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

3 **Ben Parkes · Benjamin Sultan · Philippe**
4 **Ciais**

5
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7 **Abstract** Maize (*Zea mays*) is one of the staple crops of West Africa and is
8 therefore of high importance with regard to future food security. The ability of
9 West Africa to produce enough food is critical as the population is expected
10 to increase well into the 21st century. In this study, a process based crop
11 model is used to project maize yields in Africa for global temperatures 2 K
12 and 4 K above the preindustrial control. This study investigates how yields
13 and crop failure rates are influenced by climate change and the efficacy of
14 adaptation methods to mitigate the effects of climate change. To account for
15 the uncertainties in future climate projections, multiple model runs have been
16 performed at specific warming levels of +2 K and +4 K to give a better
17 estimate of future crop yields.

18 Under a warming of +2 K the maize yield is projected to reduce by 5.9%
19 with an increase in both mild and severe crop failure rates. Mild and severe
20 crop failures are yields 1 and 1.5 standard deviations below the observed yield.
21 At a warming of +4 K the results show a yield reduction of 37% and severe
22 crop failures which previously only occurred once in 19.7 years are expected
23 to happen every 2.5 years. Crops simulated with a resistance to high temper-
24 ature stress show an increase in yields in all climate conditions compared to

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25 unadapted crops, however they still experience more crop failures than the
26 unadapted crop in the control climate.

27 **Keywords** Crop failures · Crop-modelling · Yield forecasts

28 1 Introduction

29 Maize is one of the staple crops of West Africa and contributes heavily to
30 meeting the food requirements of the region (Lobell and Gourджи, 2012). With
31 the population of West Africa expected to reach 1 billion between 2060 and
32 2070 (United Nations DESA, 2015) the need for stable and reliable food sources
33 is critical. With these two pieces of information it is clear that the production
34 of maize needs to increase to prevent food shortages and possible famines
35 across West Africa. Population change is not the only issue facing West Africa,
36 climate change is expected to alter rainfall patterns and increase temperatures
37 across the region. Much of the rainfall in West Africa is provided by the annual
38 monsoon which precludes the dry season. Under climate change the monsoon
39 may arrive later in the year, requiring the crops to grow in the hotter summer
40 months (Biasutti and Sobel, 2009; Sultan et al, 2014).

41 The impact of climate change on crop yield is key for food security. As
42 temperatures increase and rainfall patterns become more unstable the yield is
43 expected to fall in many regions, which in turn increases the number of people
44 at risk of starvation (Rosenzweig and Parry, 1994). Decreasing yields will hit
45 the poorest hardest as food prices will increase with scarcity (Rosenzweig and
46 Parry, 1994; Parry et al, 2004). Crop yields are expected to fall in richer na-
47 tions such as the United States and China, however they could respond with
48 expensive mitigation systems (Tubiello et al, 2002; Lobell et al, 2008). West
49 Africa does not have the financial might of the United States or China therefore
50 expensive mitigation systems are not a viable response to climate driven yield
51 reductions. These reductions in yields are in direct contrast with the increases
52 necessary to feed a growing population with a doubling required by 2050 (Ray
53 et al, 2013). With increasing carbon dioxide levels the potential for carbon
54 dioxide fertilisation to counteract crop yield reductions from climate change
55 exists. However for C4 grasses such as maize the response to carbon diox-
56 ide fertilisation is limited and is not enough to offset climate change induced
57 yield changes (Berg et al, 2013). There have been a number of meta-analyses
58 combining the results from several papers to provide estimates of future crop
59 responses (Roudier et al, 2011; Knox et al, 2012; Challinor et al, 2014). The
60 results in Roudier et al (2011) show that West African crops experience an
61 11% reduction in yields and that carbon dioxide fertilisation leads to poorer
62 quality crops with lower nutrient content. Maize along with other staples such
63 as rice, soybean and sorghum have been shown to provide lower amounts of
64 edible iron and zinc under elevated carbon dioxide conditions (Myers et al,
65 2014). The Knox et al (2012) meta analysis allows a closer focus on West
66 Africa and the Sahel with Sahelian maize yields expected to fall by 12.6% by
67 2050. Tropical maize in Challinor et al (2014) responds more negatively than

68 temperate maize to climate change and increasing global average temperatures
69 reduce yields by 20% at 4 K above the local average temperatures.

