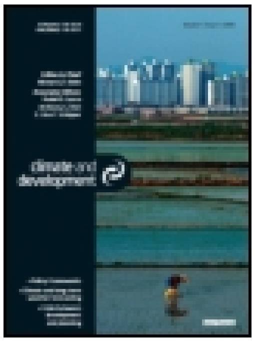

Climate and Development

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcld20

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To cite this article: Benjamin Stuch , Joseph Alcamo & Rüdiger Schaldach (2020): Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa, Climate and Development, DOI: 10.1080/17565529.2020.1760771

To link to this article: https://doi.org/10.1080/17565529.2020.1760771

CLIMATE AND DEVELOPMENT
https://doi.org/10.1080/17565529.2020.1760771

RESEARCH ARTICLE

Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa

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ABSTRACT
This study investigates the impacts of climate change in Sub-Saharan Africa on yields of maize and cereals (sorghum and millet) which are of particular importance to smallholding farmers. An ensemble of six climate scenarios are input to a crop model to compute changes in food availability (mean annual yield) and food stability (standard deviation and coefficient of variation) between the periods 1971–2000 and 2041-2070. Our results show a particular risk to food security in Central Africa where mean maize yield decreases over 89% of harvested maize areas, and its variability increases over 54% of these areas. A decline in mean maize yield is computed over 85% of harvested maize areas in West Africa, 29% in Southern Africa and 32% in East Africa. Within the limits of the analysis, we find that mean yields of tropical cereals will be more robust to climate change than maize, although yields still decrease over 23% of tropical cereal harvested areas. We find declining food stability over 37% of harvested maize areas and 46% of harvested tropical cereal areas. Our findings also indicate that a range of options including regional markets, strategic food reserves, and new cultivars could help farmers adapt to these changes.

ARTICLE HISTORY
Received 14 November 2019
Accepted 21 April 2020

KEYWORDS
Climate change; climate variability; food security; food stability; food availability; adaptation; modelling; maize; tropical cereals

1. Introduction

Food security has been a top priority in the international policy and research agenda for decades. Despite the large progress in achieving food security in most world regions (FAO et al., 2015b), it still is a key issue in Sub-Saharan Africa (SSA), the region with the highest prevalence of undernourishment (23% of the population) in the world (OECD and FAO, 2016). Food security has different dimensions (P. J. Ericksen, 2008; P. J. Ericksen et al., 2009). One widely accepted view is from World Food Summit 2009, which defines four dimensions ('pillars') of food security: availability, stability, access, utilization. Here we focus on 'availability' and 'stability'.

Research has confirmed that smallholders play a particularly important role in food security in SSA (FAO et al., 2015a; Frelat et al., 2016) (The definition of 'smallholding farm' varies from publication to publication and authors use various criteria. However, definitions based on land holding area have typical thresholds of 1–2 ha (Lowder et al., 2016)). One estimate is that around three quarters of the hungry people in Africa are smallholders (Sanchez & Swaminathan, 2005). On the production side, smallholders are the backbone of regional food supply (World Bank, 2007), generating 90% of total agricultural output in SSA (IFAD, 2011). On the consumption side, smallholders largely rely on their own agricultural activity for survival as their farms generate the principal income and/or food source for consumption (Frelat et al., 2016; Morton, 2007). Smallholders are the most vulnerable group to climate change and food insecurity because they typically depend directly on agriculture for their livelihoods and have limited coping capacities against shocks; thus any reduction or variability of agricultural productivity can threaten their food security, nutrition and well-being (Harvey et al., 2014; Hertel & Rosch, 2010; Sanchez & Swaminathan, 2005). In the face of increasing climate change impacts on agriculture and food security in SSA (Niang et al., 2014), it is urgent to identify adaptation measures, such as climate-smart agricultural cultivation practices (Lipper et al., 2014), that can help smallholder farmers in SSA cope with climate change (Harvey et al., 2014). Otherwise, it will be very difficult to achieve food security objectives such as ending hunger by 2030 (Target 2.1 of the Sustainable Development Goals).

While several agricultural impact assessments (e.g. Nelson et al., 2009; Rosenzweig et al., 2014; Schlenker & Lobell, 2010; Teixeira et al., 2013; Waha et al., 2013) have examined the important question of climate change impacts on long-term mean crop yields, a meta-analysis of Challinor et al. (2014) found only six studies which have looked at changes in the year-to-year variability of crop yields. But both aspects are important in assessing food security and in adapting to climate change (Challinor et al., 2014; Thornton et al., 2014); thus, the number of climate change assessments that analyse yield variability is recently increasing (Y. Chen et al., 2018; Leng & Hall, 2019; Ostberg et al., 2018; Vanuytrecht et al., 2016).

