitation anomalies characterise the variations from one decade to another) while projection spread markedly along a horizontal axis (temperature variations are discriminant in the projections). The projections of past and future decades and their yield response are thus clearly distinct in the figure. This shows that climate change and its consequences as projected by the models CMIP3 and CMIP5 are going to be something completely new that will be like nothing seen in Africa since the beginning of the 20th century. This underlines the scale of the future (and present) challenge of adaptation to climate change: how is it possible to adapt to an unknown (and uncertain) world?

A contrast between the western and central Sahel in the yield scenarios

Uncertainty about the future of precipitation in West Africa is also a very limiting factor for refining yield projections in response to environmental changes. Indeed, there is no agreement between climate models with regard to the impact of climate warming on rainfall in the Sahel (COOK and VIZY, 2006; DRUYAN, 2010), with some models mentioning possible aridification and others predicting increased rainfall in the future. Nonetheless, a few recent studies (BIASUTTI, 2013; MONERIE *et al*., 2013, 2012; PATRICOLA and COOK, 2010; BIASUTTI and SOBEL, 2009) have found a robust signal between the different CMIP3 and CMIP5 models, showing a late start to the monsoon in the west of the Sahel and increased rainfall at the end of the winter period in the central Sahel. This contrast between the western and central Sahel in terms of the evolution of rainfall is not found in temperatures which, in contrast, display warming along a latitudinal gradient with the northern regions of the Sahel warming more than those of the south. The increase in temperatures in the mid-21st century—exceeding +3°C in some places—is so marked that there will soon be nothing similar in recent history (BATTISTI and NAYLOR, 2009). Quantifying the

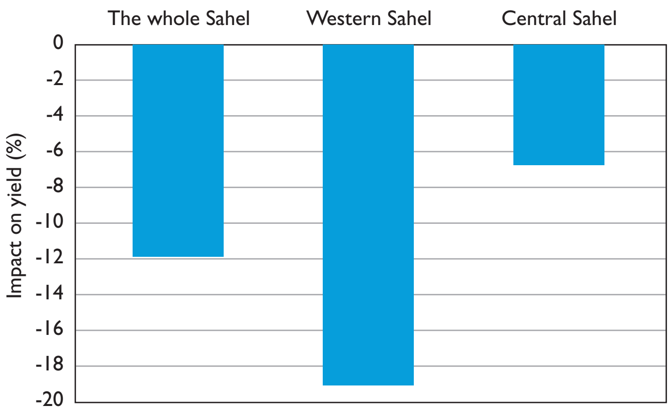

Figure 4.
Simulated response of sorghum yield to climate change.
The relative change (%) in average sorghum yield
during the periods 2031-2060 and 1961-1990 in scenario RCP8.5.
The results are shown as average for 9 GCMs,
two crop models and three sorghum varieties.
The responses are calculated for 13 stations distributed in the Sahel (left),
6 stations in the west of the Sahel (middle) and 6 stations in the central Sahel (right).
Source: after SULTAN *et al. (2014).*

impact of this shift in the seasonality of the monsoon, overlying the negative effect of warming on crops (SULTAN *et al*., 2013; ROUDIER *et al*., 2011) can be particularly important for identifying crop varieties (early or late) or practices (sowing later or earlier) capable of limiting the impacts of climate change.

Figure 4 shows the response of sorghum yields to climate change simulated by the two agronomic models SARRA-H and APSIM (SULTAN *et al*., 2014). It is noted that climate change causes sorghum yield loss of some 12% in the mid-21st century throughout the Sahel, which is strongly coherent with the figures found in the literature (ROUDIER *et al*., 2011). However, the impact differs greatly between the western and central Sahel. Indeed, yields losses are particularly high in the western Sahel (around 19%) as a result of the combination of warming and decreased precipitation at the beginning of the rainy season. In the central Sahel, temperature and precipitation operate in opposite directions—warming causes yield loss whereas increased rainfall at the end of the rainy season is favourable for growing sorghum. However, in spite of an increase in rainfall, the rise in temperatures dominates in the sign of climate change in the central Sahel, as yield losses of about 7% are observed in the mid-21st century. Comparison of the response of sorghum to climate change in the two fertilisation scenarios shows that an increase in inputs makes the crop more vulnerable to changes in temperature and precipitation with greater losses when more inputs are used. This finding is coherent with numerous studies that show that climate risk increases with intensification (see AFFHOLDER, 1997 for example).

Conclusions

Anticipating climate fluctuations and changes is primordial for Sudan-Sahelian Africa. The quantification of the agronomic impacts of climate change requires the setting up of often complex methodology using tools taken from economics (emission scenarios, farming household decision models) from climate science (climate models and projections), agronomy (agronomic models) and statistics (regionalisation and bias correction), each with their share of error and their limits. In spite of these uncertainties, it has been shown that a decrease in grain productivity in the future is plausible as an effect of climate warming. This yield decrease is particularly marked in the western Sahel where the effects of a decrease in rainfall and a rise in temperature will be combined at the horizon 2050. However, the challenge to be met lies not as much in estimation of future yields that is deterministic and probably unfeasible but in the quantification, ranking and reduction of the uncertainties related to projections of climate change impacts. The framework of the new international projects for the intercomparison of regionalisation methods CORDEX (Coordonated Regional Climate Downscaling Experiment) and for the intercomparison of agronomic models (AGMIP: Agricultural Model Intercomparison and Improvement Project) will most certainly mark a turning point leading to better allowance for this uncertainty through coordinated studies focused on the impacts of climate on agriculture. Such studies have previously been performed in a very isolated, fragmented manner. However, there should be no waiting for further certitudes before thinking about adaptation measures that are both scientifically relevant and socially acceptable as today's climate has already had an impact on the resources of rural populations. Nevertheless, the study of vulnerabilities and of adaptation to environmental changes requires dialogue between biophysical sciences (climate, hydrology, agronomy) and human sciences (demography, history, anthropology, economics). This multidisciplinary approach is crucial in addressing the question of adaptation to environmental changes in which the response of societies is set in overall social changes and in which the climate variable is far from being the one and only factor in the vulnerability of Sahelian societies.

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