70 The ability of farmers to adapt to changing climate conditions includes
71 modifying their methods or replacing their crop. Breeding a new strain of a
72 crop is a non-trivial process and the rate at which developments are made does
73 not necessarily translate to changes in the cultivated crop. Providing a new
74 variety of a crop can take up to 30 years in Africa and with accelerating changes
75 in climate this means that farmers are likely to be left behind (Challinor et al,
76 2016). Another response to climate change is to cultivate a different species,
77 either because it generates more money or because the previous species is no
78 longer viable. It is estimated that a large fraction of the maize cultivated area
79 will transition into other crops during the 21st century (Rippke et al, 2016).

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

89 2 Methods and data sources

90 The General Large Area Model for annual crops (GLAM) is a process based
91 model designed for use with large scale inputs such as those from climate mod-
92 els (Challinor et al, 2004). GLAM uses daily meteorological fields as inputs,
93 these fields are downwelling shortwave solar radiation at the surface, precip-
94 itation, maximum temperature and minimum temperature. GLAM uses the
95 same grid spacing as the meteorological inputs (50 km x 50 km, see below). In
96 addition to the meteorological inputs GLAM also uses, soil data, a planting
97 window and a dedicated parameter set for West African maize. The planting
98 window data was sourced from the Ag-GRID GGCM harmonization (Elliott
99 et al, 2015) and the soil inputs, namely the drained upper and lower limits
100 and the saturation limit, were taken from the Digital Soil Map of the World
101 using methods described in Vermeulen et al (2013). The parameter set used
102 for the simulation of the maize crop was the same as used in Challinor et al
103 (2015) and the simulations were performed using Revision 434 of GLAM V3.
104 A description of GLAM is presented in SI Section 2. To ensure that only re-
105 gions which contribute to national production were analysed, the comparison
106 between model results and observed grid based yields is restricted to pixels
107 where at least 1% of the area is used to cultivate maize. A list of the countries
108 and their maize growing area is shown in SI Table 1. To define the 1% limit
109 of growing area the maize cultivated areas from Monfreda et al (2008) were
110 used. The yield data was taken from a dataset built from satellite observations

111 combined with yields reported by the Food and Agriculture Organization of
112 the United Nations (FAO) (FAOSTAT, 2014), Iizumi et al (2014) and Iizumi
113 and Ramankutty (2016). To ensure that the study only focuses on regions
114 where GLAM is capable of reproducing observed yields, it was also required
115 that the calibrated GLAM yield be within 10% (+/-) of the observed yield for
116 that grid cell.

117 Climate change can introduce or exacerbate stresses on a crop, one po-
118 tential response is to simulate crops adapted to high temperature stress or to
119 capture runoff for use later in the season. The high temperature stress (HTS)
120 routine in GLAM reduces the yield if daily maximum temperatures are above
121 a critical temperature ($T_{Crit} = 37^{\circ}\text{C}$). The HTS routine sets the yield to zero if
122 the daily maximum temperature is above the limit of $T_{Setzero} = 45^{\circ}$ (Challinor
123 et al, 2005, 2015). The HTS routine reduces yield as a response to high temper-
124 atures during flowering which reduce the ability of the crop to produce grain.
125 For the unadapted crop simulations the HTS routine is enabled and the crop
126 yields are reduced by higher temperatures. To show the yield changes caused
127 by HTS the HTS routine is disabled to simulate a crop adapted to HTS. While
128 this crop is not necessarily physical it does serve to highlight the importance
129 of temperatures during a specific growing period. Runoff capture is a method
130 to reduce wasted water by storing it and deploying the stored water later in the
131 season. The runoff capture system in GLAM retains 50% of the runoff from
132 the surface and stores it in an arbitrarily large reservoir. The stored water
133 is deployed when the soil moisture drops below the critical limit for terminal
134 drought stress. The maximum amount of water deployed from the reservoir is
135 limited to the entirety of the stored water or the amount of water required to
136 bring soil moisture up to 80% of the drained upper limit (Parkes et al, 2018).
137 The carbon dioxide fertilisation effect was modelled using an increase in trans-
138 spiration efficiency following methods from Challinor and Wheeler (2008) and
139 physiological responses for maize from Leakey et al (2009), Leakey (2009)
140 and Ghannoum et al (2000) with final parameters shown in SI table 3.

