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The impact of future climate change and potential adaptation methods on Maize yields in West Africa

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Abstract

Maize (*Zea mays*) is one of the staple crops of West Africa and is therefore of high importance with regard to future food security. The ability of West Africa to produce enough food is critical as the population is expected to increase well into the twenty-first century. In this study, a process-based crop model is used to project maize yields in Africa for global temperatures 2 K and 4 K above the preindustrial control. This study investigates how yields and crop failure rates are influenced by climate change and the efficacy of adaptation methods to mitigate the effects of climate change. To account for the uncertainties in future climate projections, multiple model runs have been performed at specific warming levels of +2 K and +4 K to give a better estimate of future crop yields. Under a warming of +2 K, the maize yield is projected to reduce by 5.9% with an increase in both mild and severe crop failure rates. Mild and severe crop failures are yields 1 and 1.5 standard deviations below the observed yield. At a warming of +4 K, the results show a yield reduction of 37% and severe crop failures which previously only occurred once in 19.7 years are expected to happen every 2.5 years. Crops simulated with a resistance to high temperature stress show an increase in yields in all climate conditions compared to unadapted crops; however, they still experience more crop failures than the unadapted crop in the control climate.

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1 Introduction

Maize is one of the staple crops of West Africa and contributes heavily to meeting the food requirements of the region (Lobell and Gourdji 2012). With the population of West Africa expected to reach 1 billion between 2060 and 2070 (United Nations DESA 2015), the need for stable and reliable food sources is critical. With these two pieces of information, it is clear that the production of maize needs to increase to prevent food shortages and possible famines across West Africa. Population change is not the only issue facing West Africa, climate change is expected to alter rainfall patterns and increase temperatures across the region. Much of the rainfall in West Africa is provided by the annual monsoon which precludes the dry season. Under climate change, the monsoon may arrive later in the year, requiring the crops to grow in the hotter summer months (Biasutti and Sobel 2009; Sultan et al. 2014).

The impact of climate change on crop yield is key for food security. As temperatures increase and rainfall patterns become more unstable, the yield is expected to fall in many regions, which in turn increases the number of people at risk of starvation (Rosenzweig and Parry 1994). Decreasing yields will hit the poorest hardest as food prices will increase with scarcity (Rosenzweig and Parry 1994; Parry et al. 2004). Crop yields are expected to fall in richer nations such as the USA and China; however, they could respond with expensive mitigation systems (Tubiello et al. 2002; Lobell et al. 2008). West Africa does not have the financial might of the USA or China; therefore, expensive mitigation systems are not a viable response to climate driven yield reductions. These reductions in yields are in direct contrast with the increases necessary to feed a growing population with a doubling required by 2050 (Ray et al. 2013). With increasing carbon dioxide levels, the potential for carbon dioxide fertilisation to counteract crop yield reductions from climate change exists. However, for C4 grasses such as maize, the response to carbon dioxide fertilisation is limited and is not enough to offset climate change induced yield changes (Berg et al. 2013). There have been a number of meta-analyses combining the results from several papers to provide estimates of future crop responses (Roudier et al. 2011; Knox et al. 2012; Challinor et al. 2014). The results in Roudier et al. (2011) show that West African crops experience an 11% reduction in yields and that carbon dioxide fertilisation leads to poorer quality crops with lower nutrient content. Maize along with other staples such as rice, soybean and sorghum have been shown to provide lower amounts of edible iron and zinc under elevated carbon dioxide conditions (Myers et al. 2014). The Knox et al. (2012) meta-analysis allows a closer focus on West Africa and the Sahel with Sahelian maize yields expected to fall by 12.6% by 2050. Tropical maize in Challinor et al. (2014) responds more negatively than temperate maize to climate change and increasing global average temperatures reduce yields by 20% at 4 K above the local average temperatures.

The ability of farmers to adapt to changing climate conditions includes modifying their methods or replacing their crop. Breeding a new strain of a crop is a non-trivial process and the rate at which developments are made does not necessarily translate to changes in the cultivated crop. Providing a new variety of a crop can take up to 30 years in Africa, and with accelerating changes in climate, this means that farmers are likely to be left behind (Challinor et al. 2016). Another response to climate change is to cultivate a different species, either because it generates more money or because the previous species is no longer viable. It is estimated that a large faction of the maize cultivated area will transition into other crops during the twenty-first century (Rippke et al. 2016).

