



HAL
open science

Robust features of future climate change impacts on sorghum yields in West Africa

Benjamin Sultan, Kaiyu Guan, Mamoutou Kouressy, Michela Biasutti, C. Piani, G.L. Hammer, G. Mclean, David B. Lobell

► To cite this version:

Benjamin Sultan, Kaiyu Guan, Mamoutou Kouressy, Michela Biasutti, C. Piani, et al.. Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters*, 2014, 9 (10), pp.104006. 10.1088/1748-9326/9/10/104006 . hal-01317169

HAL Id: hal-01317169

<https://hal.sorbonne-universite.fr/hal-01317169v1>

Submitted on 18 May 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Robust features of future climate change impacts on sorghum yields in West Africa

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2014 Environ. Res. Lett. 9 104006

(<http://iopscience.iop.org/1748-9326/9/10/104006>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 134.157.80.213

This content was downloaded on 18/05/2016 at 09:37

Please note that [terms and conditions apply](#).

Robust features of future climate change impacts on sorghum yields in West Africa

B Sultan¹, K Guan², M Kouressy³, M Biasutti⁴, C Piani⁵, G L Hammer⁶,
G McLean⁷ and D B Lobell²

¹ Sorbonne Universités (UPMC, Univ Paris 06)-CNRS-IRD-MNHN, LOCEAN/IPSL, 4 place Jussieu, F-75005 Paris, France

² Department of Environmental Earth System Science and Center on Food Security and the Environment, Stanford University, Stanford, CA 94305, USA

³ Institute d'Economie Rurale, Mali, Africa

⁴ Lamont-Doherty Earth Observatory, NY, USA

⁵ American University of Paris, France

⁶ Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, Brisbane, Qld. 4072, Australia

⁷ Department of Agriculture, Forestry and Fisheries, Toowoomba, Qld. 4350, Australia

E-mail: Benjamin.sultan@locean-ipsl.upmc.fr, kaiyug@stanford.edu and dlobell@stanford.edu

Received 15 May 2014, revised 30 August 2014

Accepted for publication 1 September 2014

Published 8 October 2014

Abstract

West Africa is highly vulnerable to climate hazards and better quantification and understanding of the impact of climate change on crop yields are urgently needed. Here we provide an assessment of near-term climate change impacts on sorghum yields in West Africa and account for uncertainties both in future climate scenarios and in crop models. Towards this goal, we use simulations of nine bias-corrected CMIP5 climate models and two crop models (SARRA-H and APSIM) to evaluate the robustness of projected crop yield impacts in this area. In broad agreement with the full CMIP5 ensemble, our subset of bias-corrected climate models projects a mean warming of +2.8 °C in the decades of 2031–2060 compared to a baseline of 1961–1990 and a robust change in rainfall in West Africa with less rain in the Western part of the Sahel (Senegal, South-West Mali) and more rain in Central Sahel (Burkina Faso, South-West Niger). Projected rainfall deficits are concentrated in early monsoon season in the Western part of the Sahel while positive rainfall changes are found in late monsoon season all over the Sahel, suggesting a shift in the seasonality of the monsoon. In response to such climate change, but without accounting for direct crop responses to CO₂, mean crop yield decreases by about 16–20% and year-to-year variability increases in the Western part of the Sahel, while the eastern domain sees much milder impacts. Such differences in climate and impacts projections between the Western and Eastern parts of the Sahel are highly consistent across the climate and crop models used in this study. We investigate the robustness of impacts for different choices of cultivars, nutrient treatments, and crop responses to CO₂. Adverse impacts on mean yield and yield variability are lowest for modern cultivars, as their short and nearly fixed growth cycle appears to be more resilient to the seasonality shift of the monsoon, thus suggesting shorter season varieties could be considered a potential adaptation to ongoing climate changes. Easing nitrogen stress via increasing fertilizer inputs would increase absolute yields, but also make the crops more responsive to climate stresses, thus enhancing the negative impacts of climate change in a relative sense. Finally, CO₂ fertilization would significantly offset the negative climate



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

impacts on sorghum yields by about 10%, with drier regions experiencing the largest benefits, though the net impacts of climate change remain negative even after accounting for CO₂.

☐ Online supplementary data available from stacks.iop.org/ERL/9/104006/mmedia

Keywords: climate change, crop, Africa

1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014) has warned, with higher confidence than in previous reports, that climate change is likely to adversely affect food security in many regions of the world. This is especially true in developing countries where a large fraction of the population is already facing chronic hunger and malnutrition (FAO 1999, Schmidhuber and Tubiello 2007) and where widespread poverty limits the capacity to cope with climate variability and natural disasters. In such countries, progress on food security will depend partly on the effective adaptations of agriculture to climate change. Adaptation planning—such as breeding more resilient crop varieties or promoting existing varieties and practices that are more resistant to climate-induced stress (Barnabás *et al* 2008)—requires reliable scenarios of future regional agricultural production. However, producing such scenarios remains challenging, because of large uncertainties in regional climate change projections, in the response of crop to environmental changes (e.g. rainfall, temperature, CO₂ concentration) and in the adaptation of agricultural management to climate changes (Challinor *et al* 2007). For example, a meta-analysis of the literature (Knox *et al* 2012, Roudier *et al* 2011) shows that projected impacts on yield in several African countries are most frequently slightly negative (−10% to −8%), but there are large variations among crops and regions as well as large modeling uncertainties, which make it difficult to provide a consistent assessment of future yield changes at regional scale. This study performs such an assessment for West Africa.

Although climate uncertainties, particularly associated with rainfall changes, can be an important impediment to adaptation planning, there are also situations where robust changes can be identified and may allow proactive planning. Indeed, despite the widely acknowledged spread in current climate model projections of regional rainfall changes over West Africa, especially with respect to summertime rainfall totals (Druyan 2011), there is mounting evidence in climate models from the Coupled Model Intercomparison Projects CMIP3 (Meehl *et al* 2007) and CMIP5 (Taylor *et al* 2012) for a delayed monsoon, especially in the Western part of the Sahel (Biasutti 2013, Monerie *et al* 2013, 2012, Patricola and Cook 2010, Biasutti and Sobel 2009). The impact of such seasonal shift of the monsoon, compounded with the adverse effect of warming (Sultan *et al* 2013, Roudier *et al* 2011), needs to be investigated as a first step towards identifying the crop varieties (e.g. late or early sorghum) and practices (e.g. delayed or early sowing) most suitable to withstand climate change (Dingkuhn *et al* 2006).

Here we assess the impacts of climate change on the yield of sorghum, one of the main staple crops in the Sudanian and Sahelian savannas of West Africa. The study extends the work of Sultan *et al* (2013). Using the same SARRA-H crop model forced by idealized climate forcings, that study demonstrated that higher temperatures act to increase potential evapotranspiration and crop maintenance respiration and to reduce the crop-cycle length. Warming, therefore, is simulated to cause millet and sorghum yield losses in West Africa, even in the case of increased precipitation. In this study, we do not use idealized climatic changes, and instead investigate the response to a set of complete climate projections, in which temperature and rainfall vary across the season and in an internally consistent manner. We also investigate the robustness of the climate impacts by taking into account the diversity of local cultivars, the uncertainties in future climate projections and in the response of crop models, and the crop response to CO₂ increase.

In the next section we introduce the climate data (from nine CMIP5 climate models that were bias-corrected and downscaled), the two crop models (SARRA-H and APSIM), and the simulation protocols. In section 3, we analyze present and future yields to identify the areas and crop cultivars most vulnerable to climate change. Since APSIM is the only crop model including a CO₂ fertilization scheme, the inter-comparison between the two crop models will mainly assess the robustness of the response of the crop to temperature and rainfall changes while the direct effect of CO₂ will be examined separately using solely APSIM. Finally, in section 4, we discuss our conclusions.

2. Materials and methods

2.1. Weather data

Our main meteorological dataset comprises daily data from from 35 stations in nine countries across West Africa (figure 1), compiled by AGRHYMET Regional Center and National Meteorological Agencies for the 1961–1990 period. This is a dry period compared to the recent decades (Panthou *et al* 2014), but it is the only period for which a sufficient array of daily station data has been made publicly available. These stations record rainfall and several meteorological parameters at 2 m above ground level, such as solar radiation, surface wind speed, humidity and temperature. The 35 weather stations are used to perform historical crop growth simulations for validation purpose against crop yield data and to estimate the bias-correction functions. For the crop future simulations we select 13 out of the 35 stations (figure 1); these 13 stations are more evenly distributed across the study

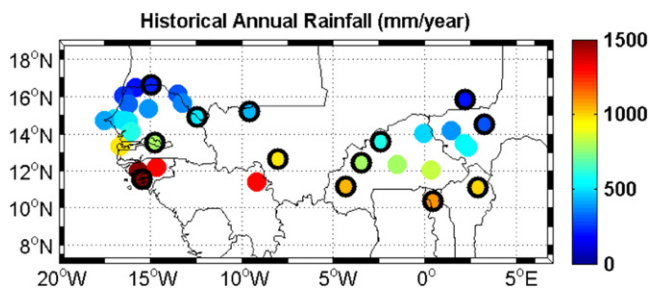


Figure 1. Map of West Africa and location of stations. Total rainfall amount (mm/year) in average over the reference period 1961–1990. Thick circles show the localization of the 13 stations used for climate change impacts scenarios.

area and the aggregated results are thus representative of the whole region, avoiding over-representing any specific area.