141 The meteorological inputs for the simulations were produced by bias cor-
142 recting the CORDEX Africa simulations. The bias correction method used was
143 multisegment statistical bias correction Grillakis et al (2013) and Papadim-
144 itriou et al (2016) and used the WFD-WFDEI dataset between 1981 and 2010
145 as a reference. The CORDEX simulations use the CMIP5 model simulations
146 as inputs to regional climate models with the aim of improving understanding
147 of regional scale systems (Nikulin et al, 2012). As part of the HELIX project
148 which focuses on high end climate change the CORDEX simulations which
149 were driven by the Representative Concentration Pathway to 8.5 Wm^{-2} (RCP
150 8.5) were selected for bias correction. The bias-corrected CORDEX-Africa data
151 has a horizontal resolution of $50 \text{ km} \times 50 \text{ km}$ and a temporal resolution of one
152 day. A GCM-RCM combination refers the outputs of one of the GCMs being
153 used to as input to one of the RCMs. For a GCM-RCM combination to be
154 used it was required that the driving GCM have global mean temperatures
155 of 4 K above the IPCC baseline (1870-1899) for 30 years before 2100. The
156 requirement of temperature and use within CORDEX-Africa resulted in the

157 eleven combinations shown in Table 1. For each GCM the 30 years where the
158 mean temperature was closest to +2 K and +4 K were used as inputs for the
159 crop model.

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

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

190 3 Results

191 GLAM simulates the historic yield using the calibrated yield gap parameter
192 and produces a multi-model mean yield of 1086 kg/ha, which is close to the
193 detrended observed yield of 1097 kg/ha. SI Figure 1 shows the difference be-
194 tween the observed yield and the multi model mean across eleven GCM-RCM
195 combinations for the time period 1986-2005. A break down of the uncertainties
196 in the replication of the observed yields is shown in SI Section 3.

197 For the future climates the results in Figure 1 show how yields change for
198 temperatures 2 K and 4 K above the control. For both future projections the
199 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 Figure 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 Figure 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 Figure 3, climate change reduces the average yield from $1086 \frac{1902}{308}$ kg/ha to $1031 \frac{1866}{219}$ kg/ha for RCP8.5 +2 K and to $647 \frac{1311}{129}$ 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, the differing times to reach the SWLs produces changes in the carbon dioxide fraction too. The GCM-RCM spread is 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 $647 \frac{1311}{129}$ kg/ha to $757 \frac{1415}{222}$ 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 Figure 4 show the changes in the 90th, 50th (median) and 10th percentile yields with error bars showing 1 standard deviation across the eleven 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 after climate change. The adaptation methods, notably HTS resistance reduce

246 the yield losses but not enough to return the yields to the same as the control
247 climate. With RCP8.5 +4 K climates the yields are reduced across the entire
248 range with the 10th percentile yield below 50% of its original value. As with
249 RCP8.5 +2 K the runoff capture scheme provides little relief from climate
250 change however the HTS resistant crop has a significantly improved median
251 and 10th percentile yield.

252 The results in the middle panel of Figure 3 show the percentage change in
253 mild crop failure rate in comparison with the control climate with unadapted
254 crops. The climate change results show an increase of 48% for +2 K and
255 more than 280% increase in mild failure rate for +4 K. The crop failure rates
256 are presented as a percentage change however their frequency is also a useful
257 metric. The control crop without runoff capture and while sensitive to high
258 temperature stress is expected to fail once every 6.6 years per grid cell, this
259 compares with once every 4.5 years for RCP8.5 +2 K and 1.7 years for RCP8.5
260 +4 K. The results for severe crop failures are shown in the bottom panel of
261 Figure 3 and mirror those from the middle panel of Figure 3. In the control
262 simulation the severe crop failure rate is once per 19.7 years per grid cell, this
263 rate drops to once every 9.6 years for RCP8.5 +2 K and once every 2.5 years per
264 cell for the RCP8.5 +4 K simulation, more than seven times more frequently.
265 The frequency of crop failures for crops grown with runoff capture is similar to
266 the unadapted crops, this is in agreement with the small yield differences. For
267 crops with high temperature stress resistance there is a reduction in failure
268 rate relative to an unadapted crop, however climate change still dominates the
269 signal. A high temperature stress resistant crop in in RCP8.5 +2 K fails mildly
270 once in 5.1 years and in RCP8.5 +4 K fails once every 3.2 years whereas the
271 control high temperature stress resistant crop fails only once every 22.0 years.