This study investigated the impact of climate change on maize yields in Africa using the bias-corrected Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa simulations for the first time. Instead of fixed times, the approach of focusing on specific warming levels was used, this removes uncertainty about climate sensitivity in the global climate models (GCMs). The CORDEX-Africa simulations were performed using six GCMs and four regional climate models (RCMs). In addition to yield changes. this study also investigated the frequency of crop failures to assess how variability changes in future climates.

2 Methods and data sources

The General Large Area Model (GLAM) for annual crops is a process-based model designed for use with large-scale inputs such as those from climate models (Challinor et al. 2004). GLAM uses daily meteorological fields as inputs, these fields are downwelling shortwave solar radiation at the surface, precipitation, maximum temperature and minimum temperature. GLAM uses the same grid spacing as the meteorological inputs (50 km x 50 km, see below). In addition to the meteorological inputs, GLAM also uses soil data, a planting window and a dedicated parameter set for West African maize. The planting window data was sourced from the Ag-GRID GGCMI harmonisation (Elliott et al. 2015) and the soil inputs, namely the drained upper and lower limits and the saturation limit, were taken from the Digital Soil Map of the World using methods described in Vermeulen et al. (2013). The parameter set used for the simulation of the maize crop was the same as used in Challinor et al. (2015) and the simulations were performed using Revision 434 of GLAM V3. A description of GLAM is presented in SI Section 2. To ensure that only regions which contribute to national production were analysed, the comparison between model results and observed grid-based yields is restricted to pixels where at least 1% of the area is used to cultivate maize. A list of the countries and their maize growing area is shown in SI Table 1. To define the 1% limit of growing area, the maize-cultivated areas from Monfreda et al. (2008) were used. The yield data was taken from a dataset built from satellite observations combined with yields reported by the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2014; Iizumi et al. 2014; Iizumi and Ramankutty 2016). To ensure that the study only focuses on regions where GLAM is capable of reproducing observed yields, it was also required that the calibrated GLAM yield be within 10% (+/–) of the observed yield for that grid cell.

Climate change can introduce or exacerbate stresses on a crop, one potential response is to simulate crops adapted to high temperature stress or to capture runoff for use later in the season. The high temperature stress (HTS) routine in GLAM reduces the yield if daily maximum temperatures are above a critical temperature ($T_{Crit} = 37$ °C). The HTS routine sets the yield to zero if the daily maximum temperature is above the limit of $T_{Setzero} = 45°$ (Challinor et al. 2005; Challinor et al. 2015). The HTS routine reduces yield as a response to high temperatures during flowering which reduce the ability of the crop to produce grain. For the unadapated crop simulations, the HTS routine is enabled and the crop yields are reduced by higher temperatures. To show the yield changes caused by HTS, the HTS routine is disabled to simulate a crop adapted to HTS. Whilst this crop is not necessarily physical, it does serve to highlight the importance of temperatures during a specific growing period. Runoff capture is a method to reduce wasted water by storing it and deploying the stored water later in the season. The runoff capture system in GLAM retains 50% of the runoff from the surface and stores it in an arbitrarily large reservoir. The stored water is deployed when the soil moisture drops below the critical limit for terminal drought stress. The maximum amount of water deployed from the reservoir is limited to the entirety of

Table 1 Growing season temperatures (T) and precipitation (P)

GCM	RCM	RCP8.5 +2 K		RCP8.5 +4 K	
		T (K)	P (%)	T (K)	P (%)
CCCma-CanESM2	SMHI-RCA4	1.05	– 4.63	3.94	– 13.17
CSIRO-Mk3.6.0	SMHI-RCA4	1.78	– 3.08	4.91	– 2.16
ICHEC-EC-EARTH	DMI-HIRHAM5	0.95	– 5.98	3.68	– 17.00
ICHEC-EC-EARTH	KNMI-RACMO22T	0.86	– 0.31	3.77	– 6.28
ICHEC-EC-EARTH	SMHI-RCA4	1.15	– 5.45	4.04	– 6.38
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	1.96	– 17.05	4.13	– 31.71
MOHC-HadGEM2-ES	KNMI-RACMO22T	1.29	– 2.16	4.00	– 10.32
MOHC-HadGEM2-ES	SMHI-RCA4	1.77	– 4.26	4.28	– 6.99
IPSL-CM5A-MR	SMHI-RCA4	1.38	– 10.36	4.42	– 19.47
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	1.94	– 14.37	4.89	– 33.34
MPI-M-MPI-ESM-LR	SMHI-RCA4	1.30	– 3.86	4.72	– 15.04