2.2. Climate scenarios and bias correction technique

We use historical simulations and the RCP8.5 projections from 9 CMIP5 (Taylor *et al* 2012) models⁸, the choice of the models was based solely on the availability of daily values of precipitation and of mean, maximum, and minimum surface temperature at the time of the study. Output from more than 20 such GCMs is available today, however the 9-model subset is a reasonable representation of the larger ensemble over Western Africa. Other variables (i.e. wind, humidity and radiation) necessary for forcing the crop models were obtained from the historical records of weather stations, based on a conditional resampling to preserve the covariance between these variables and precipitation. The historical time series of precipitation and temperature were first bias-corrected and downscaled to the necessary field scale, following a method adapted from Piani *et al* (2010). The basic idea of the method is to (i) sort by increasing accumulation the values of daily rainfall observed at a station and produced by a climate model for the same period and (ii) use a parametric function to fit the emerging *transfer function* (TF) that will map the model data to observations. The preponderance of low-intensity accumulation ensures that the fit is most accurate for the most frequent rainfall rates, distinguishing this method from other approaches that directly match the rainfall probability density function (PDF) of the model to the observed. The use of a parsimonious parametric fit prevents overfitting of the data, especially for intense events. The fit is either linear for all rainfall values, or linear for high rainfall intensity, but curving at low intensity. This functional form corrects the common bias of too many drizzle days and not enough dry days and large-accumulation days. The dry-day correction is determined internally by the fitting process and does not constitute a separate pre-processing step as in other bias-correction methodologies. The temperature terms are corrected with a similar method, but here the fit to the transfer function is always linear. Following Piani *et al* (2010), the three temperature characteristics are corrected together (as

mean daily temperature, daily range, and temperature skewness) to avoid large relative errors in the daily temperature range. Data for a singular calendar month is used to fit a set of twelve TFs, which are then interpolated to obtain a diurnally resolved TF. The TFs are derived from the historical runs for the 1961–1990 period for each individual model, and then are applied to the scenario simulations to obtain an ensemble of forcings for the 2031–2060 crop simulations.

It was shown by Chen *et al* (2011) that the large inter-decadal variability in Sahel rainfall characteristics implies that a TF based on data from one epoch does not fully remove model bias in a different epoch. We have attempted to ameliorate this problem by including, when possible, longer records in our observational datasets (additional rainfall data was provided by Adrian Tompkins in personal communication) and by polling nearby stations together, so that the observed rainfall characteristics targeted by the TF are as broadly representative as possible. The flipside of this choice is that the forcing we produced should be considered representative for broader regions, rather than the exact location of the meteorological stations. We argue that this loss of specificity is not problematic. In light of the large uncertainties in projections even at the regional scale, it would be unwise to give downscaled projections the status of bona fide local forecasts. In this study, we interpret them as regional scenarios.

Panels a and b in figure 2 show the sorted daily precipitation for southern Burkina Faso and northern Benin in the CSIRO and MIROC models against observations for the rainy season months. The two models have similar biases in the weak precipitation range—i.e. an overestimation of drizzle days—but very different behaviors in the high intensity ranges, with the MIROC model producing exuberant precipitation (well below the 1:1 line), while the CSIRO model displays the most typical bias of muted precipitation in intense events (above the 1:1 line). The functional fits of the TFs are shown as solid line, and are capable of capturing both of these divergent behaviors, so that the end result of the bias correction and downscaling is to produce similar daily values for both models (as shown in the insets; see also figure S1 in the supplementary material, available at stacks.iop.org/ERL/9/104006/mmedia).

2.3. Crop yield simulations

2.3.1. Sorghum varieties and field trials. Sorghum (*Sorghum bicolor* (L.) Moench) is Africa’s second most important crop after maize: about 23 M ha are under cultivation and production has increased from 4.6 to 12.4 million tons from 1979 to 2012 in West Africa (FAOSTAT data). Three well known sorghum cultivars in Mali (Kouressy *et al* 2008a, b) were selected to represent different plant types available to farmers in West Africa and field trials under rainfed and irrigated conditions were conducted for all three varieties in 2004 and 2005 to calibrate crop models. The agronomic research station of the Institute d’Economie Rurale (IER) is located at Sotuba (12.17N; 7.57 W), near Bamako, and is characterized by a sudano-sahelian climate with an annual

⁸ The 9 models are: CCSM4, CMCC-CM, CMCC-CMS, CSIRO-Mk3-6-0, GFDL-ESM2G, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MPI-ESM-Mr

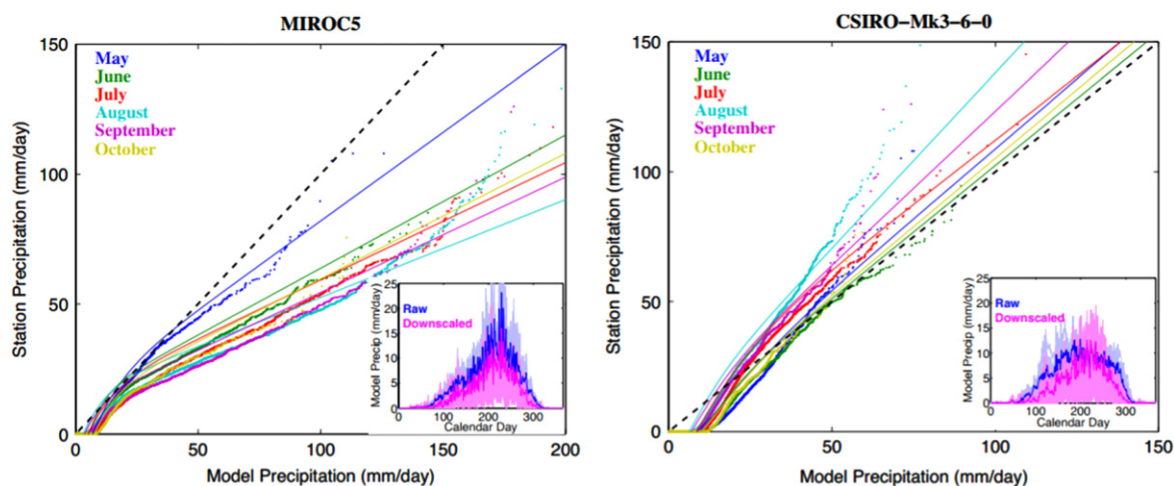


Figure 2. Precipitation downscaling and bias correction for two models: MIROC5 (left) and CSIRO-Mk3-6-0 (right). Main panels: May through October (color coded according to legend) sorted daily accumulations of precipitation from meteorological stations in southern Burkina Faso and northern Benin (y-axis) are plotted against corresponding daily accumulations in the model historical simulation (x-axis) to define the emerging transfer function (dots) and the functional fit used to downscale the GCM output (solid line); the 1:1 line is plotted in dark dashes for reference. Inset panels: raw model data for all the grid points in the same area (light blue) and their downscaled counterparts (light magenta). A representative line in each set is drawn in darker colors for clarity.

mean of maximal (minimal) daily temperature of 34.4 °C (21.9 °C) and a mean annual rainfall 900 mm per year. The three cultivars (described in several previous studies, e.g. Kouressy *et al* 2008a, b) fall into two different categories: (i) the ‘traditional’ varieties (GuineaLo and GuineaAm) which have moderate to strong photoperiod sensitivity, a flexible crop cycle length but smaller average yields; and (ii) a ‘modern’ variety (Caudat) which is an early-maturing, short duration and photoperiod-insensitive crop selected to maximize the mean yield under optimal fertility conditions. On-farm surveys, mainly in Mali but also in Senegal, Burkina Faso and Niger (Traoré *et al* 2011), have shown that ‘modern’ varieties have been so far adopted by a minority of farmers. Kouressy *et al* (2008a) demonstrated that such little adoption might be explained by a weak adaptation of short and constant duration crops to semi-arid environments. Indeed they must be sown at a specific date in order to synchronize the flowering stage with the end of the rainy season to avoid drought, pest and disease problems while photoperiod sensitive cultivars have the advantage of permitting flexible sowing dates. Furthermore, Sultan *et al* (2013) have shown that traditional photoperiod-sensitive cultivars are less affected by temperature increases, because the photoperiod limits the heat-induced reduction of the crop duration.

2.3.2. Crop modeling tool. In order to span some of the uncertainty in crop modeling, which has been shown to be an important contributor to overall uncertainty in climate change impacts (e.g., Asseng *et al* 2013), we use two different crop models calibrated against the same trials data: SARRA-H and APSIM. These models differ in their treatment of nutrients, CO₂, sowing date and more (see table S1 in the supplementary material) and agreement in their simulations might indicate a robust response of sorghum to climate change in West Africa.

