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# Assessing climate adaptation options and uncertainties for cereal systems in West Africa

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ABSTRACT

In the coming decades, the already fragile agricultural system in West Africa will face further challenges in meeting food security, both from increasing population and from the impacts of climate change. Optimal prioritization of adaptation investments requires the assessment of various possible adaptation options and their uncertainties; successful adaptations of agriculture to climate change should not only help farmers deal with current climate risks, but also reduce negative (or enhance positive) impacts associated with climate change using robust climate projections. Here, we use two well-validated crop models (APSIM v7.5 and SARRA-H v3.2) and an ensemble of downscaled climate forcing from the CMIP5 models to assess five possible and realistic adaptation options for the production of the staple crop sorghum (*Sorghum bicolor Moench.*): (i) late sowing, (ii) intensification of seeding density and fertilizer use, (iii) increasing cultivars' thermal time requirement, (iv) water harvesting, and (v) increasing resilience to heat stress during the flowering period. We adopt a new assessment framework to account for both the impacts of proposed adaptation options in the historical climate and their ability to reduce the impacts of future climate change, and we also consider changes in both mean yield and inter-annual yield variability. We target the future period of 2031–2060 for the "business-as-usual" scenario (RCP8.5), and compare with the historical period of 1961–1990. Our results reveal that most proposed "adaptation options" are not more beneficial in the future than in the historical climate (−12% to +4% in mean yield), so that they do not really reduce the climate change impacts. Increased temperature resilience during the grain number formation period is the main adaptation that emerges (+4.5%). Intensification of fertilizer inputs can dramatically benefit yields in the historical/current climate (+50%), but does not reduce negative climate change impacts except in scenarios with substantial rainfall increases. Water harvesting contributes to a small benefit in the current climate (+1.5% to +4.0%) but has little additional benefit under climate change. Our analysis of uncertainties arising from crop model differences (conditioned on the used model versions) and various climate model projections provide insights on how to further constrain uncertainties for assessing future climate adaptation options.



## 1. Introduction

West Africa faces great challenges in reaching food security in the coming decades. The population increase in West African countries will remain among the fastest in the world (United Nation, 2015), adding a large increase in food demands in countries where a large fraction of the population is still facing chronic hunger and malnutrition (Schmidhuber and Tubiello, 2007). Whether the region can meet a growing food demand is further complicated by climate change, which is projected to adversely affect crop yields

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in the future (Lobell et al., 2014, 2011, 2008; Müller et al., 2011; Schlenker and Lobell, 2010; Sultan et al., 2014, 2013). Successful adaptation of agriculture to climate change is key to meet the increasing food demands in this region.

Climate models largely agree on several aspects of future rainfall and temperature changes in West Africa (Biasutti and Sobel, 2009; Biasutti, 2013; Sultan et al., 2014). Higher temperature is expected over the whole West Africa, with a mean warming of 2.8 °C in the decades of 2031–2060 compared to the baseline of 1961–1990 (Fig. 1) for the "business-as-usual" scenario. The projected change in rainfall is more complicated and regionally dependent, with the West Sahel experiencing a delayed rainy season and an overall decrease in total rainfall amount, and the Central Sahel largely experiencing an increase in total rainfall amount (Fig. 1). These climatic changes are superimposed on top of high natural variability in seasonal rainfall, which historically has produced large inter-annual variations in rainfall and prolonged droughts (Giannini et al., 2008) and the recent increase in rainfall intensity and extreme heavy-rainfall events (Panthou et al., 2014). Both climate variability and trend pose a challenge for the primarily rain-fed agriculture systems in West Africa. Any successful adaptations should be able to cope with the short-term climate variability as well as reduce the negative impacts of climate change in the long term (Lobell, 2014; Saba et al., 2013).

Various possible adaptations for crop production have been proposed or assessed in the literature, whether related to technology, management or some combination of the two (Fisher et al., 2015). Major options include changes in crop cultivars and types (e.g. Sultan et al., 2014), improved drought and heat tolerance (e.g. Rosegrant et al., 2014; Singh et al., 2014), changes in sowing rules that shift the crop growth period (e.g. Kucharik, 2008; Lobell et al., 2012; Rosenzweig and Parry, 1994), water harvesting (e.g. Rockström and Falkenmark, 2015; Rosegrant et al., 2014) and irrigation (e.g. Rosenzweig and Parry, 1994), no-tillage (e.g. Derpsch et al., 2010), and intensification with higher planting density and/or higher fertilizer inputs, as was done during the Green Revolution (e.g. Aune and Bationo, 2008; Pingali, 2012). In the case of West Africa and nearby regions, a few adaptation options have been assessed so far through either modeling (Kassie et al., 2015; Singh et al., 2014) or experimental studies (Traore et al., 2014). However, it still remains largely unknown what possible adaptations can best enhance the resilience of crop yield in the current climate as well as be adaptive to the long-term climate change.