the stored water or the amount of water required to bring soil moisture up to 80% of the drained upper limit (Parkes et al. 2018). The carbon dioxide fertilisation effect was modelled using an increase in transpiration efficiency following methods from Challinor and Wheeler (2008) and physiological responses for maize from Leakey (2009); Leakey et al. (2009) and Ghannoum et al. (2000) with final parameters shown in SI Table 3.

The meteorological inputs for the simulations were produced by bias correcting the CORDEX-Africa simulations. The bias correction method used was multisegment statistical bias correction (Grillakis et al. 2013; Papadimitriou et al. 2016) and used the WFD-WFDEI dataset between 1981 and 2010 as a reference. The CORDEX simulations use the CMIP5 model simulations as inputs to regional climate models with the aim of improving understanding of regional scale systems (Nikulin et al. 2012). As part of the HELIX project which focuses on high-end climate change, the CORDEX simulations which were driven by the Representative Concentration Pathway to 8.5 Wm^{-2} (RCP 8.5) were selected for bias correction. The bias-corrected CORDEX-Africa data has a horizontal resolution of 50 km x 50 km and a temporal resolution of one day. A GCM-RCM combination refers the outputs of one of the GCMs being used to as input to one of the RCMs. For a GCM-RCM combination to be used, it was required that the driving GCM have global mean temperatures of 4 K above the IPCC baseline (1870–1899) for 30 years before 2100. The requirement of temperature and use within CORDEX-Africa resulted in the 11 combinations shown in Table 1. For each GCM, the 30 years where the mean temperature was closest to +2 K and +4 K were used as inputs for the crop model.

The input data are grouped by temperature into specific warming levels (SWL). As each GCM reaches the SWLs (+2 K, +4 K) at different times, the ambient carbon dioxide concentration at +2 K and +4 K varies between the models. The time slices and carbon dioxide fractions for the GCMs are shown in SI Table 3. The regional climate pattern corresponding to a global temperature change of +2 K or +4 K is not evenly distributed nor is it consistent throughout the year, the meteorological changes experienced by the maize crops in the different simulations are detailed in Table 1. The baseline for the +2 K and +4 K simulations is not the same as the control time series and therefore it is noted that the mean control temperatures are 0.70 K above the baseline for +2 K and +4 K. A mild crop failure is defined as a yield one standard deviation below the mean for that grid cell over the 20 years of the control simulation, whilst a severe crop failure is 1.5 standard deviations below the mean. The limits for crop failures are calculated for each GCM-RCM combination.

The yield results for each model were recorded and the grand ensemble mean yield was calculated along with the mean 90th and 10th percentile values across all 11 GCM-RCM combinations and presented as $\text{Mean}_{10^{th}}^{90^{th}}$. With 11 GCM-RCM combinations and multiple years of future climate analysis, there are several methods available to describe the variability in the simulations. A standard deviation of the mean yield across the GCM-RCM combinations is the uncertainty in the future climate prediction. The initial variability is low as a result of several factors bias correcting the input data to observations in addition to calibrating GLAM reproduces the observed results with minimal variability. The future climate spread contains changes in the meteorology, ambient carbon dioxide levels and the spread in the GCMs and RCMs as they advance further from the constraints of observed data. The inter annual variability (IAV) can be calculated by taking the standard deviation of each grid cell and then averaging this over the domain and GCM-RCM combinations.

3 Results

GLAM simulates the historic yield using the calibrated yield gap parameter and produces a multi-model mean yield of 1086 kg/ha, which is close to the detrended observed yield of 1097 kg/ha. SI Fig. 1 shows the difference between the observed yield and the multi-model mean across 11 GCM-RCM combinations for the time period 1986–2005. A break down of the uncertainties in the replication of the observed yields is shown in SI Section 3.

