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Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna

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Supplementary material for this article is available online

Abstract

To reduce the risks of climate change, governments agreed in the Paris Agreement to limit global temperature rise to less than 2.0 °C above pre-industrial levels, with the ambition to keep warming to 1.5 °C. Charting appropriate mitigation responses requires information on the costs of mitigating versus associated damages for the two levels of warming. In this assessment, a critical consideration is the impact on crop yields and yield variability in regions currently challenged by food insecurity. The current study assessed impacts of 1.5 °C versus 2.0 °C on yields of maize, pearl millet and sorghum in the West African Sudan Savanna using two crop models that were calibrated with common varieties from experiments in the region with management reflecting a range of typical sowing windows. As sustainable intensification is promoted in the region for improving food security, simulations were conducted for both current fertilizer use and for an intensification case (fertility not limiting). With current fertilizer use, results indicated 2% units higher losses for maize and sorghum with 2.0 °C compared to 1.5 °C warming, with no change in millet yields for either scenario. In the intensification case, yield losses due to climate change were larger than with current fertilizer levels. However, despite the larger losses, yields were always two to three times higher with intensification, irrespective of the warming scenario. Though yield variability increased with intensification, there was no interaction with warming scenario. Risk and market analysis are needed to extend these results to understand implications for food security.

Introduction

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) identified reduced crop productivity as one of the key risks for Africa and assessed risks without adaptation as very high already at a warming of 2 °C (2014). '*To reduce the risks and impacts of climate change*' the UNFCCC has established the long term temperature limit of 1.5 °C in its 2015 Paris Agreement (UNFCCC 2015), as well as, invited the IPCC to produce a special report on the impacts of 1.5 °C and in particular the differences between 1.5 °C and 2 °C global warming. Charting appropriate mitigation policies and actions require information on the costs of mitigating to 1.5 °C versus 2.0 °C (Hulme 2016) as well as on the damages associated with the two levels of global warming. Recent studies suggest substantial effects on the agricultural sector under a mitigation target of 1.5 °C (Ruane *et al* 2018a). One critical consideration is implications for crop yields and yield stability in regions currently challenged by food insecurity, such as West Africa's Sudan Savanna.

For many people in in the West African Sudan Savanna, complex combinations of semi-subsistence cereal cropping and livestock agriculture constitute their main source of livelihood (Giller *et al* 2011, Jalloh *et al* 2013). Crop productivity has an important influence on food security, contributing directly to household food availability, as well as influencing incomes, local food prices and farmers' ability to invest in other on- and off-farm livelihood activities (Vermeulen *et al* 2012, Jalloh *et al* 2013, Frelat *et al* 2016). In principle, high food prices should benefit farmers who are net food sellers (Hertel 2016), although weak market integration and the timing of buying and selling food crops often results in regional food insecurity and high sensitivity to food price shocks (Brown *et al* 2009, Wheeler and Von Braun 2013). Extreme price spikes have been found to limit investment in technologies to increase agricultural production (Kalkuhl *et al* 2016). Finally, for the most food insecure farmers with little market involvement, inter-annual yield variability represents high risk of hunger and ensuring minimal yield levels are critical.

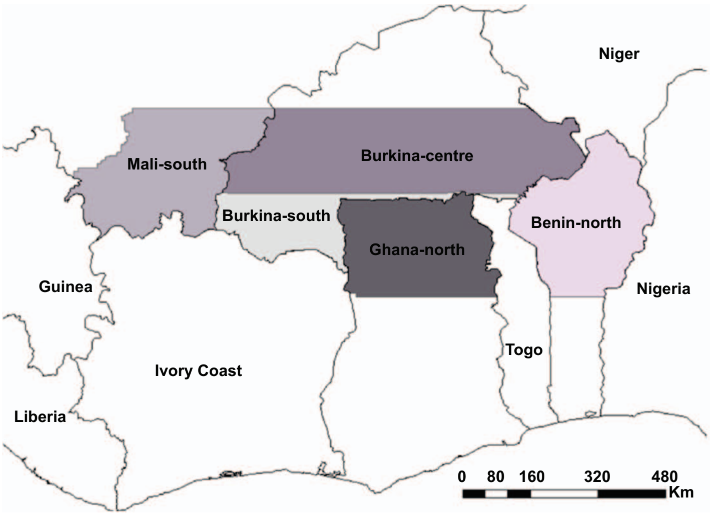
To tackle the joint challenges of food insecurity and poverty, many West African governments have adopted the Comprehensive Africa Agricultural Development Program, which promotes economic growth through the intensification and commercialization of smallholder farms (NEPAD 2003, Kolavalli *et al* 2010). However, the many constraints to sustainable smallholder intensification are significant and expected to increase with climate change (Godfray *et al* 2010), as various studies show negative impacts of climate change and variability on crop yields (Schlenker and Lobell 2010, Roudier *et al* 2011, Adiku *et al* 2015). Previous studies in West Africa have demonstrated the interaction of fertilizer intensity (Traore *et al* 2017) or variety characteristics (Sultan *et al* 2013, Sultan *et al* 2014) with climate change impacts. Therefore, given that increased fertility is a development priority that stands apart from the additional burden of climate change (Valdivia *et al* 2015), quantification of climate change impacts should be assessed for both current fertilizer rates, as well as for intensification scenarios in which nutrient are non-limiting. Further, crop management has been shown to be a key determinant of crop yield variability in low intensity farming systems (Tittonell *et al* 2008). Sowing dates are important management decisions that can have large influence on crop yields (Sultan *et al* 2005) and yield simulations (Srivastava *et al* 2016) in the region due to the high inter-annual variability of the onset of the rainy season, with farmers' sowing decisions influenced by both climatic and socio-economic factors (Mertz *et al* 2011). However, varietal characteristics, such as the degree of photoperiodism have been suggested to reduce the sensitivity of crop yields such as pearl millet to variation in sowing dates (Marteau *et al* 2011).