The SARRA-H model (version v.32) simulates yield attainable under water-limited conditions by simulating the soil water balance, potential and actual evapotranspiration, phenology, potential and water-limited carbon assimilation, and biomass partitioning (see Kouressy *et al* 2008a for a detailed review of model concepts). The simulation of these processes makes SARRA-H particularly suited for the analysis of climate impacts on cereal growth and yield in dry tropical environments (Dingkuhn *et al* 2003, Baron *et al* 2005, Sultan *et al* 2005), and its good performance has been well documented (Mishra *et al* 2008, Oettli *et al* 2011, Sultan *et al* 2013). The APSIM model (version 7.5, Hammer *et al* 2010) is designed to simulate the response of various crops to climate and management conditions as well as the long-term consequence of cropping systems on soil physical and chemical conditions (Keating *et al* 2003). The simulation of crop physiological processes uses the concept of supply and demand balances for light, carbon, water, and nitrogen (Hammer *et al* 2010). The APSIM model has successfully demonstrated its performances for C4 crop productions in Africa (Turner and Rao 2013, Akponikpè *et al* 2010).

The SARRA-H model does not explicitly simulate the effects of fertilizer, manure application, or residue on crop yields. However the impact of soil fertility was taken into account by tuning the biomass conversion ratio to an optimal level for the modern variety and to a lower level for traditional varieties that are usually cropped with low to no inputs. The APSIM model explicitly simulates the nitrogen cycle. Fertilizers, manure, and residues on the surface can be removed or added, be incorporated into soil during tillage operations, and decompose. Crop nitrogen uptake is the minimum between demand for crop growth and potential supply of nitrogen from soil and senescing leaves, and it is capped by a maximum nitrogen uptake rate (van Oosterom *et al* 2010). The nitrogen stress impacts photosynthesis, phenology and grain filling processes (Hammer *et al* 2010).

For this study, two levels of fertilizer urea with nitrogen content at 10 kg ha^{-1} and 50 kg ha^{-1} are applied every year at the time of sowing. These two levels represent low and medium fertilizer inputs, with the low level close to the reality for the historical periods from 1961–1990 (Heisey and Mwangi 1996). We chose not to reset the soil fertility parameters (including soil organic matter contents and soil nitrogen contents) in the APSIM simulation as this approach can represent more realistic transient situation of soil fertility in West Africa. It is well known that crop growth continues to withdraw soil nutrients when there are not enough inputs, which further endangers the regional food production (Sheldrick and Lingard 2004, Roy *et al* 2003). We treat the historical and future simulations in APSIM with the same initial soil fertility condition, thus our results are fair to compare the two simulations to assess the climate impacts.

Sowing dates were generated by the two crop models following two different rules. In SARRA-H sowing starts when plant-available soil moisture is greater than 8 mm at the end of the day, followed by a 20 d period during which crop establishment is monitored. If the simulated daily total biomass decreases during 11 out of 20 d, the juvenile crop is considered to have failed, triggering automatic re-sowing. Such agronomic criteria have been shown to be close to the farmers' planting rules in Niger (Marteau *et al* 2011). For the APSIM model, we first define a possible temporal window for sowing centered at the rainy season onset following the AGRHYMET definition (Brown *et al* 2010). The sowing date is the last day of the first 10 continuous days (in the sowing window) with rainfall accumulation of 20 mm, provided that at this date plant-available soil water is above 10 mm. If the above criteria are never satisfied, the last day of the sowing window is defined as sowing day. Crops can be killed by a variety of stresses, usually at the late stage of the phenology phases, and re-sowing is not implemented in the APSIM.

The plant response to CO_2 concentration is not included in the present version of the SARRA-H model. However, we used an APSIM version that has incorporated the CO_2 fertilization scheme. The CO_2 fertilization is achieved through linearly increasing the transpiration efficiency by 37% at 700 ppm compared with at 350 ppm (Harrison *et al* 2014) with no direct effect of CO_2 on radiation use efficiency.

The calibration of the SARRAH model against trials data in Mali has been detailed by Kouressy *et al* (2008a, b). For this study, we calibrate the APSIM model against the same trials data. We use the DEVEL software (Clerget *et al* 2008, Kumar *et al* 2009) to optimize parameters of thermal time requirements for phenological stage, photoperiod sensitivity, leaf appearance rate and leaf area function. All the APSIM calibrated parameters and cultivar-specific parameters are listed in table S2 in the supplementary material.

2.3.3. Crop models evaluation protocols. For validation purpose, the two crop models were run for all 35 meteorological stations in West Africa over 1961–90 and for all three sorghum cultivars. Since there are no existing data giving the proportion of each cultivar in the whole cropped area

of sorghum in West Africa, we assumed the same proportion of each cultivar in each site and average across cultivars. We also made the assumption that soil and management practices were the same in the 35 locations. Although local variations of soils and management can have a major effect on crop yields, this assumption is possible because of the relative uniformity of the soil (over 95% of soils in this region are sandy with low levels of organic matter, total nitrogen, and effective cation exchange capacity: see Bationo *et al* 2005) and management practices (little or no agricultural inputs, no irrigation, sowing after the first major rain event: see Marteau *et al* 2011). Simulations were performed without any irrigation since most crop systems are rainfed (93% of all agricultural land in Sub-Saharan Africa) and, to our knowledge, irrigation is never used for sorghum in West Africa. For validation purpose, following the work done by Sultan *et al* (2013), we scaled-up the crop yield simulations by simply averaging the crop yields of each of the 35 locations. Simulated crop yields were validated against Food and Agriculture Organization of the United Nations (FAO) annual data submitted by its member nations. We extracted national sorghum yields from the FAO on-line database (<http://faostat.fao.org/>) and computed an average of countries' national yield (Senegal, Mali, Burkina Faso, Niger, Guinea, Gambia, Guinea Bissau, Togo, Benin) over the 1961–1990 period, weighted by the national cultivated area for sorghum. Both mean and variability of simulated yields were validated against FAO observations. We assess model fidelity from the correlation between observed and predicted crop yield time series, after removal of any linear trends. FAO sorghum yields in some countries show increasing yields over 1961–1990 (Burkina-Faso, Senegal), while others face decreasing values (Chad, Niger). Local climate fluctuations may play a role in these trends, but non-climatic factors are likely to be the dominant drivers (land-degradation, intensification, intra or extra-national migrations, economic crisis). Because these potential non-climatic effects will not be simulated by any climate-driven crop model, we detrend observations and only analyze interannual variability. The linear trend equation for FAO data is $\text{yield} = 1.3 \cdot \text{year} + 568$.

Since sorting out climatic and non-climatic trends in yield is not possible, detrending might also remove potential climate effects. In such a case, climate trends would force the simulated yields to show a trend as well. Therefore, the only way to make a comparison between observations and simulations fair is to detrend both. Thus we also remove the linear trend from simulated yield time series. The linear trend equation for crop models outputs are (i) $\text{yield} = -38.2 \cdot \text{year} + 2839$; $\text{yield} = -28.7 \cdot \text{year} + 3323$ for the APSIM simulations with a fertilization rate of respectively 10 kg ha^{-1} and 50 kg ha^{-1} ; and (ii) $\text{yield} = -15.8 \cdot \text{year} + 2026$ for the SARRA-H crop model. The strong declining trends in the APSIM crop yields are due to the soil fertility loss since there was no resetting of mineral inputs after the start of the simulation.

2.3.4. Crop models scenarios protocols. The calibrated APSIM and SARRA-H models were then used to simulate

the response to climate change of the three cultivars of sorghum in West Africa. We thus forced the two crop models with bias-corrected outputs at each of the 13 selected locations from the nine GCMs over both the historical period 1961–1990 and the future period 2031–2060 under the RCP8.5 scenario. The difference between the two sets of simulations indicates the yield response to climatic changes over the intervening decades. To investigate the crop response to the elevated CO₂ concentration in the atmosphere in the RCP8.5 scenario, we performed two 2031–2060 simulations with the APSIM model: one where CO₂ concentration is at 520 ppm, and one where CO₂ concentration is kept at the historical value of 350 ppm. The latter simulation is comparable with the SARRA-H crop simulation. Comparison of the two APSIM simulations provides an estimate of future CO₂ fertilization.

3. Results

3.1. Evaluation of the simulated yields under the historical period

When looking at the deviation from the trend line with standardized yield values, the average sorghum yield simulated for our 35 locations agrees well with the observed yield variability derived from country statistics (figure 3). Indeed, when removing trends, crop yield variability is a response to climatic fluctuations in the FAO observations with a correlation coefficient between FAO yields and annual rainfall of $R=0.62$ (see rainfall time series in figure 3). The effect of heat stress is masked by the strong relationship of drought and heat in the historical record (global warming has only recently decoupled high temperature from drought, see Funk *et al* 2012). Although overestimated, this relationship between rainfall and crop yield is well represented in the crop models (table 1). As a consequence, both APSIM and SARRA-H capture the low yields of the drought years in the early 70 s and early 80 s, and they both fail to capture yields variations uncorrelated with rainfall (such as in 1967 and 1986). The inter-annual correlation coefficient between simulated and observed detrended yields is $R=0.70$ for the SARRA-H model and $R=0.52$ for the APSIM simulations run with 50 kg ha⁻¹ fertilizer rate. The correlation is lower ($R=0.44$) when using the 10 kg ha⁻¹ fertilizer rate in the APSIM model, as nutrient-deficient soils create highly nitrogen-stressed environments in which plants are not able to take advantage of increased water availability because of nitrogen stress (which exists in both high and low rainfall years).