A key distinction in defining the benefits of adaptation is made between actions that are generally beneficial to future welfare, and those that specifically reduce the impact of climate change. Our study will adopt the "impact-reducing" definition by Lobell (2014), and use his proposed framework (Fig. 2a) to quantify the true adaptation impact—as well as the impact in the current climate—of a specific adaptation option. The details for the framework and assessment criteria are provided in the Methods.

Here we use two well-validated crop models and an ensemble of downscaled climate forcing from the Climate Model Intercomparison Project, Phase 5 (CMIP5) ensemble to assess a suite of possible adaptations for the production of sorghum [Sroghum bicolor (L.) Moench] in West Africa. Sorghum is the most important cereal in the Guinea and Sudan savannah, where annual rainfall is a mere 600–1100 mm per year (Kouressy et al., 2008). This work expands on a previous impact study for the same region (Sultan et al., 2014), which identified a robust negative impact of climate change on sorghum yield and suggested that switching from the traditional to the modern cultivar is an adaptation. The current work takes a further step to assess a full suite of possible adaptations and attempts to provide guidance for prioritizing adaptation investments. We are addressing the following two questions: (1) What are the adaptation options that can both benefit farmers in the current climate and reduce impacts of climate change? (2) What causes the uncertainties of the various adaptation impacts?

## 2. Materials and methods

### 2.1. Crop models and study sites

This study focuses on the regional crop yield response in West Africa (18°W–5°W in longitude and 10°N–18°N in latitude). Detailed meteorological records from 35 stations across the region for the 1961–1990 period have been compiled by AGRHYMET Regional Center and National Meteorological Agencies. For the crop simulation we focused on 13 out of the 35 stations (Fig. 1), because these 13 stations are more evenly distributed across the study area and the aggregated results are less biased to a specific region but rather representative of the whole West Africa pattern.

Two different crop models are used in this study: SARRA-H (version v3.2) (Kouressy et al., 2008) and APSIM (version 7.5) (Hammer et al., 2010; Holzworth et al., 2014). Both models have been calibrated with the same field trial data (Dingkuhn et al., 2008; Traoré et al., 2011). They have also been validated against regional crop statistics from FAO country-level statistics, with the inter-annual correlation coefficient between simulated and observed detrended yields being 0.70 for the SARRA-H model and 0.52 for the APSIM simulations (Sultan et al., 2014). Both crop models simulate soil water balance, plant carbon assimilation, biomass partition and phenology, with APSIM having the major distinctions in (i) explicitly simulating nitrogen stress, (ii) heat stress for grain number formation, and (iii) including the $CO_2$ fertilization effect. It is worth noting that the recent SARRA-H model has incorporated advanced functionality to include nitrogen cycle and $CO_2$ fertilization effect, however here we only report the results with the SARRA-H version v3.2 since this was the version that we had when we conducted this research. The heat stress for grain number formation in APSIM happens before (150 GDD units) and shortly (50 GDD units) after the flowering period, and the formation of grain number linearly decreases with daily maximum temperature increasing from 36 °C to 40 °C (Singh et al., 2015). The $CO_2$ fertilization in APSIM is realized through linearly increasing the transpiration efficiency (i.e. reducing the potential daily water demand associated with a given level of potential photosynthesis) by 37% at 700 ppm compared with at 350 ppm based on the synthesis of multiple field and laboratory studies (Harrison et al., 2014; Lobell et al., 2015). The direct effect of $CO_2$ on radiation use efficiency is not simulated. These three unique features of APSIM lead to some differences from SARRA-H in their simulated yield response under climate change; this source of uncertainty will be discussed in Section 4. We use the calibrated soil parameters derived from the previous work in Sultan et al. (2014) for the study area. Specifically, due to the low quality of soil survey data for this region, we calibrated the soil parameters (hydraulic properties and soil organic matter) so that (1) our two crop models could simulate the relationship between historical yield and rainfall when driving with historical climate data; and (2) our two crop models could simulate the correct magnitude of yield response at different levels of fertilizer inputs (van der Velde et al., 2014).

### 2.2. Downscaled and bias-corrected climate forcing

We used historical simulations and the RCP8.5 projections from 8 general circulation models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012), namely CCSM4, CMCC-CM, CMCC-CMS, CSIRO-Mk3-6-0, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MPI-ESM-Mr. The choice of the models was based solely on the availability of daily values of precipitation and of mean, maximum, and minimum surface