272 A further simulation set was completed, where the historical carbon dioxide
273 levels were maintained at the level of 361 ppm, which is the average of the 1986-
274 2005 calibration period, and the meteorology was taken from the future climate
275 simulations. In the absence of carbon dioxide fertilisation RCP8.5 +2 K has
276 a yield of 909 kg/ha and RCP8.5 +4 K produces 455 kg/ha. The difference
277 in yields between these results and the control yield of 1086 kg/ha highlights
278 how unsuitable the future climate is likely to be for maize growth and the
279 importance of positive carbon dioxide effects in GLAM. A series of simulations
280 without carbon dioxide fertilisation were completed and the change in yield
281 and crop failure rates are shown in Figure 5. The results show only first order
282 changes, any interactions between the meteorology and carbon dioxide levels
283 are lost in this analysis. When comparing the fixed historic carbon dioxide
284 simulations with the dynamic carbon dioxide ones, it can be seen that carbon
285 dioxide fertilisation reduces yield losses from 17% to 6% for RCP8.5 +2 K and
286 from 56% to 38% for RCP8.5 +4 K.

287 4 Discussion

288 The results shown in Figure 1 show that climate change of +2 K is likely
289 to cause a reduction in maize yields in West Africa of approximately 6%. In
290 the case of climate change resulting in a global average temperature change
291 of +4 K then the maize yields are projected to reduce by 38%. The yield
292 reductions produced in GLAM are within the range found in the meta analyses
293 in Knox et al (2012) and Challinor et al (2014). In addition to the marked
294 reduction in yield, the variability in the yields is projected to increase, making
295 it difficult to plan for the future, in particular for high end climate change
296 such as RCP8.5 +4 K. The increase in variability will impact food prices and
297 reduce food security across West Africa.

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

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

325 The results decoupling the meteorology and carbon dioxide fertilisation
326 break down how the future climate will affect maize yields. The higher lev-
327 els of atmospheric carbon dioxide are able to mitigate some of the damage
328 incurred by the meteorological changes. However the overwhelming signal is
329 of a reduction in yields and this is further reason to mitigate climate change
330 and work towards maintaining the current climate. These results are in agree-
331 ment with Roudier et al (2011) and Sultan et al (2014) which both show that

332 carbon dioxide fertilisation moderates yield losses for C4 crops but does not
333 fully counteract climate change. Furthermore as discussed in Berg et al (2013)
334 and Myers et al (2014) the quality of the crops grown in under increased car-
335 bon dioxide levels is expected to be lower leading to the problem of people
336 suffering from malnutrition.

337 The results presented here are limited by the grid scale of the input data
338 and the bias correction techniques used. The large grids in the climate mod-
339 els are known to blur out large scale storms and the convective schemes are
340 unable to accurately represent the storms typically found in monsoon regions
341 such as West Africa. The importance of the resolution of models has been dis-
342 cussed in detail in Garcia-Carreras et al (2015), where it was found that the
343 parametrised convection schemes in GCMs typically produce a large number
344 of drizzle events and under predict the heavy rainfall events. This erroneous
345 distribution of rainfall will have an impact on the planting date and growth of
346 the crops. The RCMs used in this study do not have a high enough resolution
347 to explicitly resolve convection and therefore the same weakness remains. The
348 RCMs ensemble however does perform better than the GCMs and simulate
349 the West African monsoon in the correction position but with some variability
350 in the date of highest intensity (Nikulin et al, 2012). The RCMs were found
351 to contain biases that were corrected using the multisegment statistical bias
352 correction method detailed in Grillakis et al (2013) and Papadimitriou et al
353 (2016). The bias correction is attempts to reduce biases and reconstruct events
354 that are similar to observations, the accuracy of which are determined by the
355 WFD-WFDEI dataset. The bias correction also decouples the input variables
356 which may lead to events where precipitation occurs on a day without cloud
357 cover. The net effect of these changes is to provide more realistic inputs for
358 GLAM which in turn will provide more accurate projections.