For the future climates, the results in Fig. 1 show how yields change for temperatures 2 K and 4 K above the control. For both future projections, the yield reduction is centred in the Sahel; however, in isolated cells in the North of Nigeria, there is an increase in yield under RCP8.5 +2 K. The impacts of adaptation methods are shown in Fig. 2. The coastal regions have their temperatures and precipitation moderated by the sea which leads to smaller reductions in yield; however, this does not continue inland. The results in Fig. 3 show the impact of climate change and crop adaptation methods on yields. As can be seen on the left of the top panel of Fig. 3, climate change reduces the average yield from $1086\,{}_{308}^{1902}$ kg/ha to $1031\,{}_{219}^{1866}$ kg/ha for RCP8.5 +2 K and to $647\,{}_{129}^{1311}$ kg/ha in the case of RCP8.5 +4 K.

The mean yield changes are accompanied by changes in the variability too, the IAV in both the control and RCP8.5 +2 K experiments is 478 kg/ha. However, as the yield in the RCP8.5 +2 K experiment is lower than in the control, the proportional size of IAV is larger (44% and 46% of mean respectively). This means that in the RCP8.5 +2 K experiments, the yields are more variable than in the control. In the case of RCP8.5 +4 K, the IAV is reduced to 384 kg/ha, this is 59% of the mean yield indicating that the proportional variability has increased. In addition to the IAV, there is a spread of yields associated with the different GCM-RCM combinations. Due to the calibration to observed yields, the control GCM-RCM spread is low (6 kg/ha), this model variability increases to 125 kg/ha for RCP8.5 +2 K and 101 kg/ha for RCP8.5 +4 K. These values are 0.6%, 12% and 16% of the mean respectively. The spread is a result of multiple factors, the input meteorological data spreads as a result of the different GCM and RCM model physics and the differing times to reach the SWLs produces changes in the carbon dioxide fraction too. The GCM-RCM spread is

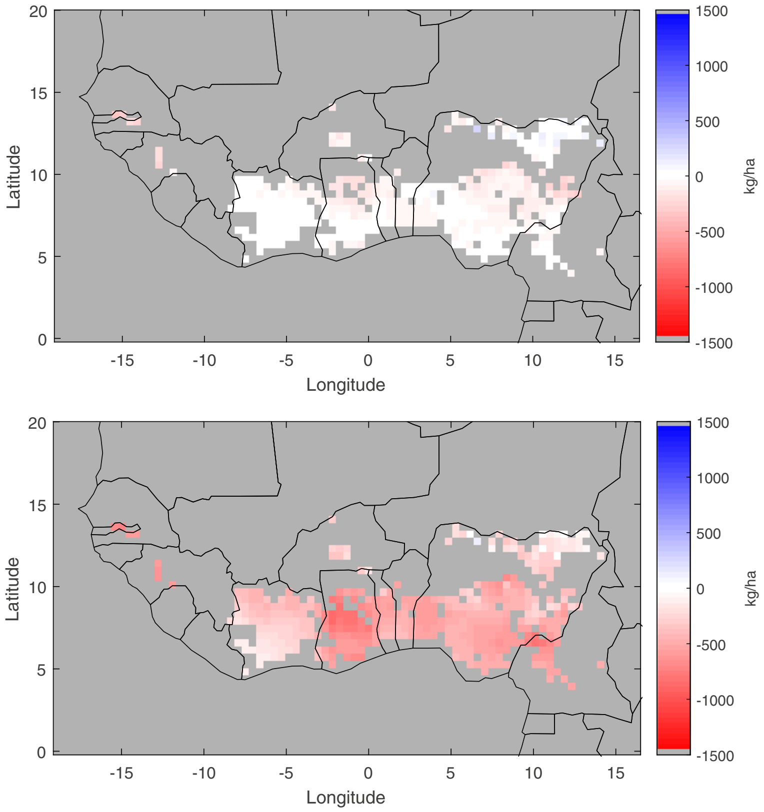

Fig. 1 Map showing the change in yield between the control simulation and RCP8.5 +2 K (top) and RCP8.5 +4 K (bottom) with unadapted crops. The results are a mutli-model average across 11 GCM-RCM pairings

smaller for RCP8.5 +4 K than for RCP8.5 +2 K, but it is a larger fraction of the observed yield indicating the increase in spread further into the projections.