Since, crop production provides the largest share (ca. 60%) of consumed food in smallholder households in SSA (Frelat et al., 2016) any change in mean crop yields has an impact on the food security pillar 'food availability'. Therefore, gaining an understanding about the expected trends in mean yields

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Supplemental data for this article can be accessed at https://doi.org/10.1080/17565529.2020.1760771

provides valuable information to identify and implement suitable adaptation measures that help cope with adverse trends or that gain the most from beneficial trends. In addition, it is important to analyse changes in the year-to-year variability of crop yields because they directly affect the food security pillar 'stability' in SSA. This relates to the high importance of annual food production on the persistence of yearly food availability and food access in SSA and, i.e. in smallholder households (Frelat et al., 2016; Sanchez & Swaminathan, 2005). Gaining an understanding about the expected changes in the year-to-year variability of crop yields is crucial to identify sound agricultural adaptation measures that can lessen the variability of annual food production in SSA. Based on these relationships between crop yields and food security in SSA, there is a need for additional agricultural assessments that assess both changes to long-term mean yields as well as year-to-year variability of yields (Funk et al., 2008; Porter et al., 2014).

Here we examine the impacts of climate change on food security in SSA. We focus on 2 pillars of food security: food availability and food stability. As indicators of these pillars, we use changes in mean yields and change in year-to-year variability of yields respectively. The present study has large-scale coverage of West, East, Central and Southern Africa and evaluate and compare climate change impacts across these regions. We emphasize the mid-term future (2041–2070), which is important because it is distant enough to capture important impacts of climate change, but close enough to the present to be relevant to decision makers that need to anticipate and prepare a response to climate change. The driving climate variables are analysed to explain model results and as input to assessing agricultural adaptation measures.

We focus on currently cultivated areas of two crop types, particularly important for food security in SSA: maize and tropical cereals (sorghum and millet). These crop types are important because they are the dominant types in terms of harvested areas (73% of harvested grain production areas (2011–2013 mean; FAO, 2015a)) and widely distributed across different agro-climatic conditions (Schlenker & Roberts, 2009; P. Singh et al., 2017). Together they make a critical contribution to food availability in Africa by satisfying 86% (maize) and 88% (tropical cereals) of their demands in Africa (FAO, 2015b). Moreover, only 6.1% (maize) and 0.3% (tropical cereals) of the produced food is exported overseas (FAO, 2015b), showing that nearly all of the harvest remains in the region. By concentrating on areas that are already cultivated, our impact analysis reflects the conditions on land that is most relevant to the agricultural sector in SSA currently and likely also in the future.

2. Methods and materials

2.1. Crop modelling and climate scenarios

The core of the analysis of climate impacts on food security is a comparison between simulated yields of annual maize and tropical cereals for a baseline period (1971–2000) and a scenario period (2041–2070). Yields are simulated with the process-based crop model LPJmL (Bondeau et al., 2007) which computes potential crop yields at a grid cell resolution of 0.5°. Crop yields are simulated for the annual growing period, which is determined dynamically in the LPJmL model by the simulated sowing day (function of climate) and the simulated harvest day (heat unit concept; see Supplementary Material S1.2). Crop yields are simulated on harvested areas from the year 2005 (Figure 1) according to the Spatial Production Allocation Model (SPAM; HarvestChoice, 2014).

The crop yield modelling, in turn, is driven by a set of 6 climate change scenarios (Table 1), each driven by a separate Global Circulation Models (GCMs) based on the high-end RCP 8.5 emission scenario (Van Vuuren et al., 2011). Using output from an ensemble of GCMs rather than a single GCM partly takes into account the uncertainty of climate modelling results. Since GCM output cannot directly be applied in bio-physical impact models (Ramirez-Villegas et al., 2013) due to coarse spatial resolution and biases particularly in precipitation (Supit et al., 2012) the applied GCM data are statistical bias corrected and spatially downscaled according to Piani, Haerter,