With this context, our study objectives were to quantify the impacts of 1.5 versus 2.0 °C global warming on maize, pearl millet and sorghum (main staple food crops) in the Sudan Savanna of West Africa for current crop varieties and management. Specifically, the first objective was to quantify the projected impacts of the two warming scenarios on: (1) mean yield levels and (2) inter-annual yield variability. A second objective was to understand the drivers of yield losses (e.g. shorter growing season duration, CO_2 fertilization effects, etc) for each of the two warming scenarios. The final objective was to assess potential interactions between the warming scenarios and the level of intensification (e.g. current fertilizer versus an intensification case with not limiting fertility). The study was conducted using two crop models calibrated to local varieties and conditions typical of the Sudan Savanna zone of West Africa.

Methods

Description of study region

The study region encompassed southern Mali, southern Burkina Faso, central Burkina Faso, northern Benin and northern Ghana, (latitude: 8.9°N–12.9°N and longitude: −8.6° to 4.1°) (figure 1). The study region was so delineated based on the availability of both crop management data and crop model calibration datasets. The region is characterized by a uni-modal rainfall pattern (Callo-Concha *et al* 2013) and agriculture is dominated by smallholder rainfed mixed crop and livestock systems. Key constraints to agriculture include low soil fertility, low input use, weak market infrastructure and highly variable rainfall distribution (Callo-Concha *et al* 2013). The soils are increasingly degraded due to low input production of the main food crops: maize, pearl millet and sorghum.



Sub-region	Maize	Millet	Sorghum
	Variety (cycle length in days)		
Benin-north	EVDT-97 (90-95)	Bolga-local (90)	Kadaga (90)
Burkina-south	Obatanpa (100-105)	CIVT (90-95)	CSM335 (125)
Burkina-centre	Obatanpa (100-105)	CIVT (90-95)	CSM63E (90-100)
Mali-south	Obatanpa (100-105)	CIVT (90-95)	CSM335 (125)
Ghana-north	Obatanpa (100-105)	Bolga-local (90)	Kadaga (90)

Figure 1. The study region and delineation of the five sub-regions used to define varieties and crop sowing windows. The table indicates the varieties for each crop used per region. The growth duration of each variety in days from emergence to maturity is shown in parentheses.

Simulation experiment

Two crop models were used in the study. CSM-DSSAT (Jones *et al* 2003, Hoogenboom *et al* 2015) has been widely applied and validated in the region (MacCarthy *et al* 2010, Naab *et al* 2015, Akinseye *et al* 2017, Parkes *et al* 2017, Amouzou *et al* 2018). SIMPLACE is a crop model framework that has been widely used in climate change impact assessments (Webber *et al* 2015, Srivastava *et al* 2018) and selected as it accounts for interactions between crop heat stress and drought caused by drought-induced canopy warming (Gabaldón-Leal *et al* 2016). Descriptions of the two models are presented in the SI materials.

Climate impacts on grain yield of maize, pearl millet and sorghum were assessed for three climate scenarios: baseline, 1.5 °C and 2.0 °C of global warming relative to pre-industrial levels (Mitchell *et al* 2017). Climate scenarios were available for three general circulation models (GCMs) models with 200 years of data each (described below), allowing robust estimation of crop yield variability. For each of the three crops, simulations were conducted for region specific varieties (figure 1), three sowing windows (early, medium and late) and two intensification cases: current fertilizer use (nitrogen and water limited simulations) and an intensification case with non-limiting fertility (water limited simulations). Varieties, crop sowing windows and associated sowing rule, and current fertilizer rates were defined by regional crop modelling experts from the CIWARA network (climate, crop, and economics modelers established in West Africa by the Agricultural Model Intercomparison and Improvement Project, AgMIP; Rosenzweig *et al* 2013, Adiku *et al* 2015) during a workshop at WASCAL in Ouagadougou, in October 2016. Details are given in the following sections. SIMPLACE was setup under ambient and elevated CO_2 concentrations ([CO_2]), whereas DSSAT considered elevated [CO_2] only for this study. In SIMPLACE, transpiration was reduced as a linear function of elevated [CO_2], based on data indicating a 13% reduction in transpiration for C4 crops when [CO_2] increased from 380–550 ppm (Kimball 2016). The increase in radiation use efficiency (RUE) for the three crops was based on the parameterization of Lintul-5 (Wolf 2012) which had a 3.5% increase with [CO_2] increased from 380–550 ppm for C4 crops. The DSSAT models have CO_2 effect parameterized in their species files. Initial soil water content was set to 60% of available water capacity on April 1, which is approximately two months before sowing, and re-initialized each year.

Climate data

Half a degree additional warming, prognosis and projected impacts (HAPPI) daily climate data (Mitchell *et al* 2017) were used at a spatial resolution of 0.25° for three GCM (ECHAM6, MIROC5, NorESM1) and three scenarios: current baseline (2006–2015), 1.5 °C and 2.0 °C warmer than pre-industrial levels. The HAPPI experiment was designed to explicitly test the impacts of 1.5 °C versus 2.0 °C global warming and as such climate data does not correspond to a particular time period, but rather have an average global temperature of 1.5 °C or 2.0 °C above pre-industrial levels over each available 10 year period (Mitchell *et al* 2017). For each of our three GCMs and scenarios, we used 20 sets of these 10 year climate series, resulting in a 200 year time series to allow robust quantification of changes in mean yield and yield variability. Baseline and ambient [CO_2] was 390 ppm (corresponding to ~2010 levels). Elevated [CO_2] was set at 423 ppm for the 1.5 °C scenario and 486 ppm for the 2.0 °C scenario (Mitchell *et al* 2017, Ruane *et al* 2018b). Weather variables used were daily maximum and minimum temperature, daily precipitation, daily solar radiation, and daily wind speed. As all simulations were conducted in the rainy season, daily dew point temperature was estimated as daily minimum temperature to determine the vapour pressure (Allen *et al* 1998). Summary statistics are reported for absolute changes in the annual (table S1 and figures S1–S4 available at stacks.iop.org/ERL/13/034014/mmedia) and growing season (table S2) average daily minimum and maximum temperatures, precipitation and radiation sums.