The crops grown with runoff capture show a smaller change in yields than the high temperature stress adapted crops and this is repeated for all climate conditions. The yield increase seen with crops with high-temperature stress adaptation is more significant at higher temperatures indicating that high-temperature stress resistance may ameliorate some of the losses induced by climate change. However, an increase in yields from $647\,^{1311}_{129}$ kg/ha to $757\,^{1415}_{222}$ kg/ha does not alter the fact that significant reductions in yields are expected. Average yields however are not the only response to measure crops, the variability in yields can easily lead to economic crisis or even famine. The reductions in yields, especially those in RCP8.5 +4 K, are amplified by the meteorological changes shown in Table 1. The changes in yields are not uniform and there is a compression of yields towards the lower values with increases in temperature. The results in Fig. 4 show the changes in the 90th, 50th (median) and 10th percentile yields with error bars showing 1 standard deviation across the 11 GCM-RCM combinations. For the control climatology, the adaptation methods increase the lower yields more than the higher ones indicating that poor yields could be improved with adaptation. For the RCP8.5 +2 K climate the 90th and 50th percentile yields do not change much; however, the decrease in the 10th percentile yield shows that low yield cells are worse off

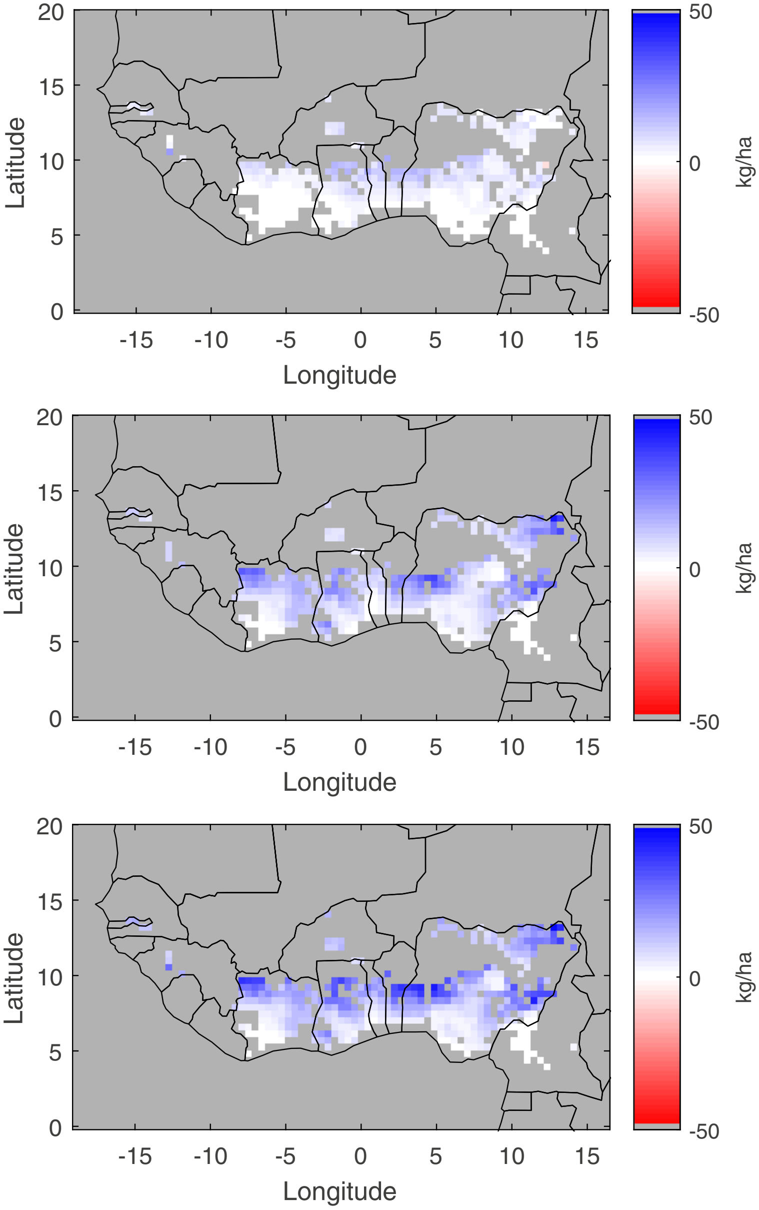

Fig. 2 Map showing the change in yield between the control simulation and control with high-temperature stress-adapted crops (top), crops grown with runoff capture (middle) and water and high-temperature stress-adapted crops (bottom)

after climate change. The adaptation methods, notably HTS resistance, reduce the yield losses but not enough to return the yields to the same as the control climate. With RCP8.5 +4 K climates, the yields are reduced across the entire range with the 10th percentile yield