Although our models capture quite well the variability of crop yields, the mean yield and the yield variance (table 1) are overestimated, especially with the APSIM simulations with the highest fertilization rates. Such an overestimation is a common shortfall of crop simulations for Sub-Saharan Africa: crop models are usually calibrated against data collected in controlled environments and thus do not account for non-climatic factors like pests, weeds and soil-related constraints

(Challinor *et al* 2004, Challinor *et al* 2005, Bondeau *et al* 2007). Furthermore, spatial heterogeneity in management, planting dates, cultivars, soils and other factors likely also reduce interannual variability in FAO yields compared to more homogeneous simulations performed in this study. The assumption we make in this study is that this positive mean bias in crop production is relatively constant in time, and thus that the simulated (climate-driven) yield mean and variability can still be compared between historical and future periods.

Finally, in order to assess whether the downscaled GCMs adequately represent observed climate conditions for crop model applications, we compared mean yields simulated under the historical period by using observations or downscaled GCMs outputs to force the two crop models (figure S1). We found that although there is some dispersion from one GCM to another, the multi-model ensemble mean yield under historical conditions is very close to the mean yield simulated with observed weather data (figure S1).

3.2. Climate change scenarios

Figure 4 shows the annual rainfall (figure 4 (a)) and the mean surface temperature (figure 4(b)) changes under the scenario RCP8.5 for the 2031–2060 period. The changes are computed as averages across the nine GCM simulations for each of the 13 stations. Future changes in rainfall clearly depict a West-East dipole with annual rainfall increasing in eight stations located in Central Sahel while rainfall is stagnating or decreasing in stations located in the Western part of the Sahel. The rainfall increase can reach +100% in two Southern stations located in Burkina Faso and Ghana. Regional mean rainfall changes for the full set of stations and subsets in the Western and Central Sahel are shown for each individual GCM in figure 4(c). The dipole pattern is a very consistent feature across GCM simulations with 7 out of 9 GCM simulating less rainfall in the future in the Western Sahel and 8 out of 9 GCM showing a rainfall increase in Central Sahel. Although the precise location of the separation line in the dipole varies, a similar rainfall response in the Sahel is found in several studies using different subsets of CMIP5 models (Monerie *et al* 2012, 2013, Biasutti 2013) and CMIP3 models (Biasutti and Sobel 2009, Fontaine *et al* 2011, Monerie *et al* 2013), different emission scenarios, and different periods (typically looking further out in the future). Figure 5 shows that the rainfall deficit is essentially concentrated in early monsoon season in the Western part of the Sahel in June–July (figure 5(a)) while positive rainfall changes are found in late monsoon season all over the Sahel in September–October (figure 5(b)). It suggests a shift in the seasonality of the monsoon which may start later in the Western part of the Sahel and become more active in fall especially in Central Sahel. This change in seasonality is also very consistent with previous studies using completely different sets of GCM simulations from the CMIP3 (Biasutti and Sobel 2009) and the CMIP5 (Biasutti 2013).

In contrast with rainfall changes, the temperature changes pattern (figures 4(b) and (d)) is quite homogeneous in longitude while presenting a latitudinal gradient: the warming is

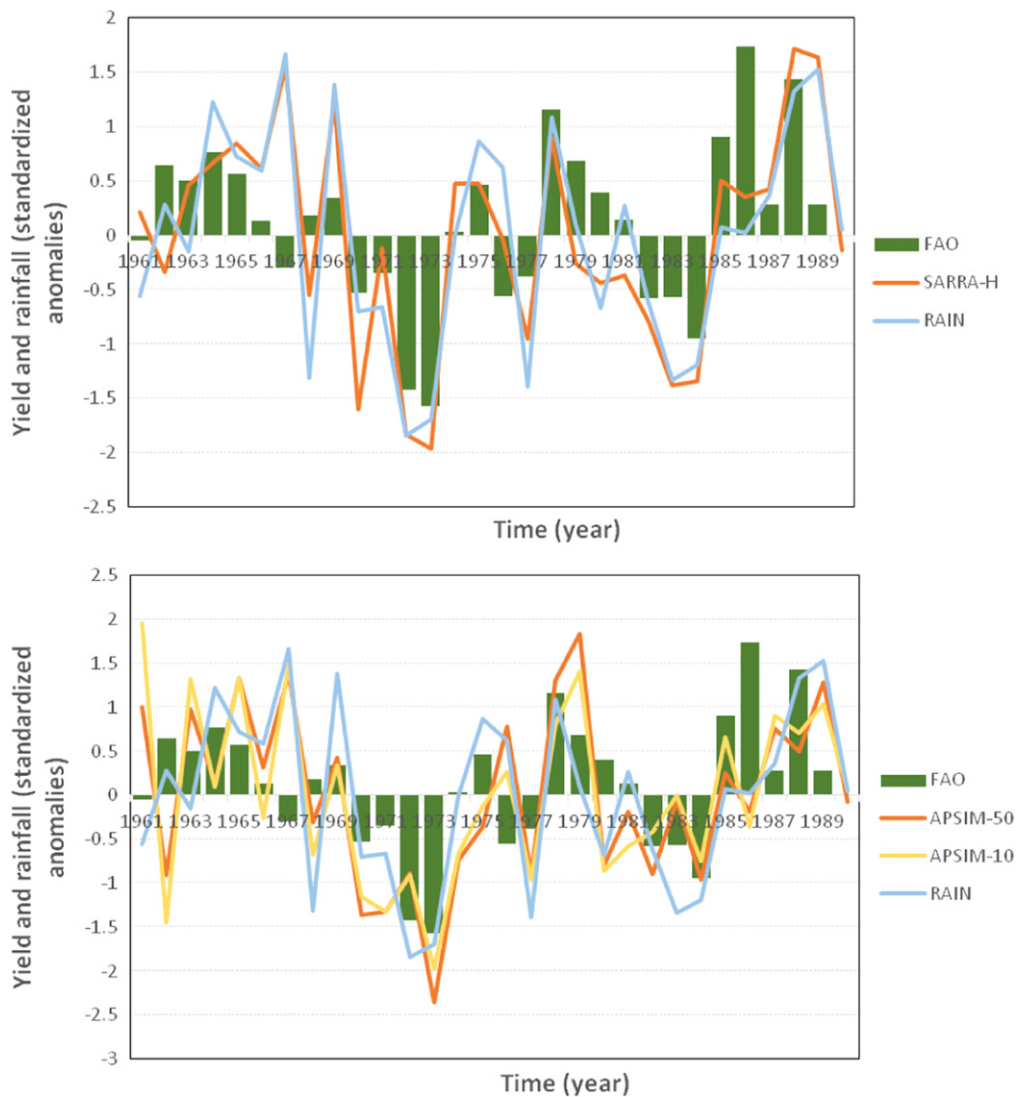


Figure 3. Evaluation of the two crop models. Comparisons in terms of the deviation from the trend line with standardized yield values between simulated yield (multi-variety and multi-sites average of sorghum) from SARRA-H (top panel) and APSIM (bottom panel; with the two fertilization rates 10 kg ha⁻¹ and 50 kg ha⁻¹) and observed FAO yield. The observed yield is an average of countries' national yield (Senegal, Mali, Burkina Faso, Niger, Guinea, Gambia, Guinea Bissau, Togo, Benin) weighted by the national cultivated area. The blue line represents the average rainfall over the 35 stations. A linear trend signal has been removed in all time series.

Table 1. Comparisons between simulated mean yield and observed FAO mean yield. Comparisons between simulated SARRA-H and APSIM mean yield (multi-variety average of sorghum) and observed FAO mean yield. Simulated values are from crop models computations over the 1961–1990 baseline averaging over the 35 stations across West Africa. The observed yield is an average over the 1961–1990 baseline of countries' national yield (Senegal, Mali, Burkina Faso, Niger, Guinea, Gambia, Guinea Bissau, Togo, Benin) weighted by the national cultivated area (of sorghum or millet) given by the FAO. The year 1990 was removed since the observed FAO value was below 2.5 standard deviations. The right column shows the correlation between the mean crop yield and the total annual rainfall.