Soil data

In SIMPLACE, soil data was aggregated to the spatial resolution of the climate input data by selecting the area majority soil type after masking soils for agricultural land use. Source soil maps were the national soil maps (1:200 000) of Burkina Faso (BUNASOL 2012) and Benin (Volkoff 1976), both of which follow variants of the French soil classification system (CPCS 1967), while the soil map (1:250 000) of Ghana was from the Soil Research Institute and followed the FAO methodology. Soil profiles were assigned based on profile information collected in Benin (Igue *et al* 2003, Igué *et al* 2004). For Mali, key soil properties were derived from the Africa Soil Information Service (AfSIS) database (Romero *et al* 2012), aggregated to 0.25° using the majority soil texture in each simulation unit. Though total available water content (TAW) was the same for both models, additional soil parameters were needed for DSSAT due to additional soil processes considered in DSSAT (e.g. soil organic nitrogen mineralization), which were obtained from the AfSIS database (Romero *et al* 2012).

Crop varieties and management

Cultivars were defined for each sub-region (table S3) based on expert knowledge, their wide-use by farmers, appropriate length of the growing season, availability of datasets for models cultivar calibration, with preference given to varieties that previously had been calibrated and published for DSSAT (for details on model calibration, see SI materials). For each crop and sub-region, three sowing windows were defined based on expert knowledge for early, medium and late sowing (table S8). The sowing windows were used with sowing rules to determine the simulated sowing date in each year. Sowing rules determined the day of sowing based on when cumulative precipitation in the simulation unit over a five day period was greater than or equal to 25 mm after the start of the sowing window. If this condition was not met within a sowing window, sowing occurred on the last day in the respective window. Fertilization rates varied for the two intensification cases: current fertilizer use and intensification (non-limiting nutrients). For the current fertilizer case, no fertilizer was applied to millet or sorghum, while maize received 12 kg N ha^{-1} in Ghana-north, 15 kg N ha^{-1} in Benin-north, Burkina-centre, and Burkina-south and 14 kg N ha^{-1} in Mali-south. Other nutrients were assumed non-limiting with the explicit assumption that nitrogen was the most limiting nutrient. In the non-limiting fertilizer intensification case, the crop models were run without nutrient limitation.

Data analysis

Final grain yields were both mapped at the simulation unit level as well as aggregated to the regional level by averaging yields in each year over the 652 simulation units. Regional aggregate yields did not consider weighting by current production areas. Yield distributions were plotted by considering yields over all 200 years in any given scenario- crop- GCM- sowing-intensification- CO_2 combination. Average yields were determined by averaging over the 200 years in any such combination and relative yield changes, ΔYield, calculated as:

$$\Delta\text{Yield} = \frac{\text{Yield}_{\text{scenario}} - \text{Yield}_{\text{baseline}}}{\text{Yield}_{\text{baseline}}} * 100\,[\%] \tag{1}$$

where $\text{Yield}_{\text{scenario}}$ is the simulated yield for a scenario and $\text{Yield}_{\text{baseline}}$ is the simulated yield in the baseline. Inter-annual yield variability was quantified with the coefficient of variation (CV) over the 200 year sample for each respective scenario- crop- GCM-sowing-intensification- CO_2 combination as:

$$\text{CV} = \frac{\sqrt{\frac{|Y_i\overline{Y}|}{N}}}{\overline{Y}} * 100[\%] \tag{2}$$

where Y_i is the simulated yield in year i, $\bar{Y}$ is the mean yield, and N is the number of years considered. The CV was quantified for each 200 year sample for each respective scenario- crop- GCM- sowing- intensification- CO_2 combination.

Results

Baseline yield simulations

Both crop models simulated similar baseline yield levels for the three crops, for both current and intensification fertilization cases (figure 2). However, sorghum grain yields in the intensification case were noticeably lower for DSSAT than for SIMPLACE. This is the result of previous DSSAT calibration exercises to reduce yield potential levels. Both crop models simulated millet yields as somewhat higher than expected, though likely reflecting the higher yield potential of the hybrid variety, CIVT, used for three of the five sub-regions (figure 1).

Changes in mean yields and variability

Across sowing dates and with current fertilizer rates, both maize and sorghum yields were projected to decrease for the region by 2% for 1.5 °C warming and 5% for the 2.0 °C warming scenario (figure 3). Millet yields were not projected to change with either