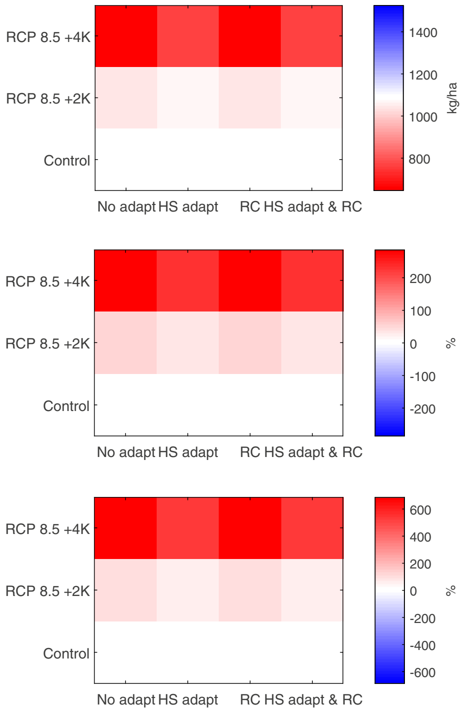

Fig. 3 Heatmap showing the difference in yields (top), mild crop failures (middle) and severe crop failures (bottom) for three climate conditions and four crop adaptation methods. No adapt shows the crops with no adaptation methods, HS adapt indicates high-temperature stress-adapted crops, RC indicates crops grown with runoff capture. HS adapt and RC shows high-temperature stress-adapted crops grown with runoff capture. RCPs are the representative concentration pathways and are grouped by temperature to 2 K and 4 K

below 50% of its original value. As with RCP8.5 +2 K, the runoff capture scheme provides little relief from climate change; however, the HTS-resistant crop has a significantly improved median and 10th percentile yield.

The results in the middle panel of Fig. 3 show the percentage change in mild crop failure rate in comparison with the control climate with unadapted crops. The climate change results show an increase of 48% for +2 K and more than 280% increase in mild failure rate for +4 K.The crop failure rates are presented as a percentage change; however, their frequency is also a useful metric. The control crop without runoff capture and whilst sensitive to high temperature stress is expected to fail once every 6.6 years per grid cell, this compares with once every 4.5 years for RCP8.5 +2 K and 1.7 years for RCP8.5 +4 K. The results for severe crop failures are shown in the bottom panel of Fig. 3 and mirror those from the middle panel of Fig. 3. In the control simulation, the severe crop failure rate is once per 19.7 years per grid cell, this rate drops to once every 9.6 years for RCP8.5 +2 K and once every 2.5 years per cell for the RCP8.5 +4 K simulation, more than seven times more frequently. The frequency of crop failures for crops grown with runoff capture is similar to the unadapted crops, this is in agreement with the small yield differences. For crops with high-temperature stress resistance, there is a reduction in failure rate relative to an unadapted crop; however, climate change still dominates the signal. A high-temperature stress-resistant crop in in RCP8.5 +2 K fails mildly once in 5.1 years and in RCP8.5 +4 K fails once every 3.2 years, whereas the control high-temperature stress-resistant crop fails only once every 22.0 years.

A further simulation set was completed, where the historical carbon dioxide levels were maintained at the level of 361 ppm, which is the average of the 1986–2005 calibration period, and the meteorology was taken from the future climate simulations. In the absence of carbon dioxide fertilisation, RCP8.5 +2 K has a yield of 909 kg/ha and RCP8.5 +4 K produces 455 kg/ha. The difference in yields between these results and the control yield of 1086 kg/ha highlights how unsuitable the future climate is likely to be for maize growth and the importance of positive carbon dioxide effects in GLAM. A series of simulations without carbon dioxide fertilisation were completed and the change in yield and crop failure rates are shown in Fig. 5. The results show only first-order changes, any interactions between the meteorology and carbon dioxide levels are lost in this analysis. When comparing the fixed historic carbon dioxide simulations with the dynamic carbon dioxide ones, it can be seen that carbon dioxide fertilisation reduces yield losses from 17 to 6% for RCP8.5 +2 K and from 56 to 38% for RCP8.5 +4 K.