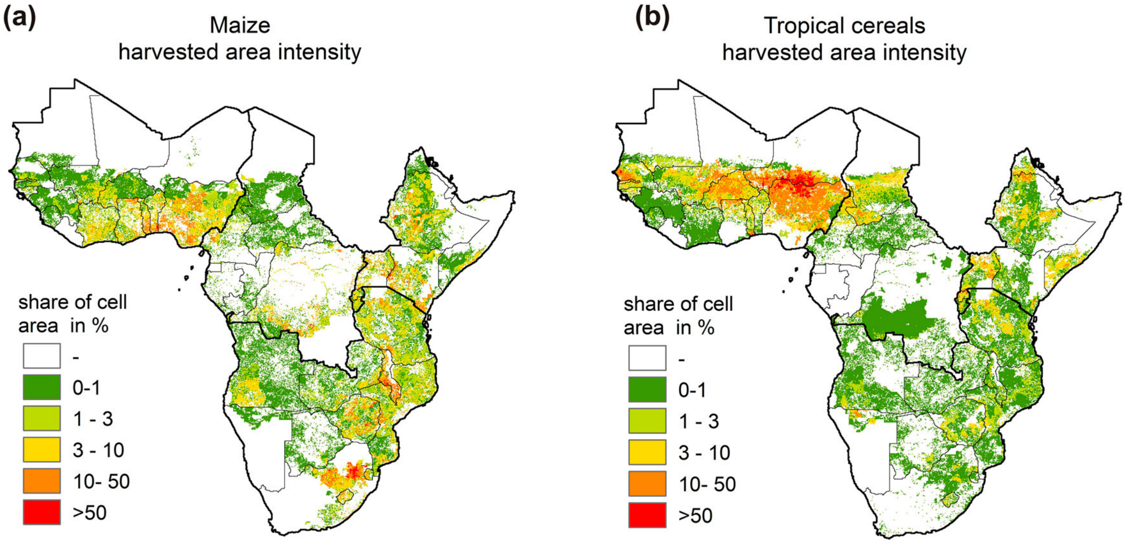

Figure 1. Base-maps showing the intensity of harvested rain-fed areas for maize (a) and tropical cereal (b) for the year 2005 (data adjusted from SPAM); the total harvested land of maize is 243,902 km^2 and for tropical cereals is 348,310 km^2. Thick lines indicate border of UNEP-GEO SSA regions; thin polygons show national borders.

et al. (2010), Piani, Weedon, et al. (2010), and Haerter et al. (2011). The statistical bias correction has the advantage of accounting for changes in mean climate and climate variability between the baseline and the scenario period (Supit et al., 2012), an important precondition for our analysis. For validation the utilized bias correction method is applied to the simulated period 1990–1999 and is successfully tested against the corresponding reference data regarding mean and variance values (Piani, Weedon, et al., 2010). The utilized ensemble data provide input about changing climate mean and variability patterns at an accurate temporal and spatial resolution to drive the LPJmL model. Additional information on the climate data is provided in the Supplement (S1.1).

2.2. Yield and climate statistics

As discussed previously, we focus on 2 ‘pillars’ of food security – food availability and food stability. As indicators of these pillars, we use changes in mean yields and changes in year-to-year variability (SD and CV values) of yields, respectively. Changes in mean yield indicate the average impacts of climate change on food production, and changes in SD and CV indicate its impact on year-to-year variability. SD indicates the year-to-year variability in typical units of yield, whereas the CV is the normalized variability relative to the calculated mean yield. The combined analysis of SD and CV indicates whether the annual variability changes in absolute magnitudes (as indicated by the SD) or in values relatively to its mean (as indicated by the CV). Both are important for interpreting climate change impacts on the stability dimension of food security as well as for formulating sound agricultural adaptation options under projected climate change impacts (see Sections 3 and 4).

Climate change impacts are simulated at the grid cell scale and presented in grid scale maps and regional scale aggregated data. Regional boundaries are taken from the United Nations Environmental Program – Global Environmental Outlook (UNEP-GEO) (Figure 1). Regional weighted yield statistics are calculated by first multiplying the annual yield of a particular crop type in each grid cell by its harvested area, summing these values over the region, and then dividing the sum by the total harvested area in the region. The weighted annual yields are then used to compute the mean, SD and CV values for the 30-year baseline and scenario periods, respectively.

To better understand the influence of temperature or precipitation on crop yields and to discuss agricultural adaptation options, we calculate the arithmetic mean, SD, and CV of the driving temperature and precipitation data during the simulated annual growing period.

3. Results

The spatial distribution of modelled crop yield for the baseline period, and changes between the scenario and baseline periods, are shown in Figure 2 (maize) and Figure 3 (tropical cereals). Corresponding temperature and precipitation values are shown in the Supplement (Figure S1–S4). Figure 4 shows harvested maize (a) and tropical cereal (b) areas according to the occurrence of temperature stress in the baseline or scenario period (see caption of Figure 4 for explanation of temperature stress). These figures show the median values of food security indicators from the scenario ensemble.

Table 2 shows aggregated regional statistics about yield change affected harvested areas of maize and tropical cereals whereas tabs. 3 and 4 shows aggregated regional yield statistics of maize and tropical cereals respectively (each table present median values of the scenario ensemble). The variety of ensemble results is shown in the boxplots of Figure 5. One boxplot is presented per region and yield statistic (mean, SD, and CV). Each boxplot consists of six values according to the six climate scenarios analysed. The longer the boxplot, the larger the variation in simulated regional crop yield changes due to differences in climate scenarios. (See caption of Figure 5 for further explanation of the boxplots.) The range of the driving temperature and precipitation values across the ensemble is shown in the supplement (Figures S5–S8).