	Mean	Coefficient of variation	Correlation with rainfall
FAO Observations	588 kg ha ⁻¹	7%	0.62
SARRA-H Simulations	1781 kg ha ⁻¹	15%	0.90
APSIM-10 Simulations	2248 kg ha ⁻¹	20%	0.57
APSIM-50 Simulations	2879 kg ha ⁻¹	15%	0.67

more intense in the Northern Sahel where temperature changes exceed +3 °C in some stations (figure 4(b)). The mean warming is about +2.4 °C but the spread between GCM is large ranging from +2.0 °C (MIROC5 and MPI-ESM-Mr) to

+3.9 °C (IPSL-CM5A-LR) for the 13-station average. The spread is due to differences across models both in climate sensitivity and in rainfall changes (more rain is associated with cooler surface temperatures, because of attendant

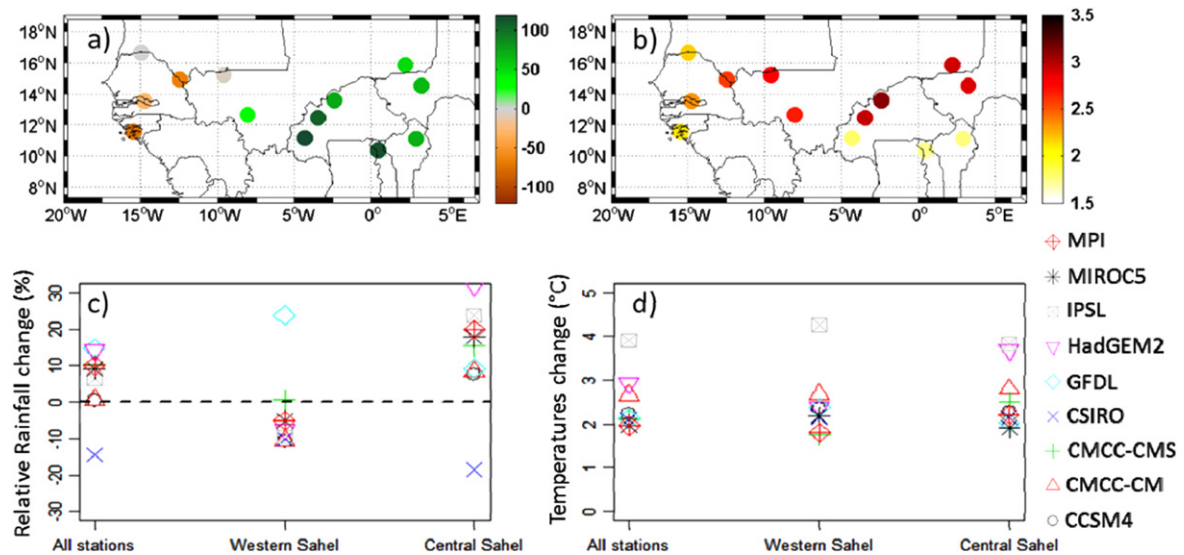


Figure 4. Annual rainfall and mean surface temperature changes under the RCP8.5 scenario. Upper panel: (a) relative rainfall changes (%) and (b) absolute temperature changes (°C) between the periods 2031–2060 and 1961–1990 are computed as averages across the nine GCM simulations for each of the 13 stations. Bottom panel: (c) relative rainfall changes (%) and (d) absolute temperature changes (°C) are computed for each GCM in average across each station, for the six western stations and for the six eastern stations.

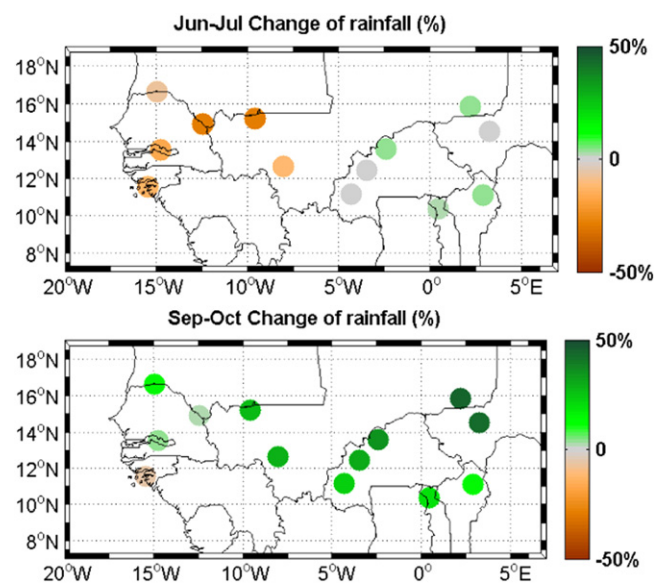


Figure 5. Seasonal rainfall changes under the RCP8.5 scenario. Relative rainfall changes (%) between the periods 2031–2060 and 1961–1990 in June–July (upper panel) and September–October (bottom panel). Relative rainfall changes are computed as averages across the nine GCM simulations for each of the 13 stations.

changes in soil moisture and cloudiness). Yet, in all cases the warming is strong enough that Sahelian temperatures are simulated to become so hot as to have no analog during the 20th century (the same was true for CMIP3 projections, Battisti and Naylor 2009).

3.3. Impacts on sorghum yields

In response to climate change, mean sorghum yields decrease in 12 out of 13 stations, when we average simulations from the two crop models and the three varieties of sorghum

(figure 6(a)). The mean yield loss over West Africa is –13%, consistent with the meta-analysis of Roudier *et al* (2011) that found mean yield loss in West Africa of about –10%. Here we found that this negative impact follows the West-East dipole of rainfall changes with a larger yield loss in Western stations (14–29%) than in the Central Sahel, where the mean yield change ranges from –13% to +7%. Consistent with a dominant role for heat stress, simulated crop yields tend to decrease in the future even where rainfall increases, as in the Central part of the Sahel. The decrease of mean yield in 2031–2050 is a robust feature in our simulations since there is a good agreement across climate and crop models in the yield decrease (figure 6(b)). More than 90% of all simulations lead to a yield decrease in 4 out of 6 stations located in the Western Sahel. The agreement between simulations in a projected yield decrease is lower in the Central Sahel. This is to be expected given that in the Western Sahel both decreasing rain and temperature warming tend to suppress yields, while in Central Sahel rain and temperature changes act in opposite directions.

In addition to the reduction of mean yield, future projections also show an increase of the year-to-year variability of the yields of sorghum (figure 6(c)) especially in the Western Sahel where some stations experience an increase of relative yield variability of more than 20%. Changes in yield variability are not consistent across all simulations, but are robust in Western Sahel, where yield is reduced and thus relative variability is projected to increase from 53 to 85% (figure 6(d)).

The impact of climate change on the mean crop yield is remarkably similar between SARRA-H and APSIM with 10 kg ha⁻¹ fertilization rate (figure 7(a)). Averaged across West Africa, the two models simulate a yield loss of the same magnitude (–10.0% and –10.8% respectively for SARRA-H and APSIM) as well as a more pronounced impact in the

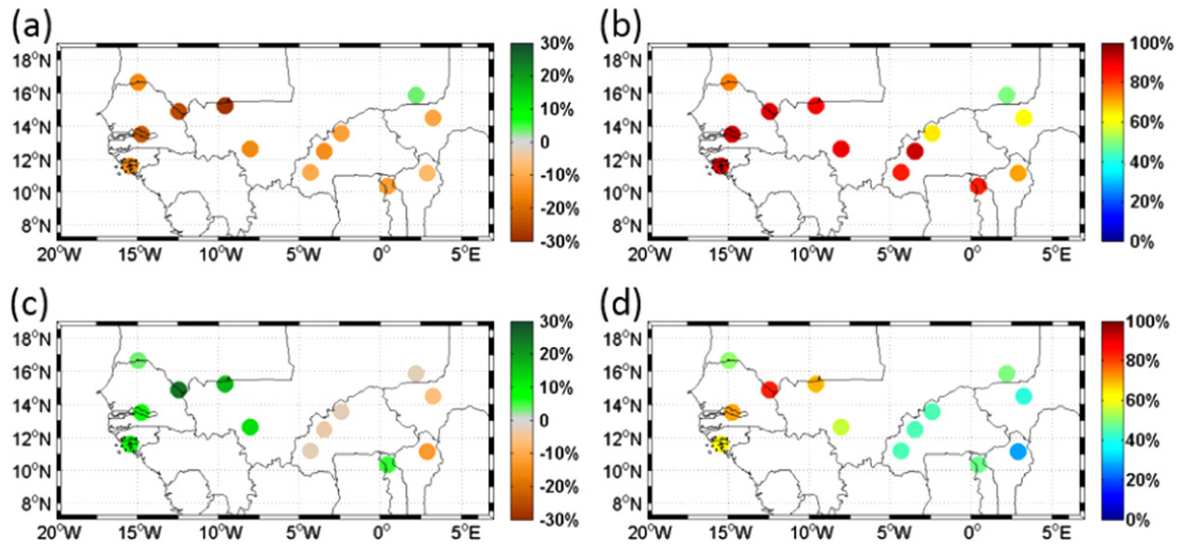


Figure 6. Simulated changes in mean yield and variability under the RCP8.5 scenario. Left panel: relative changes (%) between the periods 2031–2060 and 1961–1990 in mean yield of sorghum (a) and in coefficient of variation of yields (c). Simulated yields are mean yields from the two crop models and the three varieties of sorghum. Right panel: agreement across all model simulations (in %) in the decrease of mean yield (b) and the increase of the coefficient of variation (d) in the 2031–2060 period. This agreement is computed using the nine GCMs, the two crop models and the three varieties of sorghum. In both panels, a weight of ¼ has been given to the two APSIM runs (10 kg ha⁻¹ and 50 kg ha⁻¹) and a weight of ½ to the SARRA-H runs to avoid oversampling of the APSIM simulations.