4 Discussion

The results shown in Fig. 1 show that climate change of +2 K is likely to cause a reduction in maize yields in West Africa of approximately 6%. In the case of climate change resulting in a global average temperature change of +4 K, then the maize yields are projected to reduce by 38%. The yield reductions produced in GLAM are within the range found in the meta-analyses in Knox et al. (2012) and Challinor et al. (2014). In addition to the marked reduction in yield, the variability in the yields is projected to increase, making it difficult

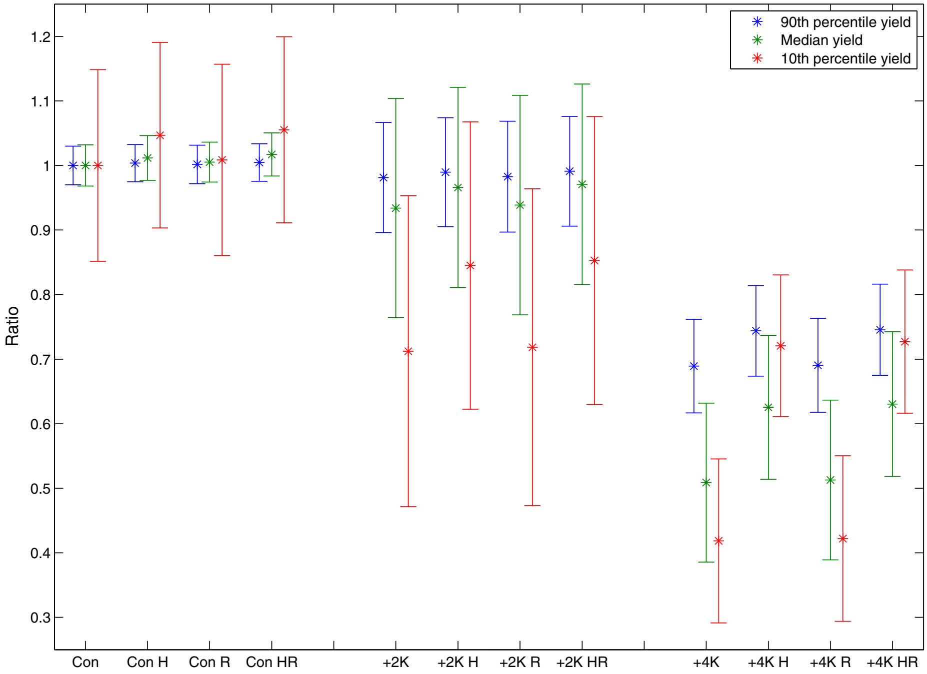

Fig. 4 Ratio of 90th, 50th and 10th percentile yields to the unadapted control crop for different climate conditions and adaptation methods. H indicates an HTS-resistant crop, R indicates a crop grown with runoff capture, HR is an HTS-resistant crop grown with runoff capture. Error bars show 1 standard deviation of the ratios across the 11 GCM-RCM combinations

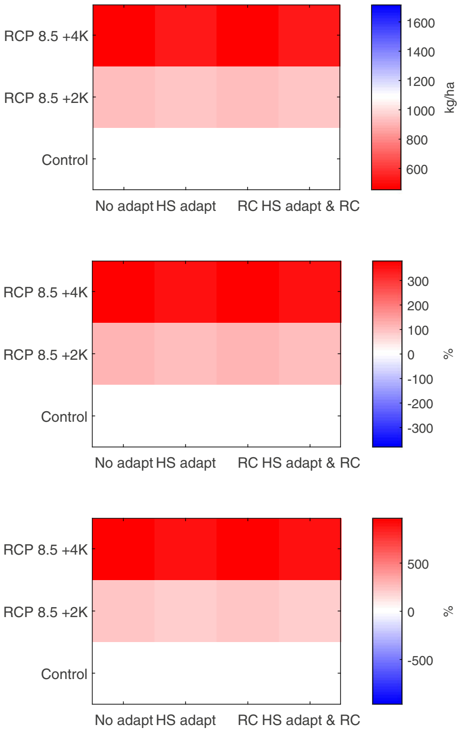

Fig. 5 Heatmap showing the difference in yields (top), mild crop failures (middle) and severe crop failures (bottom) for three climate conditions and four crop adaptation methods where carbon dioxide fertilisation has not been simulated. No adapt shows the crops with no adaptation methods, HS adapt indicates high-temperature stress-adapted crops, RC indicates crops grown with runoff capture. HS adapt and RC show high-temperature stress-adapted crops grown with runoff capture. RCPs are the representative concentration pathways and are grouped by temperature to 2 K and 4 K

to plan for the future, in particular for high-end climate change such as RCP8.5 +4 K. The increase in variability will impact food prices and reduce food security across West Africa.