3.1. Maize mean yield

Table 3 shows that mean maize yields decrease in West (−13%) and Central Africa (−10%), and increase in Southern (+13%) and East Africa (+25%). Looking beyond these aggregated regional values, it becomes apparent that a large fraction of each region is affected by a decrease in mean yield: 85% in West, 89% in Central, 29% in Southern and 32% in East Africa (Table 2). Decreases in yield result mostly from intensified heat stress, rather than from changes in precipitation. The average temperature during the growing period in harvested maize areas increases in West Africa from 27.3°C to 29.9°C and in Central Africa from 25.0°C to 27.8°C. This, coupled with an increase in the SD of mean monthly temperature in Central Africa (from 0.5 to 0.8 K) and West Africa (1.1 to 1.4 K) indicate a higher occurrence of high heat stress events (> 26°C for maize). Under elevated heat stress, maize yields in these regions cannot benefit from increased soil moisture resulting from increased precipitation (+7% in West and +13% in Central Africa, Table 3).

In contrast, higher mean maize yields in Southern and East Africa in the scenario period can be explained by both

Table 1. Climate scenarios and driving force of the investigated climate scenario ensemble.

GCM name	Modelling centre or group	Emission scenario used to drive model
cmcc-cesm	Centro Euro – Mediterraneo per I Cambiamenti Climatici	RCP 8.5
cnrm-cm5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	RCP 8.5
ecearth-dmi	EC-EARTH consortium	RCP 8.5
hadgem2-es	Met Office Hadley Centre and additional realisations contributed by Instituto Nacional de Pesquisas Espaciais	RCP 8.5
ipsl-cm5a-lr	Institut Pierre-Simon Laplace	RCP 8.5
mpi-esm-lr	Max Planck Institute for Meteorology	RCP 8.5