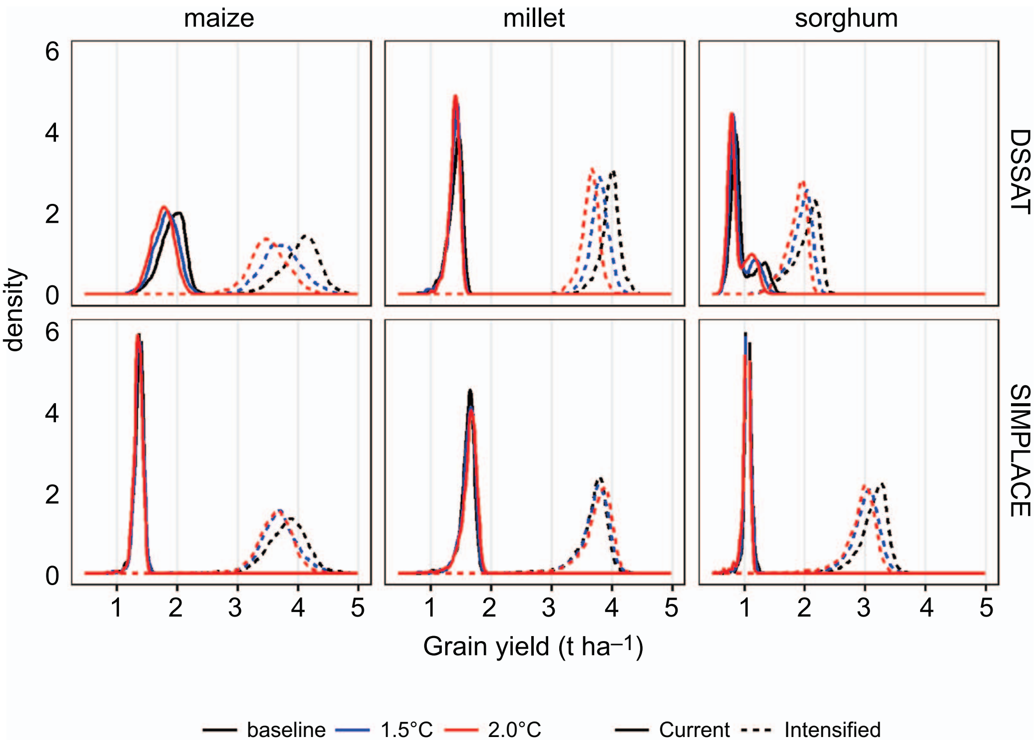


Figure 2. Simulated distribution of grain yields of maize, millet and sorghum for the West African Sudan Savanna region baseline climate (2006–2015, black), 1.5 °C (blue) and 2.0 °C (red) warming scenarios. Distributions are shown for current fertilizer levels (solid lines) and the intensification case (broken lines) for regional average yield across 200-run-years, three sowing windows and three GCMs. DSSAT simulations are in the top row and SIMPLACE simulations in the bottom row. In the two warming scenarios, effects of elevated [CO_2] are included.

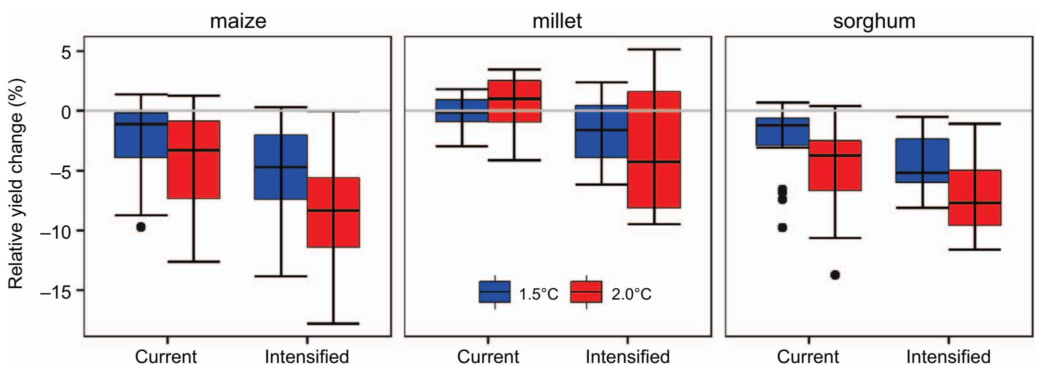


Figure 3. Simulated impact of 1.5 °C (blue bars) and 2.0 °C (red bars) warming on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the current baseline period (2006–2015). Impacts are shown for systems with current fertilizer levels and for fully fertilized case (intensified), considering the effects of elevated [CO_2]. Uncertainty captured in the depth of the box-and-whisker plots covers three GCMs, two crop models and three sowing windows.

warming scenario. In the intensification case, yield losses were greater than in the current fertilizer case for all crops and warming scenarios. With unlimited fertilizer use, the differences in losses between the two warming scenarios increased for maize and millet. For maize, the difference increased to 4% units and to 1% unit for millet. For sorghum the difference between 1.5 °C and 2.0 °C scenarios remained unchanged from the current fertilizer case at 2% units. While relative losses tended to increase between the warming scenarios (for maize and millet) in the intensification case, it is noteworthy that yields remained significantly higher than those in the current fertilizer case, irrespective of the level of warming (figure 2).

The two crop models generally agreed on higher average losses with 2.0 °C compared to 1.5 °C global warming (figure S6). Losses tended to be larger for DSSAT, particularly for millet in the intensification case. Based on the SIMPLACE simulations with and without CO_2 effects, consideration of elevated [CO_2] fertilization had minimal effects on relative yield changes in the current fertilization case (figure S7). Across crops and sowing windows, elevated [CO_2] had no impact on yield changes in the 1.5 °C warming

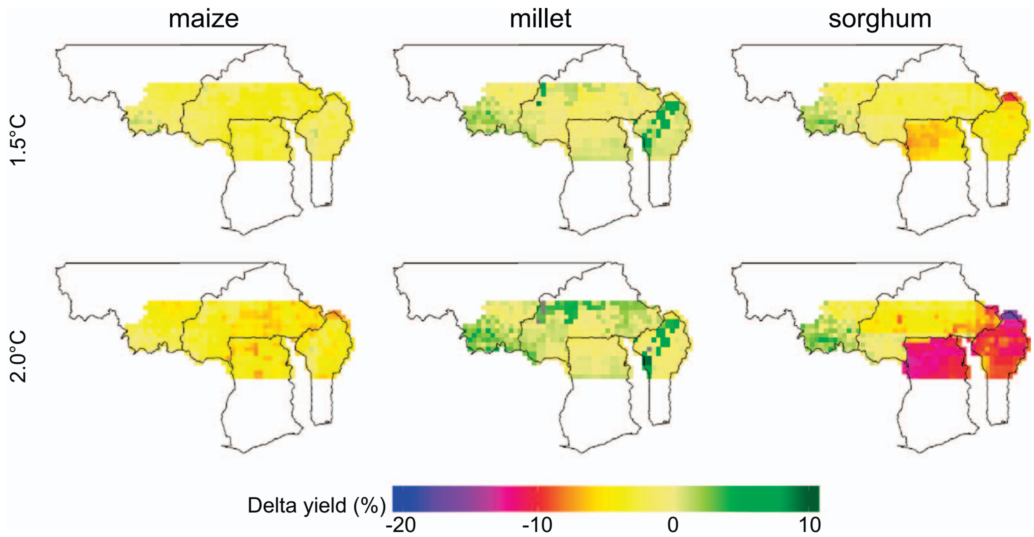


Figure 4. Simulated impact of 1.5 °C and 2.0 °C warming on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the baseline period (2006–2015). Impacts are shown for systems with current fertilizer levels, and considering fertilization effects of elevated [CO_2]. Mapped values are averaged across three GCMs, 200 years, three sowing dates and both crop models (see section 2).