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

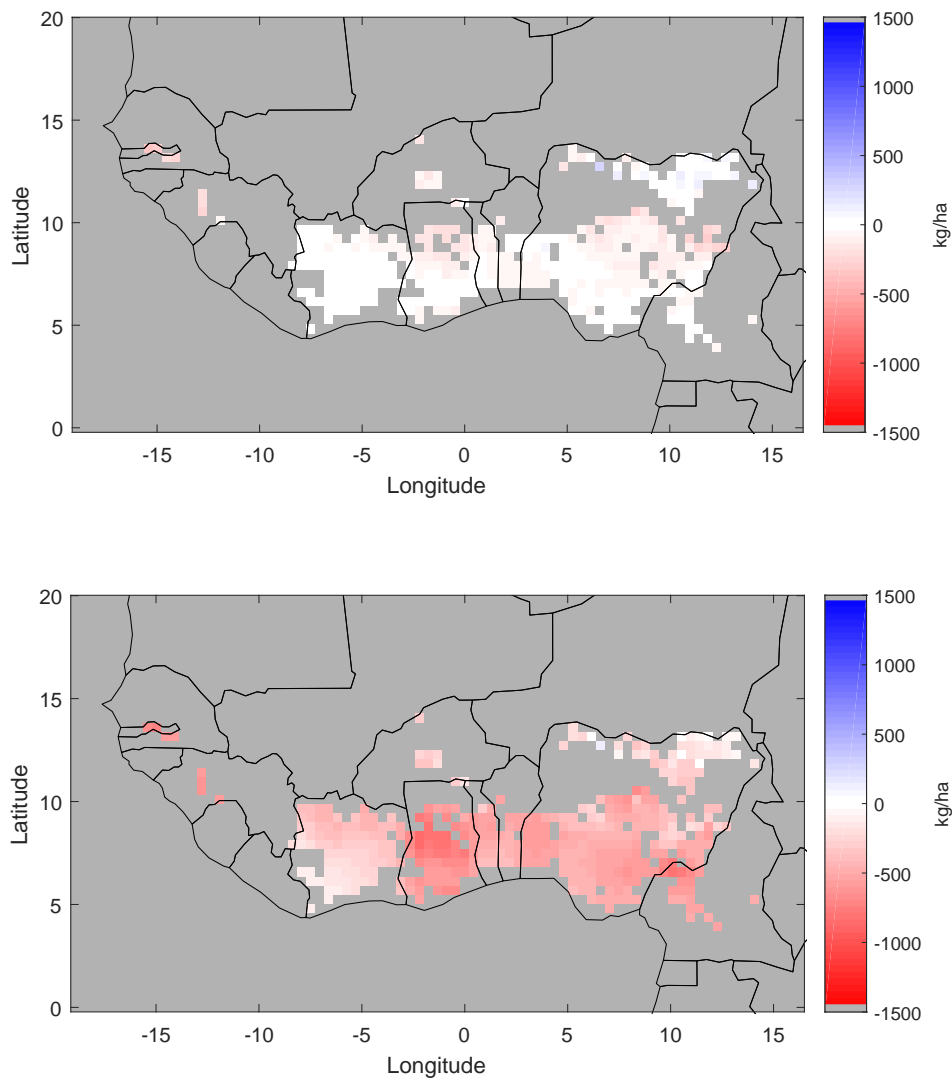


Fig. 1 Map showing the change in yield between the control simulation and RCP8.5 +2 K (top) and RCP8.5 +4 K (bottom) with unadapted crops. The results are a multi-model average across eleven GCM-RCM pairings.