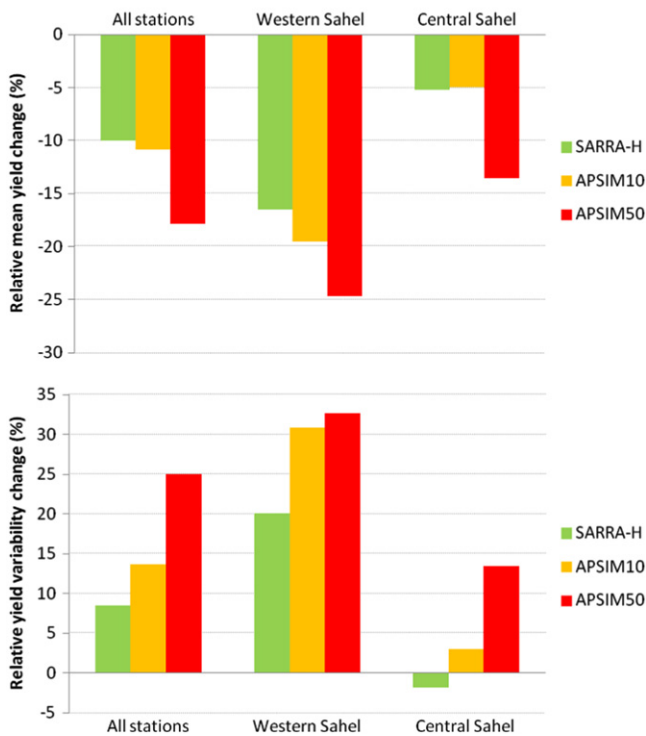


Figure 7. Simulated changes in mean yield and variability across Sahel. Upper panel: relative changes (%) between the periods 2031–2060 and 1961–1990 in mean yield of sorghum in average across the 9 GCM simulations and the three varieties of sorghum. The relative changes are computed on average across the 13 stations (all stations), across the 6 western stations (Western Sahel) and across the 6 eastern stations (Central Sahel). Bottom panel: same but for the relative change in the coefficient of variation.

Western Sahel (−16.5% and −19.6% respectively). The increase of crop yield variability is also very consistent between crop models both in magnitude and in its spatial pattern (figure 7(b)). In the Western Sahel the increase of yield variability is +20.2% and +30.8% respectively for SARRA-H and APSIM. Such consistency between two completely different crop models affirms the robustness of the projections of crop yields under climate change scenarios. While fertilization a higher fertilization rate (10 kg ha⁻¹ vs 50 kg ha⁻¹) increased absolute yield in the APSIM simulations, the climate-induced yield reductions were larger for the high nitrogen fertilization case. A higher fertilization rate leads to a more detrimental impact of climate change everywhere in the Sahel with a decrease of mean crop yield of −17.8% and an increase of variance of almost 25% in average across the 13 stations in West Africa. The different APSIM results from two fertilizer rates demonstrate that when nitrogen stress is decreased or minimized, sorghum yields become more responsive to water and heat stresses brought forth by climate change (i.e. robust rainfall decreases and temperature increases).

The short-duration, modern variety of sorghum tends to be more resilient to the adverse effects of climate changes than the two traditional varieties, in that both the yield loss and the variability increase are weaker (figure 8). This is especially true in the APSIM model, which simulates large differences between cultivars and even positive impacts in Central Sahel with the modern short-duration variety (figure S2 in the supplementary material). The advantage of the short-duration photoperiod insensitive cultivar might be a consequence of the seasonality shift of the monsoon with less rainfall at the beginning of the rainy season and more rainfall in late monsoon season. Indeed, in both crop models, sowing

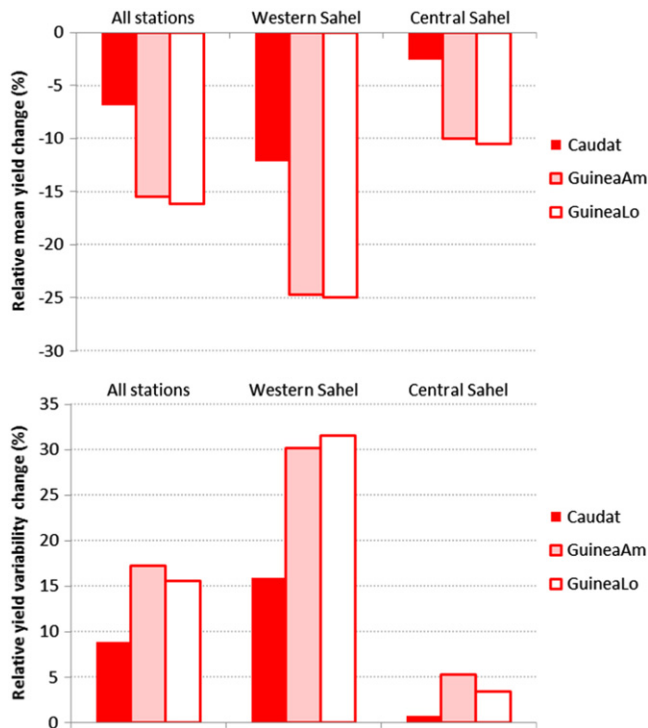


Figure 8. Changes in mean yield and variability across varieties. Upper panel: relative changes (%) between the periods 2031–2060 and 1961–1990 in mean yield of sorghum on average across the 9 GCM simulations for each of the three varieties of sorghum. Simulated yields are mean yields from the two crop models and a weight of ¼ has been given to the two APSIM runs (10 kg ha⁻¹ and 50 kg ha⁻¹) and a weight of ½ to the SARRA-H runs to avoid oversampling of the APSIM simulations. Results per crop model are shown in figure S1. The relative changes are computed in average across the 13 stations (all stations), across the 6 western stations (Western Sahel) and across the 6 eastern stations (Central Sahel). Bottom panel: same but for the relative change in the coefficient of variation.

is delayed (by 7.3 and 4.1 d respectively in SARRA-H and APSIM; table S3 in the supplementary material). In the SARRA-H model, this delays maturity of the photoperiod insensitive cultivar by 3.3 days. Warming still acts to shorten the crop cycle length, but the delay in maturity date ameliorates this effect. Such a delay in maturity is not simulated for the two photoperiod sensitive varieties (table S3) for which the flowering date is relatively independent of sowing date (Kouressy *et al* 2008a). The photoperiod-sensitive varieties have thus a larger reduction of their growing season compared to the modern photoperiod-insensitive variety and are not able to take advantage of more rainfall in late monsoon season.

Finally, we show the effect of CO₂ in the APSIM model (figure 9). CO₂ fertilization positively increases the crop yields by 6–10% across the whole region, though the net impact of climate change for crop yields is still negative after accounting for CO₂ effects, except in Central Sahel. Different fertilizer inputs have a slight impact on the positive benefits of CO₂ fertilization (10 kg ha⁻¹: +7.5%; 50 kg ha⁻¹: +9.6%), and the three cultivars show little difference in the benefits (figure S3 in the supplementary material). However, the impacts of CO₂ fertilization vary clearly with mean annual rainfall, with dry areas having the largest benefits (figure 9(b)). APSIM

simulates the CO₂ fertilization effects through an increase in transpiration efficiency, thus drier areas benefit more than wetter ones from the increased water use efficiency.

4. Summary and discussion

We assess the impacts of near-term climate change on the mean and variability of yields for traditional and modern sorghum varieties in West Africa, accounting for uncertainties both in future climate scenarios and in crop models. We constructed regional bias-corrected forcings from nine GCMs extracted from the CMIP5 archive and used two crop models (SARRA-H and APSIM) with different treatments for nutrients and other key variables to obtain the most robust projections to date of future crop yields in this region. This approach emphasizes the range of possible outcomes for the region, at the expense of trying to determine the most likely outcome for any given locality. Thus, we pool together results from climate and crop models with diverse skills and sensitivities and we make no attempt to determine the exact soil and treatment conditions for each station in the analysis. In viewing our results, one should be mindful of both the qualitative robustness of the climate change signal, and the quantitative range of possible outcomes.

In West Africa, future climate projections from our subset of bias-corrected GCMs show a mean warming of +2.8 °C in 2031–2060 compared to our baseline period 1961–1990. This warming is accompanied by robust changes in rainfall showing a West-East dipole with less rain in the Western part of the Sahel (Senegal, South-West Mali) and more rain in Central Sahel (Burkina Faso, South-West Niger). The rainfall deficit is essentially concentrated in the early monsoon season in the Western Sahel while positive rainfall changes are found in late monsoon season all over the Sahel. Both the West-East dipole in mean rainfall changes and the late start of the monsoon are consistent with previous studies using raw output from larger GCM ensembles.