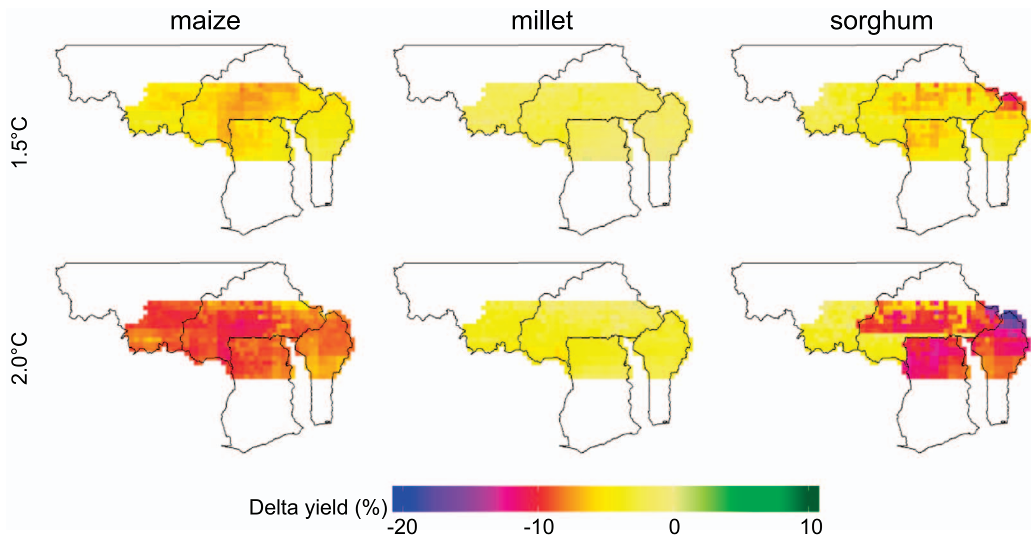


Figure 5. Simulated impact of 1.5 °C and 2.0 °C warming on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the baseline period (2006–2015). Impacts are shown for systems with intensified fertilizer use case, considering fertilization effects of elevated [CO_2]. Mapped values are averaged across three GCMs, 200 years, three sowing dates and both crop models.

scenario and reduced yield losses by 2% units for the 2.0 °C scenario. In the intensification case, elevated [CO_2] had a slightly larger impact, and resulted in reducing losses by 1% unit for the 1.5 °C warming scenario and by 4% units for the 2.0 °C scenario (figure S7).

Averaged across GCMs and sowing dates, there was fairly limited spatial variation across the study region for average yield changes for maize and millet for both fertilizer cases (figures 4 and 5). In contrast, sorghum yield changes exhibited more spatial variation, particularly in Northern Benin and Northern Ghana (figure 4). Most variation between regions for sorghum can be explained by the use of very different varieties that differed in development cycle and photoperiod sensitivity, as compared to maize and millet (figure 1). For sorghum, spatial variability of yield changes increased in the intensification case (figure 5), though the main spatial patterns between regions were the same as in the current fertilizer case, with the exception of the Burkina-centre sub-region, where yields seem to be more negatively impacted compared to the current fertilizer case.

The following discussion on crop yield variability considers only climate as a driver, as in this study the crop models only captured climatic variability and not other drivers of variability. Model inputs such as fertilizer and variety choice were either fixed or