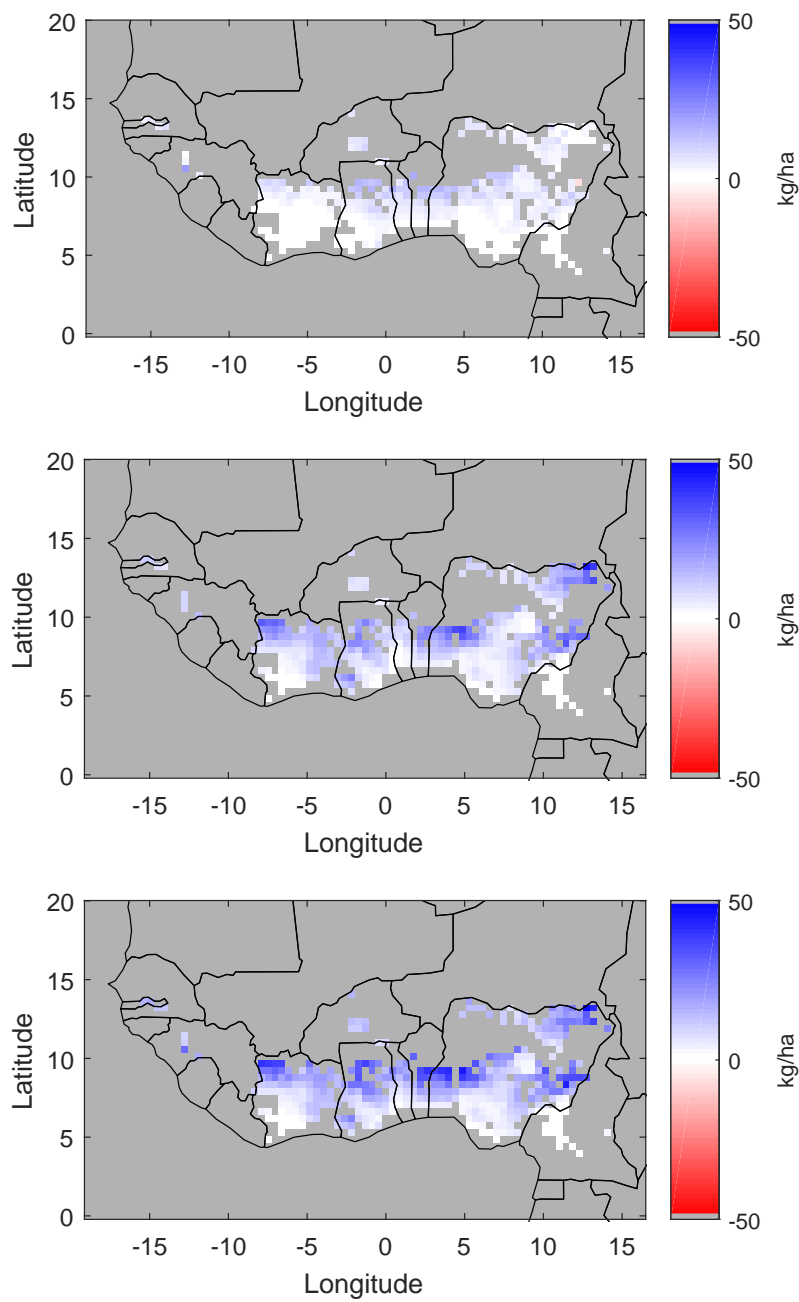


Fig. 2 Map showing the change in yield between the control simulation and control with high temperature stress adapted crops (top), crops grown with runoff capture (middle) and water and high temperature stress adapted crops (bottom).