The +2 K results show that even if the Paris Accord comes to fruition and climate change is limited to two degrees above the IPCC baseline, there will still be significant problems in Africa. Some of the damage attributed to climate change can be ameliorated by using runoff capture or crops resistance to high temperature stress. There are very small differences in yields between runoff capture fed crops and the control and this is likely due to the low amount of water lost to runoff in the simulations. The average runoff from the control simulations is 3 cm/season. For maize, the high-temperature stress-resistant crops do show a significant difference from the control simulations. This indicates that high temperature stress during flowering is one of the causes of lower yields; however, as the yield damage is not completely removed with a high-temperature stress-resistant crop, there are other changes such as rainfall frequency and higher temperatures later in the season which have an effect too. With both adaptation methods deployed in a future climate scenario, there are still more crop failures than the current one. Therefore, mitigation of climate change is likely to do more to prevent crop failures than either of the adaptation methods discussed here. When breeding a crop for high-temperature stress resistance, the desired behaviour is not guaranteed to be introduced without other undesired traits (Wahid et al. 2007).

The increase in variability translates to an increase in the crop failure rate, the mild crop failure rate increases from once every 8 years to once every three at +2 K and nearly every other year at +4 K. Severe crop failures instead of being a relatively rare problem (19.7 years) arrive with distressing frequency at +2 K (9.6 years) and at +4 K they are every 2.5 years. With crop failures of this frequency, it is a forgone conclusion that without significant changes West Africa will not be able to feed its current population, let alone the projected one.

The results decoupling the meteorology and carbon dioxide fertilisation break down how the future climate will affect maize yields. The higher levels of atmospheric carbon dioxide are able to mitigate some of the damage incurred by the meteorological changes. However, the overwhelming signal is of a reduction in yields and this is further reason to mitigate climate change and work towards maintaining the current climate. These results are in agreement with Roudier et al. (2011) and Sultan et al. (2014) which both show that carbon dioxide fertilisation moderates yield losses for C4 crops but does not fully counteract climate change. Furthermore, as discussed in Berg et al. (2013) and Myers et al. (2014), the quality of the crops grown in under increased carbon dioxide levels is expected to be lower leading to the problem of people suffering from malnutrition.

The results presented here are limited by the grid scale of the input data and the bias correction techniques used. The large grids in the climate models are known to blur out large-scale storms and the convective schemes are unable to accurately represent the storms typically found in monsoon regions such as West Africa. The importance of the resolution of models has been discussed in detail in Garcia-Carreras et al. (2015), where it was found that the parametrised convection schemes in GCMs typically produce a large number of drizzle events and under predict the heavy rainfall events. This erroneous distribution of rainfall will have an impact on the planting date and growth of the crops. The RCMs used in this study do not have a high enough resolution to explicitly resolve convection and therefore the same weakness remains. The RCMs ensemble however does perform better than the GCMs and simulate the West African monsoon in the correction position but with some variability in the date of highest intensity (Nikulin et al. 2012). The RCMs were found to contain biases that were corrected using the multisegment statistical bias correction method detailed in Grillakis et al. (2013) and Papadimitriou et al. (2016). The bias correction attempts to reduce biases and reconstruct events that are similar to observations, the accuracy of which are determined by the WFD-WFDEI dataset. The bias correction also decouples the input variables which may lead to events where precipitation occurs on a day without cloud cover. The net effect of these changes is to provide more realistic inputs for GLAM which in turn will provide more accurate projections.

A further limitation of the project is the single crop model used to simulate crops in the future climate scenarios. Expansion of the project by completing simulations of more crops within GLAM or using multiple crop models will reduce uncertainty in the final results. GLAM was used as part of a multi-model project in Parkes et al. (2018) where it was found to be effective at calculating mean yields but overestimating IAV. The overestimated IAV leads to an underestimate of the crop failure rate and therefore the crop failure rates in this study may be below those found whilst using other models.

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