In our simulations, climate change leads to a decrease in sorghum yields everywhere in West Africa—even in the Central Sahel where rainfall is increasing. In addition, the coefficient of variation of yields increases, which might indicate a greater risk of crop failures under a warmer climate. These findings are robust across the two crop models used in this study and are consistent with previous findings for C₄ crops, e.g. maize (Jones and Thornton 2003, and Schlenker and Lobell 2010), millet, and sorghum (Sultan *et al* 2013). All these studies confirm that temperature increase is the main driver of adverse yield changes in the future.

To define adaptation strategies for agriculture in Africa, we must be able to identify the most vulnerable areas and to specify crop varieties with the most robust characteristics for withstanding climate change. Here we find that the impacts of climate change are greatest in the Western part of the Sahel (mean yield losses of some 16–20% and increased interannual variability), where the projected warming is associated with a decrease of rainfall especially during the early monsoon season. East–West differences in climate and impacts

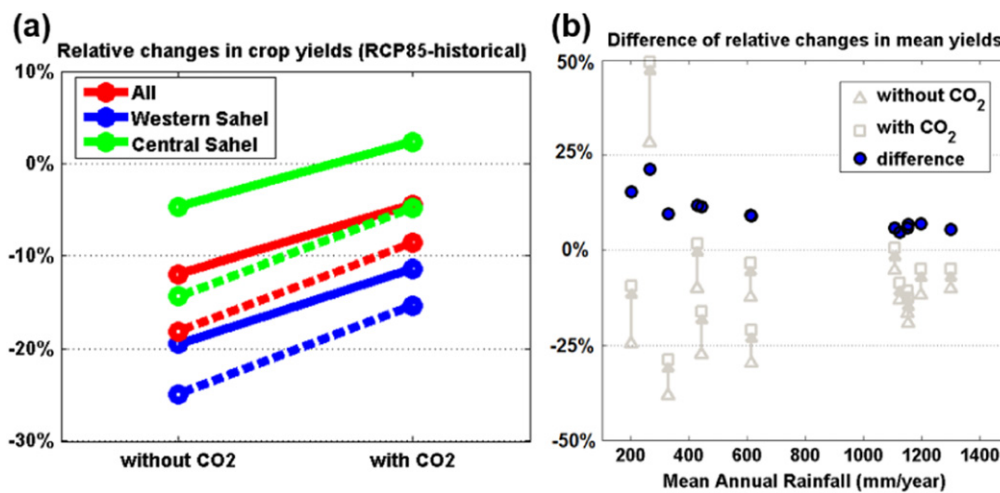


Figure 9. Effects of CO₂ on climate change impacts on crop yields. (a) Effects of CO₂ on relative changes (%) in mean crop yields. The solid and dashed lines refer to 10 kg ha⁻¹ and 50 kg ha⁻¹ fertilizer inputs. The results are averaged over all GCM model ensembles and three crop cultivars. (b) Station-level relative yield changes (%) averaged over both nutrient levels with or without CO₂ effects, and also the benefits of CO₂ fertilization in terms of relative changes in crop yields, as a function of mean annual precipitation (mm/year).

projections are a highly consistent feature across the climate and crop models used in the study.

Our simulations also show that the effect of climate change is not identical for all cultivars of sorghum: adverse impacts on mean yield and yield variability were found to be the lowest for modern cultivars with a short and nearly fixed growth cycle. This finding is in contrast with the conclusions of Sultan *et al* (2013): using the same SARRA-H model, they found that modern cultivars were most susceptible to climate change. That study only considered uniform changes in rainfall patterns, but we suggest that changes in the seasonality of the monsoon—with less rainfall at the beginning of the rainy season—can greatly affect crop growth. Indeed, in our simulations, the seasonality shift leads to a delayed sowing in both crop models, which shortens the rainy season and makes short-duration varieties more adapted in the future. This result is consistent with the study from Kouressy *et al* (2008a), which demonstrated that potentially high-yielding and photoperiod-insensitive modern cultivars display an advantage where the rainy season is short. In our case modern varieties offer a double-benefit of higher yields and more resilience to climate change. In future scenarios, with a low nitrogen stress (50 kg ha⁻¹), the APSIM model simulates yields that are 68% higher with modern varieties compared to the two other varieties. This yield benefit can be up to 128% with the SARRA-H model which has no nitrogen stress.

The interaction between water stress and nitrogen stress in the nutrient-deficient Sahel is another interesting emerging pattern. When soil receives little inputs and is over-exploited as it is often in the Sahel (Sheldrick and Lingard 2004, Roy *et al* 2003), the crop system is much less responsive to changes in other environmental variables (e.g. temperature and rainfall). Particularly in the Sahel, the benefits of reduced water stress by increased rainfall can be largely offset by the increased nitrogen stress induced by leaching. This is why increasing fertilizer inputs can make the Sahel agricultural system more responsive to climatic stresses and produce more

negative impacts (in a relative sense, %) in crop yields under climate change, though the absolute yield would increase by 30% from 10 kg ha⁻¹ to 50 kg ha⁻¹ (table S3). Our results are consistent with another modeling study (Turner and Rao 2013), which shows that the impact of warming is minimum for low-input, small-holder, sorghum farmers in some African region, as these systems are too much nutrient-stressed. Thus, while increasing fertilizer inputs and restoring nutrients imbalance increase overall food production and have fundamental benefits for the agricultural development of Africa (Vitousek *et al* 2009), the trade-off is that the improved agro-systems would be more sensitive to climate change.

The impact of higher atmospheric CO₂ concentration is a major source of uncertainty in crop yield projections (Sousana *et al* 2010, Roudier *et al* 2011). There is an ongoing debate about the extent of impacts of CO₂ fertilization on crop yields in observations and models (Long *et al* 2006, Ainsworth, Long 2005). In our simulations, CO₂ fertilization would significantly reduce the negative climate impacts, increasing sorghum yields on average by 10%, and drier regions would have the largest benefits. This estimate, based on the APSIM model, is much higher than in a previous study for C4 crops (Berg *et al* 2013), though both studies agree that the largest impacts happen in arid regions. The only effect of CO₂ in APSIM-sorghum is to increase the transpiration efficiency (by 37% when CO₂ concentration rises from 350 ppm to 700 ppm), which increases the water use efficiency and as a result has more benefits for dry regions or drought years. The differences among various crop models (Tubiello and Ewert 2002) as well as between model simulations and field experiments (Ainsworth *et al* 2008) are still large, and these differences highlight the large uncertainties in this critical issue. Future research based on observations is urgently needed to clarify how to best model the impacts of CO₂ fertilization. However CO₂ fertilization effects are unlikely to modify the main conclusions of this study. Indeed, even after accounting for CO₂, yield losses remain more important in the

Western Sahel and shorter duration varieties more resilient to climate change.

Acknowledgements

This work has been funded by the French National Research Agency (ANR) through the ESCAPE project (ANR-10-CEPL-005), US National Science Foundation (SES-1048946) and the France-Stanford Center for Interdisciplinary Studies.