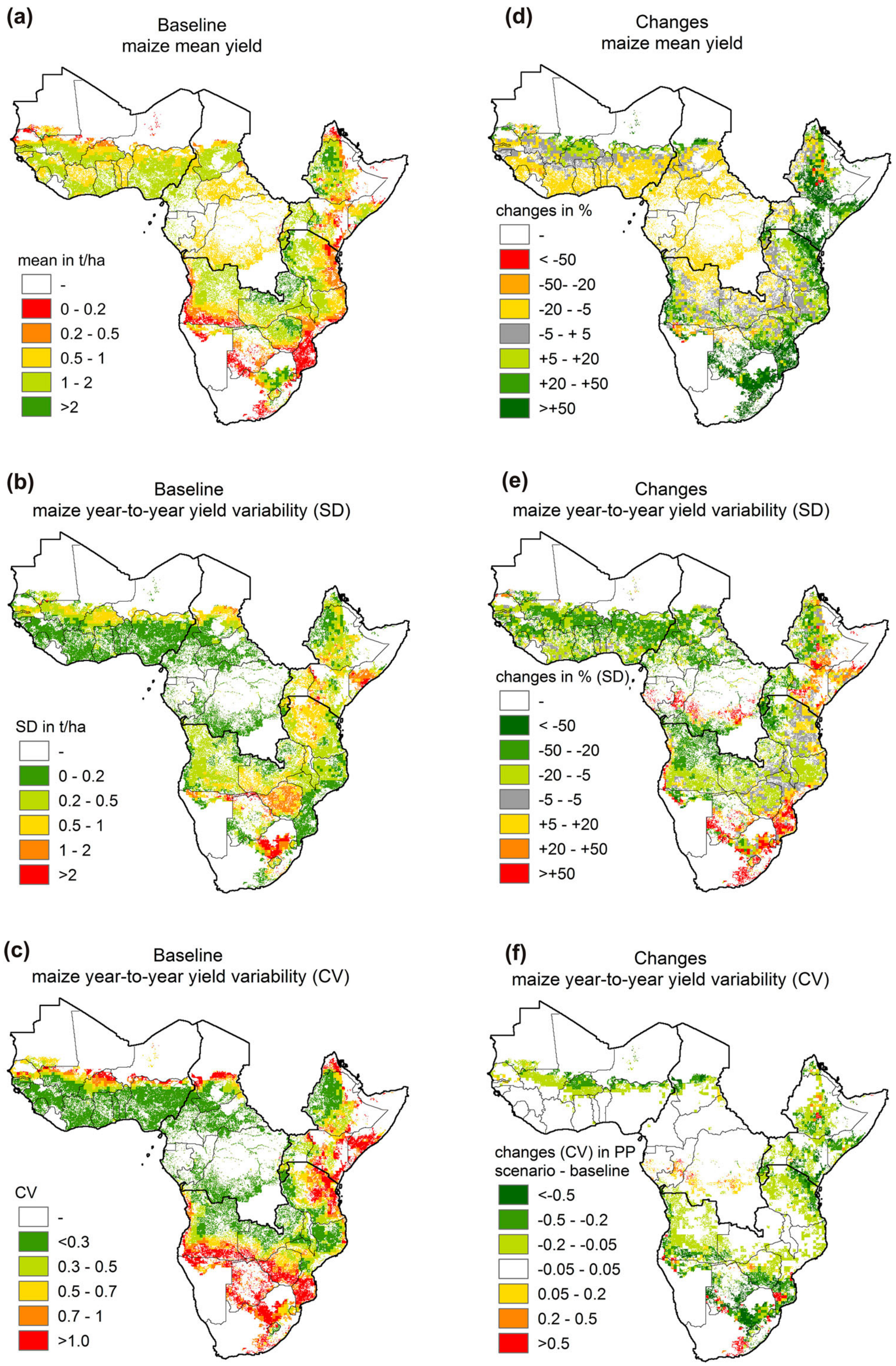

Figure 2. Simulated spatial distribution of maize yield for the baseline period (1971-2000) (a–c) and the difference between the scenario period (2041–2070) and baseline period (d-f). The maps show median values at the grid cell level over the climate scenario ensemble. Row 1 shows long-term mean yield, while row 2 (SD) and row 3 (CV) show year-to-year yield variability. Thick borders indicate UNEP-GEO regions. Colours use the traffic light scheme to indicate the relative potential of each cell to support food availability and food stability. In the baseline green colours indicate areas with high mean yield (a) and areas with low year-to-year yield variability (b–c). In contrast, red colours indicate areas with low mean yield (a) and areas with high year-to-year yield variability (b–c). In the scenario green colours indicate potential beneficial impacts on food availability (c) and food stability (e–f) whereas red colours indicate adverse impacts respectively.

temperature and precipitation changes. In these regions, mean monthly temperature increases from 22.0°C to 24.7°C and from 21.5°C to 24.2°C, respectively. Hence, temperatures shift from the lower end to the center of the optimum temperature range for maize productivity (21–26°C, see supplement S1.2). Figure 4(a) also indicates blue areas where global warming has reduced low-temperature stress and orange areas where previously non-stressed areas now experience heat stress from higher temperatures. Overlaying these areas with harvest intensities in Figure 1(a) shows that some intensively harvested areas may benefit from a reduction in low-temperature stress. Nevertheless, the total harvested maize area in SSA falling