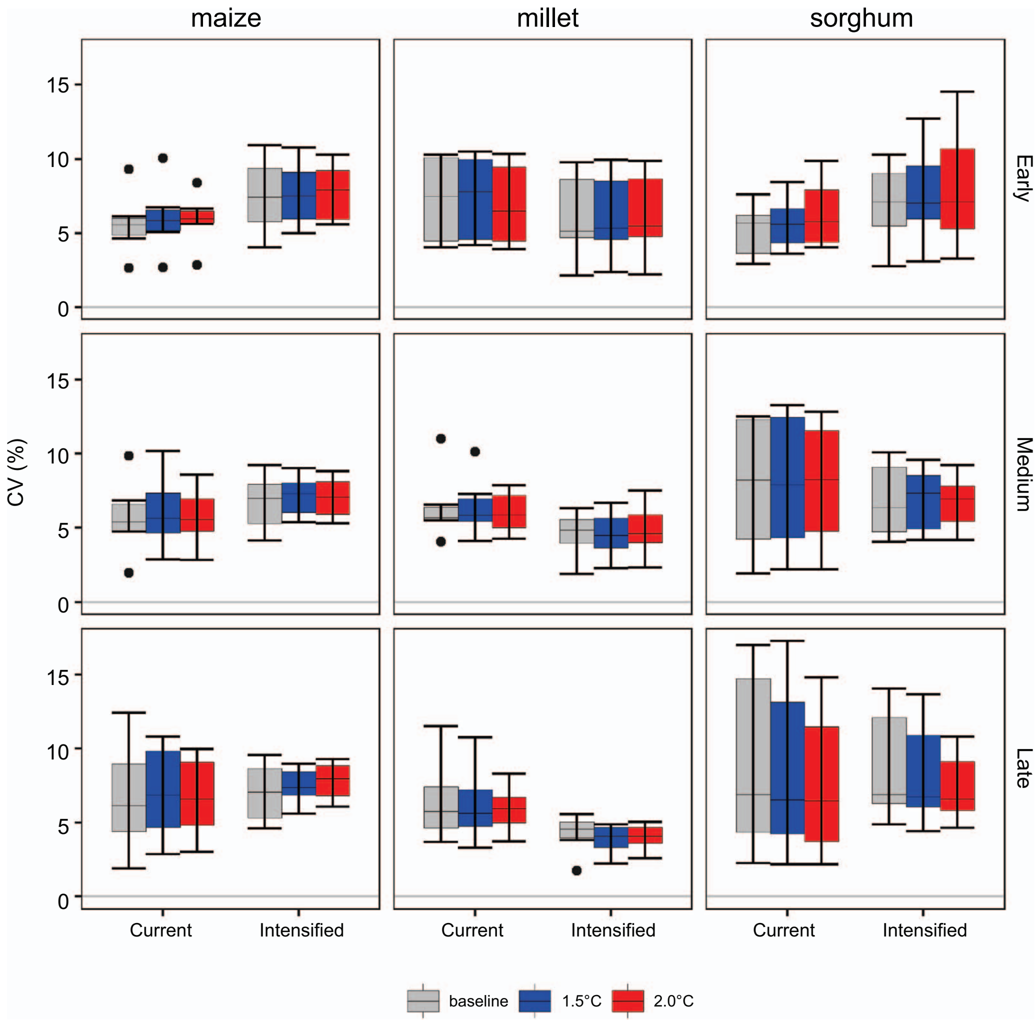


Figure 6. Simulated coefficient of variation (CV) for baseline (grey, 2006–2015), 1.5 °C (blue) and 2.0 °C (red) warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region across each 200 year simulation set. Impacts are shown for current fertilizer levels and for fully the fertilized case (intensified), considering elevated atmospheric [CO_2] effects, for each of the three sowing windows: early (top row), medium (middle row) and late (bottom row). Uncertainty (box depth) captured in each boxplot is attributed to the three GCMs and two crop models.

varied with climate, as in the case of the sowing dates. Averaged across all sowing dates, yield variability did not differ between the baseline and either warming scenarios for any crop (figures S8 and S9), though significant interactions existed between crops, sowing window and the intensification case (figure 6). Irrespective of the warming scenario, climate-driven crop yield variability for maize and sorghum increased from 5% in the current fertilization case to 7% with intensification while no change was observed for millet (figure 6). Consideration of elevated [CO_2] had no influence on the CV for the simulations by SIMPLACE for either warming or intensification scenario (figure S10).

Drivers of yield change in average and low yielding years

To understand the drivers of yield differences between the two scenarios and intensification cases, the relative yield changes were plotted together with the relative changes in the growing season cycle duration for each crop, scenario, and crop model, averaged across sowing dates and GCMs (figure 7). Under current fertilization levels, shortening of the growing season was the most important cause of lowered mean yield, both on average (figure 7) and in years with the lowest yields (figures S11 and S12). The reduction in growing season length was similar and consistent across crops, sowing dates and crop models (figure S13). Neither [CO_2] effects nor nutrient status affected the development rate of the crops in either crop model. With 1.5 °C warming, the length of the growing season (in days) decreased by 4% for all crops, sowing dates and crop models. In the 2.0 °C scenario, the reduction of the growing season was slightly higher and more variable, ranging between 5%–7% based on the different photoperiod sensitivities of the crops and how photoperiod is represented in the models.

However, despite projecting similar shortened growing seasons, the two crop models projected different impacts on final grain yield. Assessing the causes of these differences falls beyond the scope

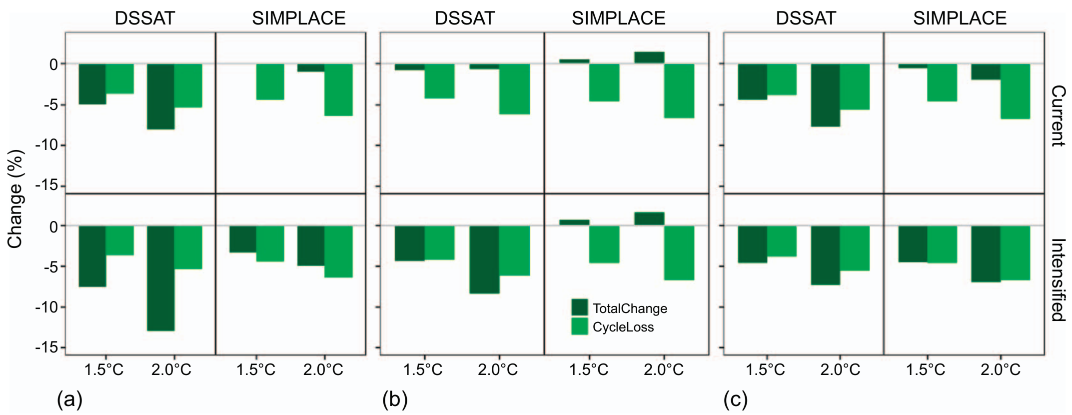


Figure 7. Comparing total yield changes (dark green) with the relative change in growing season duration (green) for 1.5 °C and 2.0 °C warming scenarios on (*a*) maize, (*b*) millet and (*c*) sorghum yields for the West African Sudan Savanna region for current fertilization (top row) and intensified, non-limiting fertilization (bottom row) relative to baseline climate (2006–2015). Simulations are shown for both crop models in adjacent panels for (*a*) maize, (*b*) millet and (*c*) sorghum. All simulations considered elevated [CO_2] and are averaged across sowing dates and GCMs.

of this study, but could be related to different sensitivities of these crops models to drought and heat stress, with new experimental evidence suggest the temperature effect on rate of single grain growth in DSSAT (RGFIL, in the species file) may be too strong (Lizaso *et al* 2017). Further, DSSAT captures potential interactions of soil organic carbon mineralization and nitrogen leaching with altered rainfall and temperature which were not considered in the current implementation of SIMPLACE. Despite uncertainties, the results suggest that heat and/or drought stress intensified with DSSAT, as the relative yield losses were higher than the relative shortening of the growing season. On the other hand, the results suggest that drought and heat stress may have been reduced in SIMPLACE due to either accelerated development escaping hotter/drier conditions, or altered patterns of water use (through changes in leaf area index, LAI) as the relative yield losses were not as large as the reductions in crop cycle duration (figure 7).