References

- Ainsworth E A, Leakey A D B, Ort D R and Long S P 2008 FACING the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated (CO₂) impacts on crop yield and food supply *New Phytologist* **179** 5–9
- Ainsworth E A and Long S P 2005 What have we learned from 15 years of free-air CO₂ enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO₂ *New Phytologist* **165** 351–71
- Akponikpè P I, Gérard B, Michels K and Biolders C 2010 Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel *Eur. J. Agronomy* **32** 144–54
- Asseng G *et al* 2013 Uncertainty in simulating wheat yields under climate change *Nat. Clim. Change* **3** 827–32
- Barnabás B, Jäger K and Fehér A 2008 The effect of drought and heat stress on reproductive processes in cereals *Plant Cell Environ.* **31** 11–38
- Baron C, Sultan B, Balme M, Sarr B, Lebel T, Janicot S and Dingkuhn M 2005 From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact *Phil. Trans. R. Soc. B* **360** 2095–108
- Bationo A, Kihara J, Waswa B, Ouattara B and Vanlauwe B 2005 Integrated soil fertility management technologies for sustainable management of sandy Sahelian soils *Proc. of the Int. Symp. on 'The management of tropical sandy soils for sustainable agriculture- a holistic approach for sustainable development of problem soils in the tropics'* November 2005 (Khon Kaen, Thailand)
- Battisti D and Naylor R L 2009 Historical warnings of future food insecurity with unprecedented seasonal heat *Science* **323** 240
- Berg A, de Noblet-Ducoudré N, Sultan B, Lengaigne M and Guimberteau M 2013 Projections of climate change impacts on potential crop productivity over tropical regions *Agric. Forest Meteorol.* **170** 89–102
- Biasutti M 2013 Forced Sahel rainfall trends in the CMIP5 archive *J. Geophys. Res. Atmos.* **118** 1613–23
- Biasutti M and Sobel A H 2009 Delayed Sahel rainfall and global seasonal cycle in a warmer climate *Geophys. Res. Lett.* **36** L23707
- Bondeau A, Smith P C, Zaehle S *et al* 2007 Modelling the role of agriculture for the 20th century carbon balance *Glob. Change Biol.* **13** 679–706
- Brown M E, de Beurs K and Vrieling A 2010 The response of African land surface phenology to large scale climate oscillations *Remote Sens. Environ.* **114** 2286–96
- Challinor A J, Wheeler T, Craufurd P Q *et al* 2004 Design and optimisation of a large-area process based model for annual crops *Agric. Forest Meteorol.* **124** 99–120
- Challinor A J, Wheeler T, Craufurd P Q *et al* 2005 Simulation of crop yields using ERA-40: limits to skill and nonstationarity in weather–yield relationships *J. Appl. Meteorol.* **44** 516–31
- Challinor A, Wheeler T, Garforth C, Craufurd P and Kassam A 2007 Assessing the vulnerability of food crop systems in Africa to climate change *Clim. Change* **83** 381–99
- Chen C, Haerter J O, Hagemann S and Piani C 2011 On the contribution of statistical bias correction to the uncertainty in the projected hydrological cycle *Geophys. Res. Lett.* **38** 20403
- Clerget B, Dingkuhn M, Goze E, Rattunde H F W and Ney. B 2008 Variability of phyllochron, plastochron and rate of increase in height in photoperiod-sensitive sorghum varieties *Ann. Bot.* **101** 579–94
- Dingkuhn M, Baron C, Bonnal V, Maraux F, Sarr B, Sultan B, Clopes A and Forest F 2003 Decision support tools for rainfed crops in the Sahel at the plot and regional scales *Decision Support Tools for Smallholder Agriculture in Sub-Saharan Africa—A Practical Guide* ed T E Struif Bontkes and M C S Wopereis (Wageningen, The Netherlands: CTA) pp 127–39
- Dingkuhn M, Singh B B, Clerget B, Chantereau J and Sultan B 2006 Past, present and future criteria to breed crops for water-limited environments in West Africa *Agric. Water Manage.* **80** 241–61 (1-3 SPEC. ISS.)
- Druryan L M 2011 Studies of 21st-century precipitation trends over West Africa *Int. J. Climatol.* **31** 1415–572
- FAO 1999 Food insecurity: when people must live with hunger and fear of starvation *The State of Food Insecurity in the World* (Rome: FAO) p 32
- Fontaine B, Roucou P and Monerie P-A 2011 Changes in the African monsoon region at medium-term time horizon using 12 AR4 coupled models under the A1b emissions scenario *Atmos. Sci. Lett.* **12** 83–8
- Funk C, Rowland J, Adoum A, Eilerts G, Verdin J and White L 2012 A climate trend analysis of Senegal *Famine Early Warning Systems Network* (Reston, VA: U.S. Geological survey) pp 1–4
- Hammer G L, van Oosterom E, McLean G, Chapman S C, Broad I, Harland P and Muchow R C 2010 Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops *J. Exp. Bot.* **61** 2185–202
- Harrison M T, Tardieu F, Dong Z, Messina C D and Hammer G L 2014 Characterizing drought stress and trait influence on maize yield under current and future conditions *Glob. Change Biol.* **20** 867–78
- Heisey P W and Mwangi W 1996 Fertilizer use and maize production in sub-saharan Africa *CIMMYT Economics Working Paper 96-01. Mexico, D.F.: CIMMYT*
- IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II.* (Cambridge, UK: Cambridge University Press)
- Jones P and Thornton P 2003 The potential impacts of climate change on maize production in Africa and Latin America in 2055 *Glob. Environ. Change* **13** 51–9
- Keating B *et al* 2003 An overview of APSIM, a model designed for farming systems simulation *Eur. J. Agronomy* **18** 267–88
- Knox J, Hess T, Daccache A and Wheeler T 2012 Climate change impacts on crop productivity in Africa and South Asia *Environ. Res. Lett.* **7** 034032
- Kouressy M, Dingkuhn M, Vaksmann M, Clément-Vidal A and Chantereau J 2008b Potential contribution of dwarf and leaf longevity traits to yield improvement in photoperiod sensitive sorghum *Eur. J. Agronomy* **28** 195–209
- Kouressy M, Dingkuhn M, Vaksmann M and Heinemann A B 2008a Adaptation to diverse semi-arid environments of sorghum genotypes having different plant type and sensitivity to photoperiod *Agric. Forest Meteorol.* **148** 357–71
- Kumar S S, Hammer G L, Broad I, Harland P and McLean G 2009 Modelling environmental effects on phenology and canopy development of diverse sorghum genotypes *Field Crops Res.* **111** 157–65

- Long S P, Ainsworth E A, Leakey A D B, Nösberger J and Ort D R 2006 Food for thought: lower-than-expected crop yield stimulation with rising CO₂ concentrations *Science* **312** 1918–21
- Marteau R *et al* 2011 The onset of the rainy season and farmers' sowing strategy for pearl millet cultivation in Southwest Niger *Agric. Forest Meteorol.* **151** 1356–69
- Meehl G A *et al* 2007 THE WCRP CMIP3 multimodel dataset: a new era in climate change research *Bull. Am. Meteorol. Soc.* **88** 1383–94
- Mishra A *et al* 2008 Sorghum yield prediction from seasonal rainfall forecasts in burkina faso *Agric. Forest Meteorol.* **148** 1798–814
- Monerie P-A, Fontaine B and Roucou P 2012 Expected future changes in the African monsoon between 2030 and 2070 using some CMIP3 and CMIP5 models under a medium-low RCP scenario *J. Geophys. Res.* **117** D16111
- Monerie P-A, Roucou P and Fontaine B 2013 Mid-century effects of climate change on African monsoon dynamics using the A1B emission scenario *Int. J. Climatol.* **33** 881–96
- Oettli P, Sultan B, Baron C and Vrac M 2011 Are regional climate models relevant for crop yield prediction in West Africa? *Environ. Res. Lett.* **6** 014008
- Panthou G, Vischel T and Lebel T 2014 Recent trends in the regime of extreme rainfall in the Central Sahel *Int. J. Climatol.* doi:10.1002/joc.3984
- Patricola C M and Cook K H 2010 Northern African climate at the end of the 21st century: integrated application of regional and global climate models. *Clim. Dyn.* **35** 193–212
- Piani C, Weedon G P, Best M, Gomes S M, Viterbo P, Hagemann S and Haerter J O 2010 Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models *J. Hydrol.* **395** 199–215
- Roudier P, Sultan B, Quirion P and Berg A 2011 The impact of future climate change on West African crop yields: what does the recent literature say? *Glob. Environ. Change* **21** 1073–83
- Roy R N, Misra R V, Lesschen J P and Smaling E 2003 Assessment of soil nutrient balance: approaches and methodologies, 14 (Rome: FAO) www.fao.org/docrep/006/y5066e/y5066e00.htm#Contents
- Schlenker W and Lobell D 2010 Robust negative impacts of climate change on African agriculture *Environ. Res. Lett.* **5** 014010
- Schmidhuber J and Tubiello F N 2007 Global food security under climate change *Proc. Natl. Acad. Sci. USA* **104** 19703–8
- Sheldrick W F and Lingard J 2004 The use of nutrient audits to determine nutrient balances in Africa *Food Policy* **29** 61–98
- Soussana J-F, Graux A-I and Tubiello F N 2010 Improving the use of modelling for projections of climate change impacts on crops and pastures *J. Exp. Bot.* **61** 2217–28
- Sultan B, Baron C, Dingkuhn M and Janicot S 2005 Agricultural impacts of large-scale variability of the west African monsoon *Agric. Forest Meteorol.* **128** 93–110
- Sultan B, Roudier P, Baron C, Quirion P, Muller B, Alhassane A, Ciais P, Guimberteau M, Traoré S B and Dingkuhn M 2013 Assessing climate change impacts on sorghum and millet yields in West Africa *Environ. Res. Lett.* **8** 014040
- Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98
- Traoré S B *et al* 2011 Characterizing and modeling the diversity of cropping situations under climatic constraints in West Africa *Atmos. Sci. Lett.* **12** 89–95
- Tubiello F N and Ewert F 2002 Simulating the effects of elevated CO₂ on crops: approaches and applications for climate change *Eur. J. Agronomy* **18** 57–74
- Turner N C and Rao K 2013 Simulation analysis of factors affecting sorghum yield at selected sites in eastern and southern Africa, with emphasis on increasing temperatures *Agric. Syst.* **121** 53–62
- van Oosterom E, Borrell A, Broad S C I and Hammer G 2010 Functional dynamics of the nitrogen balance of sorghum: I. N demand of vegetative plant parts *Field Crops Res.* **115** 19–28
- Vitousek P M *et al* 2009 Nutrient imbalances in agricultural development *Science* **324** 1519–20