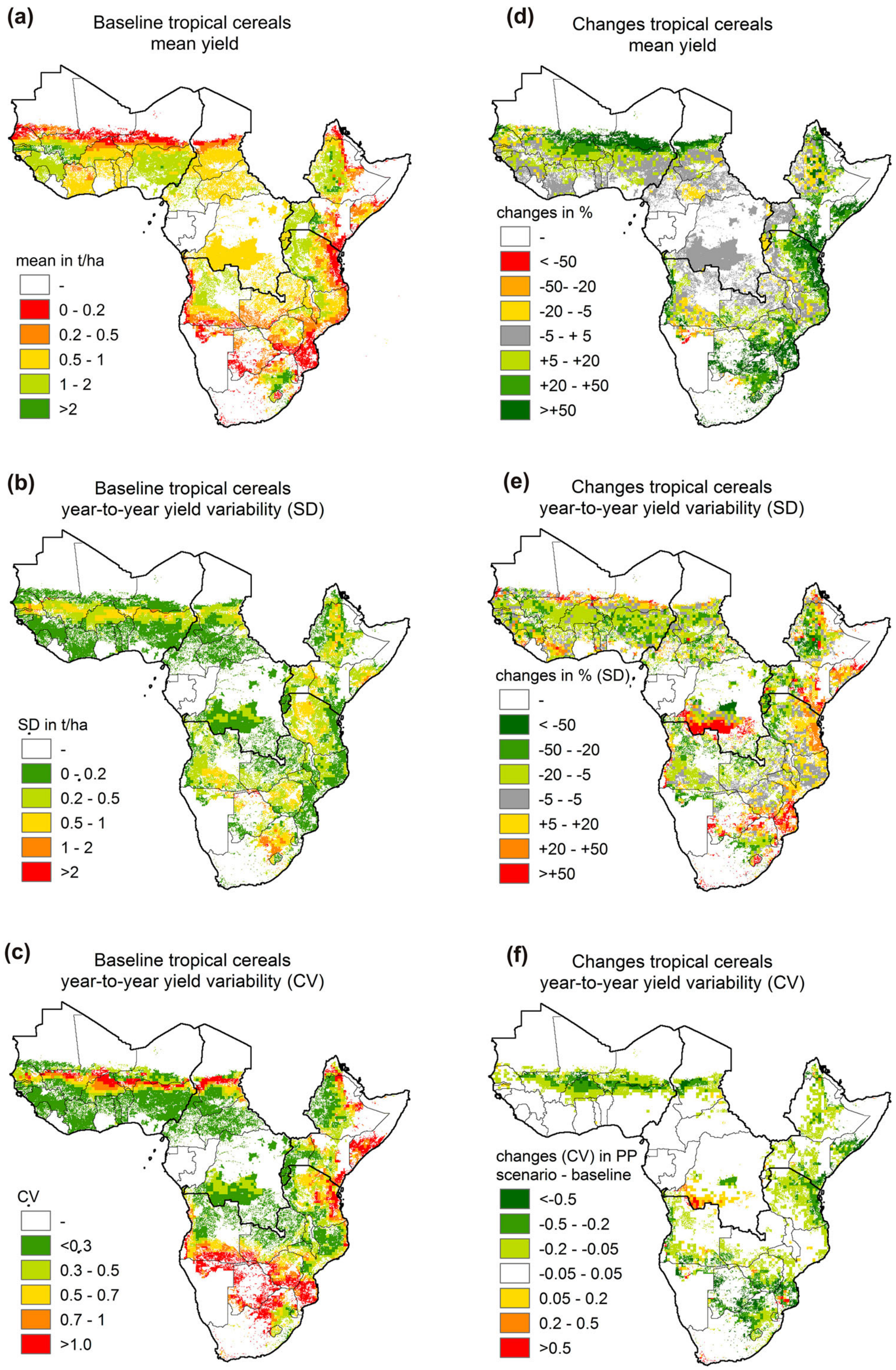

Figure 3. Same as Figure 2, but for tropical cereals.

within the envelope of optimum temperatures decreases from 42% (baseline) to 38% (scenario) and the temperature stress affected area increases from 36% to 55% respectively. Moreover, an increase in precipitation in Southern and East Africa (+8% and +3%, respectively) makes conditions somewhat more favourable for maize production in these dry regions. These climate signals correspond to higher aggregated regional mean yields. However, Figure 2 shows that the direction of change of yield has an irregular pattern in both regions, likely related to the spatial variation of agro-climatic conditions within these regions.

Figure 5 (row 1, column a) shows ensemble results for the changes of the regional mean of maize yield between baseline and scenario periods. Despite the wide variation in ensemble results, all simulations show a decrease in mean yields of maize in West and Central Africa, and an increase in East

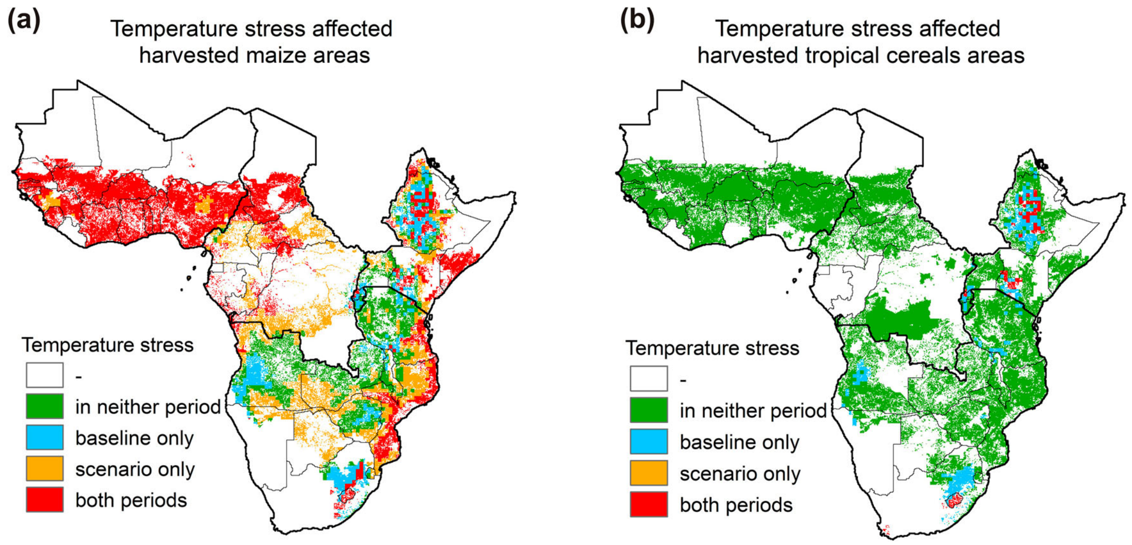

Figure 4. The occurrence of temperature stress over harvested areas of maize (a) and tropical cereals (b) during their growing periods in the baseline or scenario period, as indicated. Temperature stress occurs when the temperature is outside of an assumed envelope of optimum temperatures (21–26°C for maize and 20–40°C for tropical cereals). Green areas are not affected by low- or high-temperature stress in the baseline (1971–2000) nor in the scenario (2041–2070) period. Blue areas are affected by low-temperature stress in the baseline but are not affected by temperature stress in the scenario (due to projected warming). Orange areas are not temperature-stressed in the baseline but become heat-stressed in the scenario. Red areas are low- or high-temperature-stressed in both periods. The figure was created from the median temperature value of the climate scenario ensemble.

and Southern Africa (with one outlier scenario in Southern Africa). Hence, climate scenarios from six different models produce consistent results for regional mean maize yield.