The contributions of elevated [CO_2] and heat stress to yield changes were evaluated for the SIMPLACE simulations (figures S14 and S15). Under current fertilizer levels, elevated [CO_2] offset some losses in the 2.0 °C scenario, reducing yields losses by 1%–2% units, though clearly less than the magnitude of the shortened growth duration. In the intensification case, the benefit of elevated [CO_2] increased to 4% units in the 2.0 °C scenario. The intensity of heat stress was shown to decrease in all warming scenarios, intensification cases and sowing dates (figure S15). This may be due to either the earlier maturity avoiding higher temperatures and a possible reduction in drought stress resulting in relatively cooler canopies and less heat stress in the SIMPLACE model (Webber *et al* 2016). The decrease was less pronounced when the effects of elevated [CO_2] were included due to the canopy temperature model simulating higher canopy temperatures with reduced stomatal conductance at elevated [CO_2] (Kimball 2016, Webber *et al* 2018).

Discussion and conclusions

Significance and limitations of the study

The study is the first we know of that explicitly compared the impacts of 1.5 °C versus 2.0 °C on mean yields and yield variability for food crops in West Africa. Another recent study quantified impacts of 1.5 °C warming on maize in West Africa (Parkes *et al* 2017), though it did not assess the damages or impacts of the additional half- degree of warming, seen as critical as countries attempt to formulate policies in response to the Paris agreement (Hulme 2016, Schleussner *et al* 2016a). This study may be considered unique in that it conducted regional gridded simulations using crop models calibrated with local experimental datasets, varieties and realistic range of probable sowing dates (Adiku *et al* 2015), based on expert consultation. The study also simultaneously evaluated climate impacts on current low fertilizer input cropping systems and intensive, non-nutrient limited systems. As such, it provides useful insights into possible interactions of climate change and current efforts to improve livelihoods and food security by promoting sustainable intensification of cropping systems (NEPAD 2003).

An important aspect of this study is the process by which it was conducted. It was undertaken as an activity to support the establishment of a loose and informal network of agricultural impact modellers in West Africa to build the region's adaptive capacity. Co-authors were respectively scientists or PhD students of the West African Science Service Center on Climate Change and Adapted Landuse (WASCAL), members of CIWARA (a network of crop, climate, and economic modellers that forms the West African hub of AgMIP), the MACSUR European modelers' network, and various universities and research centers in Europe, Ghana and the United States. CIWARA currently forms the core of the network, while WASCAL is a newly established international institution with the ambition to make climate impact science available to support policy making on land and resource use, and food security. This study was also conducted in coordination with the AgMIP Coordinated Global and Regional Assessments (CGRA; Rosenzweig 2016) of the agricultural implications of 1.5 °C and 2.0 °C Global Warming (Ruane 2016). The AgMIP CGRA links multiple scales, disciplines, and models to add a richer perspective to complex interactions and changes within the agricultural sector.

Despite these unique features, the study also suffers from limitations. The diversity of varieties used in the study could have been improved and expanded (Gbegbelegbe *et al* 2017), and was largely limited by a lack of good quality datasets to allow calibration of the models for different cultivars, particularly LAI which is crucial for correct simulation of radiation capture and partitioning of water use between transpiration and evaporation. Another source of uncertainty in calibration of the varieties is related to their photoperiod response, which will have implications for the simulated inter-annual variability. Nevertheless, the study was able to capture a much greater degree of variability in varieties and management than is possible in global gridded studies (Müller *et al* 2017). Another limitation is that the study considered only two crop models and the models sometimes had different responses, as now demonstrated in a number of studies (Asseng *et al* 2013, Bassu *et al* 2014). DSSAT was selected as it is perhaps the most widely applied and evaluated model in the region. SIMPLACE has recently been improved to consider heat stress impacts on flowering and yield formation (Gabaldón-Leal *et al* 2016) and account for interactions between heat and drought caused by drought-induced canopy warming, while DSSAT does not predict canopy warming under drought stress. Further, a simplistic representation of soil carbon dynamics and mineralization was considered by reinitializing the models each year. However, it is expected that consideration of both current low and intensified fertilization cases can capture some of the resulting uncertainty related to interactions of climate and nutrient status.

Implications of 1.5 °C versus 2.0 °C warming

Our results suggest that 2.0 °C global warming would cause greater yields reductions for maize and sorghum than the 1.5 °C warming scenario, irrespective of the intensification case. These results are largely consistent with substantial reductions in maize and small reductions for millet in West Africa simulated in global models and a regional study for Senegal of the 1.5 °C and 2.0 °C scenarios (Ruane *et al* 2018a). Results based on ISIMIP fast-track global gridded crop models found a reduction in West African median maize yields of around 2.5% under a 1.5 °C and 2 °C scenario including effects of [CO_2] fertilization and around −11% (−13%) for 1.5 °C (2 °C) warming without CO_2 fertilization relative to the 1986–2005 reference period (Schleussner *et al* 2016b). In a study investigating millet and sorghum's response to a range of temperature and rainfall changes in West Africa, Sultan *et al* (2013) found yield losses increased linearly as temperatures exceeded 2 °C even in high rainfall conditions, with positive yield impacts with warming up to 1.0 °C if rainfall increased by 20% independent of any elevated [CO_2] effects. Similar to findings from Traore *et al* (2017), relative yield losses were lower for millet than maize (and additionally sorghum in our case). Likewise, Adiku *et al* (2015) and Singh *et al* (2017) reported positive impacts of climate change on millet yields in the region when [CO_2] effects were included for some locations and climate models. Millet is generally considered the most heat and drought tolerant cereal crop (Varshney *et al* 2017) and this is reflected in the models (e.g. higher optimal temperature range for RUE and lower crop coefficient values for water use for millet than for maize or sorghum in SIMPLACE), resulting in no yield losses with warming for either model in the current fertilizer case. However, in the intensification case, DSSAT projected losses while SIMPLACE projected small yield increases. Possible explanations are that (1) DSSAT simulates higher LAI than SIMPLACE with higher fertilizer rates leading to more water stress and/or (2) DSSAT is more sensitive to water stress than SIMPLACE. Further, both of these factors are expected to interact with elevated [CO_2], though there is still a great deal of uncertainty in this response and there are no experimental datasets available to calibrate this response in millet. Clearly, this should be further investigated in future studies.