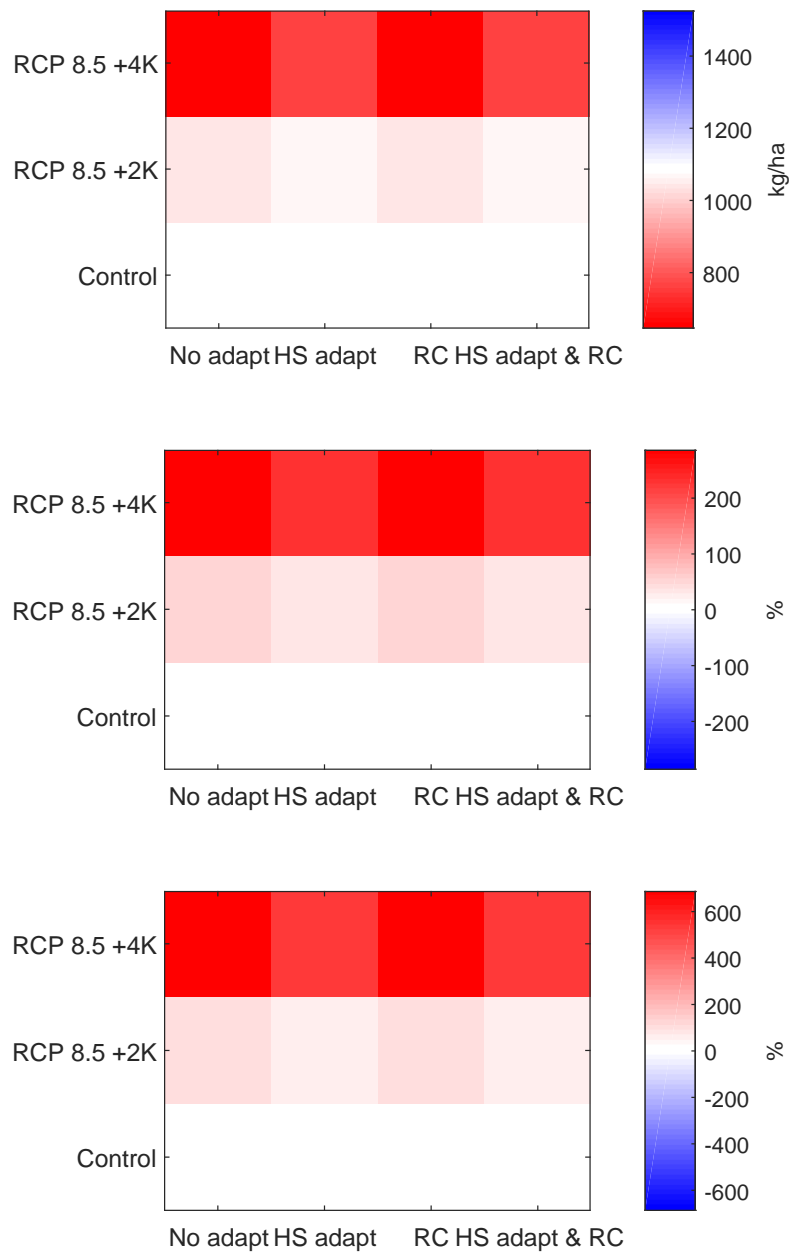


Fig. 3 Heatmap showing the difference in yields (top), mild crop failures (middle) and severe crop failures (bottom) for three climate conditions and four crop adaptation methods. No adapt shows the crops with no adaptation methods, HS adapt indicates high temperature stress adapted crops, RC indicates 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.

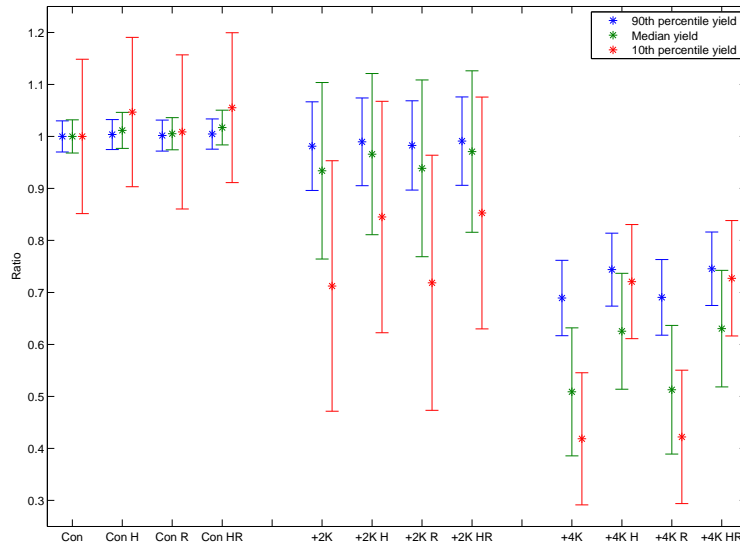


Fig. 4 Ratio of 90th, 50th and 10th percentile yields to the unadapted control crop for different climate conditions and adaptation methods. H indicates a HTS resistant crop, R indicates a crop grown with runoff capture, HR is a HTS resistant crop grown with runoff capture. Errorbars show 1 standard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