3.2. Maize year-to-year yield variability

The year-to-year variability of maize yield (CV values) decreases in East Africa (−2 pp) and Southern Africa (−5 pp), whereas it increases in Central Africa (+2 pp). West Africa shows no change. Recalling that the CV of yield is computed by dividing its SD by its mean we now discuss the changes in CV in light of changes in these statistics (Table 3). The reduction in CV in Southern Africa stems from the fact that mean yield increases proportionately more than its SD. In East Africa, mean yields increases and its SD decreases; thus, CV decreases. CV increases in Central Africa because mean yield decreases and its SD increases. In West Africa, the mean and SD decrease proportionally the same; thus, CV remains constant, but at a markedly lower mean level. Between 18% (West) and 48% (Southern) of currently harvested maize areas will be affected by increased magnitudes of year-to-year yield variability (SD values, Table 2).

The changes in year-to-year variability of maize yield are mostly temperature-driven in all regions. In Central and West Africa, scenario temperatures during the growing period often exceed the temperature optimum of maize productivity (see mean maize yield analysis) even in a characteristic cold month. A characteristic cold month is here defined as the mean temperature value minus the SD temperature value. Under these conditions, any variability in temperature during the growing period, drives change in the level of heat stress intensity. As a response to these variable heat stress levels, maize yield variability increases relatively to the declining mean maize yields in these regions. The increase in precipitation in Central Africa (+13%) and West Africa (+7%) has little effect on maize yields because water stress is already low in growing areas (as indicated by high monthly mean precipitation values and low month-to-month variability of precipitation under baseline conditions).

By contrast, in East and Southern Africa some harvested maize areas are currently exposed to stress from cold rather than warm temperatures (Figure 4(a)). The simulated increase in the regions` average temperature from 21.5°C to 24.2°C (East Africa) and from 22.0°C to 24.7°C (Southern Africa) as well as the moderate increases in month-to-month temperature variabilities from 0.8 to 1.0 K (East Africa) and from 1.1 to 1.2 K (Southern Africa) indicate, on average a less frequent and intense level of cold-temperature stress (<21°C) in the

Table 2. Harvested area (maize and tropical cereals) for the baseline and their share that is affected by decreasing mean yield and increases in year-to-year yield variability (SD and CV values) in the scenario period (2041–2070).

Crop	Region	Harvested area (km^2)	Area of decreased mean yield	Area of increased yield variability (SD value)	Area of increased yield variability (CV value)
maize	Southern	109 103	29%	48%	20%
maize	East	41 913	32%	38%	19%
maize	West	72 462	85%	18%	38%
maize	Central	20 424	89%	45%	54%
trop_cereals	Southern	25 498	34%	47%	24%
trop_cereals	East	31 810	41%	55%	40%
trop_cereals	West	270 115	19%	46%	14%
trop_cereals	Central	20 888	34%	39%	38%