Significantly, we found no evidence to suggest that yield variability would increase with the additional half degree of warming for most combinations of crops and sowing windows investigated, which contradicted our initial hypothesis that the warmer scenario would lead to increased variability with heat stress and drought becoming more frequent at higher temperatures. However, it appears that as higher average temperatures accelerated development that the crops were able to escape hotter periods. In any case, simulated heat stress was rather reduced in all scenarios (figure S14). Finally, the importance of intensification for the region is noted, as yield changes due to intensified fertilization emerged as a factor 2–3 times more important than climate change impacts.

Drivers of yield changes

Shortened crop duration was identified by both crop models as an important cause of the reduced yields with both scenarios (figures 7 and S13). Although it cannot be explicitly tested in the current study, it appears that the two crop models differed to the degree in which they projected drought stress to increase (figure 7). The simulations with DSSAT seem to suggest drought stress may have increased, while the SIMPLACE simulations suggest drought and heat stress decreased due to escape with earlier crop maturity (figure 7). This remains an important source of uncertainty and has implications for possible adaptations. If drought stress is in fact increasing, it implies that there may be little opportunity to adopt longer season varieties to gain back the portion of the season (and radiation capture) lost due to accelerated development. Results reported by Singh *et al* (2017) indicated that drought and heat tolerant cultivars with long duration will be needed under climate change to avoid yield losses. This is an aspect that should be evaluated in more detail and could be assessed by adding simulations with potential yield levels and quantifying the yield changes due to water stress in each warming scenario.

The limited response to elevated [CO_2], particularly under current fertilizer levels, was not unexpected for these C4 crops (Berg *et al* 2013, Kimball 2016) and similar to the results reported by Deryng *et al* (2016) for tropical rainfed systems. However, we note that it became more important in the intensification case. The increase in leaf area index with intensification may have led to more frequent instances of drought stress. Under these conditions, elevated [CO_2] is expected to have a positive impact on yield response of C4 crops (Durand *et al* 2017) as C4s reduce transpiration rates and delay the onset of terminal drought conditions (Kimball 2016). Higher [CO_2] for the 2.0 °C scenario offset some losses associated with accelerated development, but did not compensate for it. Sultan *et al* (2014) found consideration of [CO_2] fertilization offset yield losses under climate change in sorghum by as much as 10% (Sultan *et al* 2014). The limited response of these C4 crops contrasts sharply with the strong [CO_2] response under the same HAPPI 1.5 °C and 2.0 °C scenarios for C3 crop production as reported in Ruane *et al* (2018a). This underscores both the need for continued research to close substantial model and observational uncertainties (Ruane *et al* 2018a), as well as the greater risk posed by climate change to tropical regions where C4 cereals dominate.

Insights for adaptations

Our results suggest that climate change impacts will be more negative for more intensive systems with the negative impacts of an additional half-degree of warming becoming more pronounced. That the negative impacts of climate change on West African cereal crops increased under intensification with higher fertilizer rates is supported by the finding of Sultan *et al* (2014) and Traore *et al* (2017). However, interpretation of these results should be cautious, as, irrespective of warming scenario, yield levels were far greater with intensification than with current fertilizer rates (figure 2). As expected, actual yield variability increased with higher fertilizer use as indicated by the wider distributions (figure 2) and higher CVs (figure 6). However, the increase in relative variability was modest and there was no interaction with climate scenarios (figure 6). Placing this in a risk context requires additional economic analysis and consideration of the ability of farmers to take risk (e.g. access to savings or credit) (Webber *et al* 2014).

The simulated reduced drought and heat losses with the SIMPLACE model suggest that there may be an opportunity to adopt longer season varieties to increase yields or to reduce yield losses. However, further study is needed to understand the difference between the DSSAT and SIMPLACE models in terms of their simulated changes in drought stress. Longer season sorghum varieties grown in southern Mali and central Burkina Faso experienced lower negative yield impacts than the shorter cycle varieties grown in the other regions, in line with previous results (Sultan *et al* 2013, Traore *et al* 2017). Beyond adopting varieties with higher thermal time requirement, it may be possible to exploit existing genetic diversity in terms of photoperiod response. Our sorghum varieties differed both in their sensitivity to photoperiod, as well as the critical day length below which photoperiod effects ceased. The benefit of photoperiod sensitivity under climate change appears to vary with climate scenario, as some studies demonstrated positive effects of photoperiod sensitivity attributed to it effect in reducing the onset of anthesis with warmer temperatures allowing for more assimilate accumulation before anthesis (Traore *et al* 2017), whereas other studies suggest negative effects of photoperiod which seem related to shifting rainy season associated with monsoon onset (Sultan *et al* 2014). This is an area that should be further explored, but with an ensemble of crop models to capture uncertainty in response (Bassu *et al* 2014).

To conclude, by quantifying the impact of 1.5 °C versus 2.0 °C global warming on grain yields of the three main staple crops in the Sudan Savanna of West African, this study provides an important piece of information needed to assess risks to food security of an additional half-degree of global warming. The study found that the 2.0 °C scenario had more negative impacts on yield than the 1.5 °C warming scenario, though we found no evidence to suggest that yield variability would increase with the extra half degree of warming. While negative impacts increased as fertilizer use intensified, absolute yield levels under intensification including climate change impacts were significantly higher than yields with current fertilizer use and climatic conditions. Extending these results to infer implications for food security is critical and must include economic and risk assessment to better assess the interactions between vulnerability to yield variability and intensification. Further integrated economic analysis including satellite observations and land use models would allow exploring the implications of either negative climate change impacts or intensification on resulting landuse change and consequences for other ecosystem services.

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