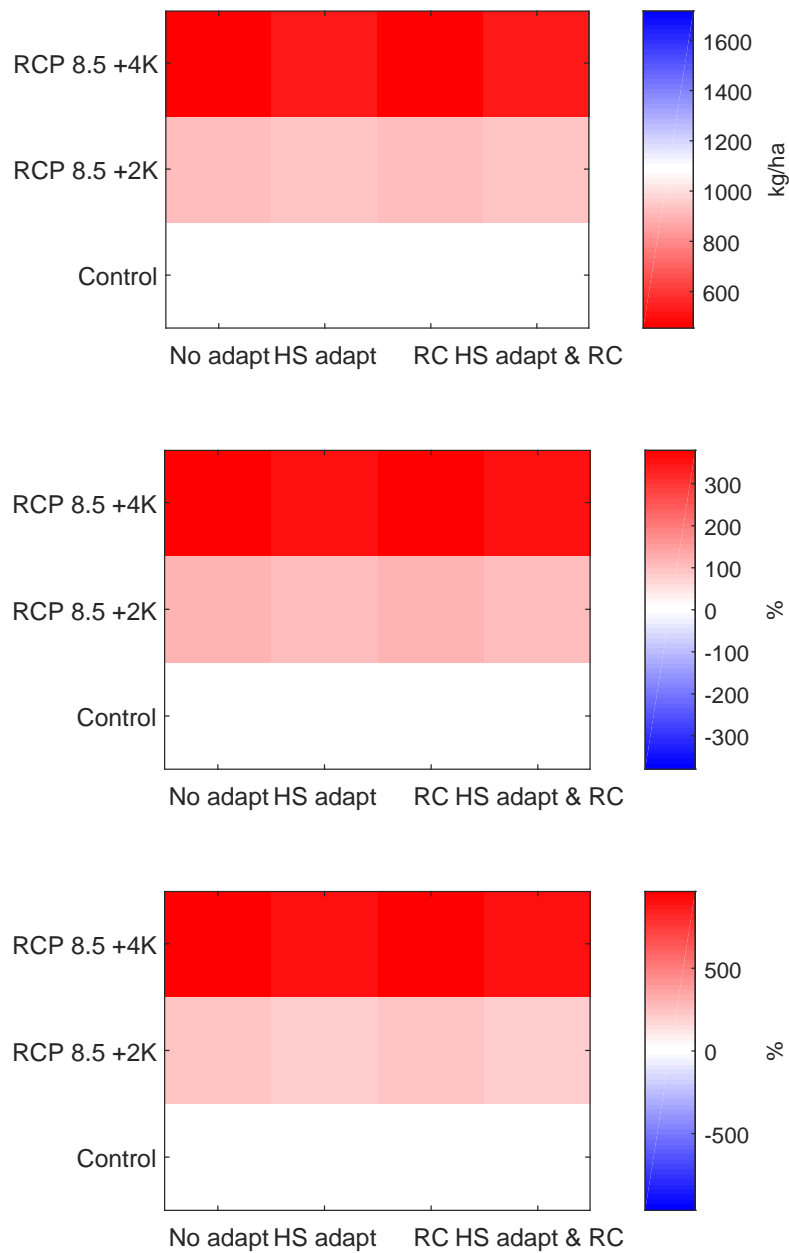


Fig. 5 Heatmap showing the difference in yields (top), mild crop failures (middle) and severe crop failures (bottom) for three climate conditions and four crop adaptation methods where carbon dioxide fertilisation has not been simulated. No adapt shows the crops with no adaptation methods, HS adapt indicates high temperature stress adapted crops, RC indicates crops grown with runoff capture. HS adapt and RC 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.

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

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