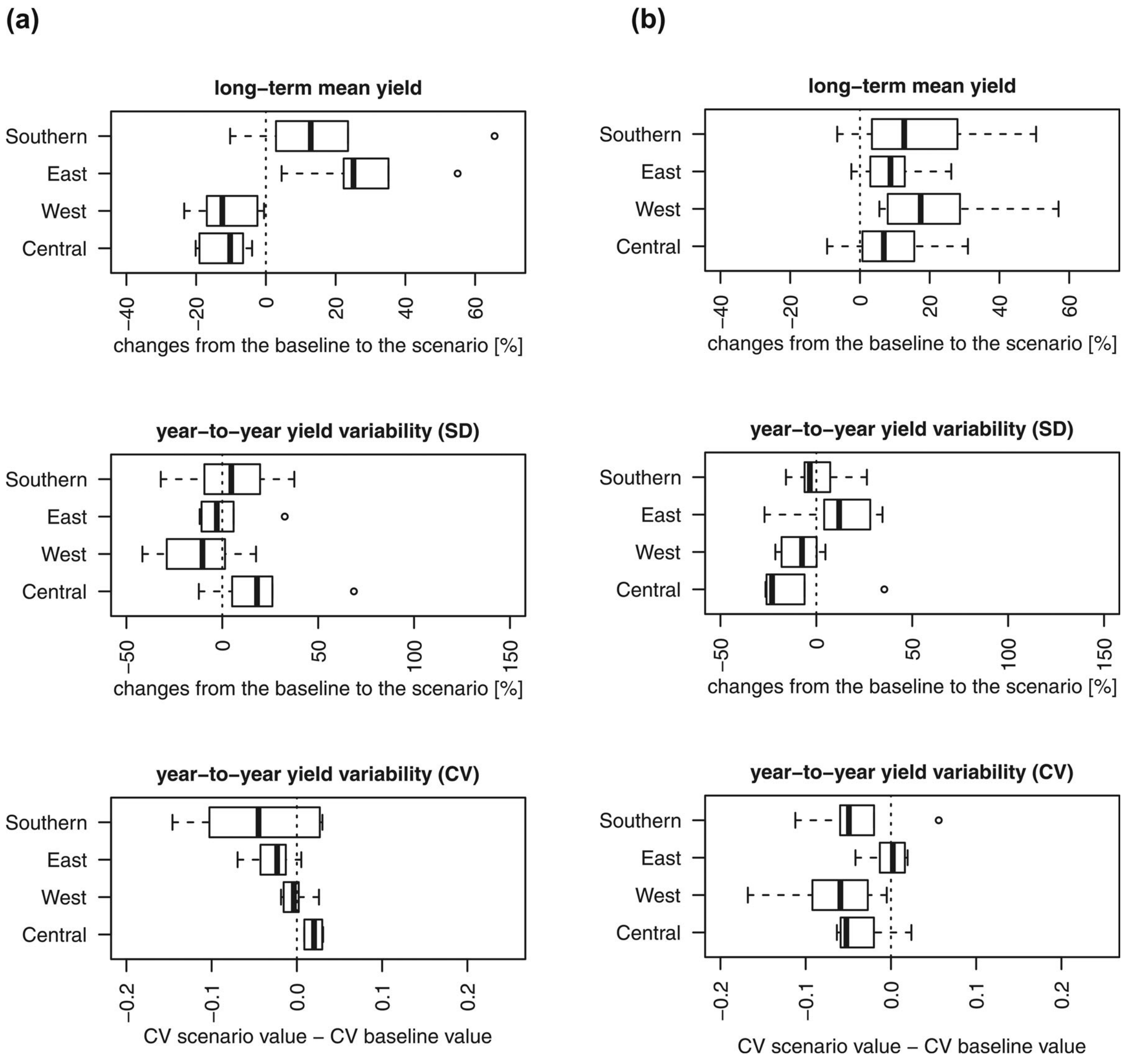

Figure 5. Computed climate change impact on changes in maize yield (column a) and changes in tropical cereal yield (column b). Each boxplot represents an ensemble of six values, based on RCP 8.5 scenarios from six climate models. The thick line indicates the median result of the ensemble. The left and right sides of the boxplots represent the 25th and 75th percentile of the ensemble, respectively. Whiskers indicate extreme values up to 1.5 times the box width. Values beyond that range are assumed to be ensemble outliers and are shown as circles. In general, the smaller the boxplot, the greater the consistency in ensemble results. In general, decreasing SD values indicate a decrease in absolute year-to-year yield variability, whereas increasing SD values show an increase in absolute yield variability. The same accounts for changes in CV values but in terms of year-to-year yield variability relatively to its mean yield.

scenario. These changes also indicate that growing season temperatures are more likely to fall within the optimum temperature range of maize productivity (21–26°C) as compared to the baseline period. Likewise, because it is temperature-driven, the year-to-year variability of maize yield (CV values) also decreases in East and Southern Africa and does not respond to increased precipitation variability. Thus, maize production becomes more stable relatively to its mean production.

As a qualification, it should also be noted that any additional global warming beyond our ensemble values or any increase in temperature variability is likely to push temperatures outside of the optimum range of maize productivity and lead to a decrease in mean yield and/or an increase in production variability. That is likely until the end of this century.

The boxplots in Figure 5 (column 1, row 3) show moderate differences between the different climate sceanrios in the simulated changes in year-to-year variability of maize yield (CV values) between the different climate scenarios (with the exception of the Southern African region). There is very strong agreement for Central Africa in terms of computed CV which show moderate increase in all scenarios. The boxplots show a tendency of moderate increases in absolute year-to-year yield variability (SD values) in Central Africa and of moderate decreases in West Africa. No robust trend can be identified for SD values in East and Southern Africa.

3.3. Tropical cereals mean yield

Mean yields of tropical cereals increase in all regions, from +7% in Central Africa to +17% in West Africa (Table 4). Despite these positive aggregated trends, a large proportion of the harvested area in each region (between 19% in West and 41% in East Africa; Table 2) experiences mean yield decreases. Warming does not have a big impact on yield because scenario temperatures continue to mostly fall within the optimum range for tropical cereal production (20°C-40°C, see supplement S1.2).

Table 3. Simulated regional yield, precipitation, and temperature data on harvested maize areas for baseline period (1971–2000), and changes between the scenario period (2041–2070) and baseline.

Region	Period	Yield			Precipitation			Temperature		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Southern	Baseline Scenario	1.5 t/ha +13%	0.42 t/ha +5%	0.28 −0.045 pp	134 mm +7.6%	51 mm +13.4%	0.375 +0.014 pp	22.0°C +2.7K	1.1 K 0.0K	0.052 0.003 pp
East	Baseline Scenario	1.5 t/ha +25%	0.19 t/ha −3%	0.13 −0.023 pp	145 mm +2.5%	34 mm +3.2%	0.238 0.002 pp	21.5°C +2.7K	0.8 K +0.2K	0.039 +0.004 pp
West	Baseline Scenario	1.1 t/ha −13%	0.08 t/ha −10%	0.07 +0.004 pp	184 mm +6.8%	50 mm +13.2%	0.270 +0.033 pp	27.3°C +2.6K	1.1 K +0.3K	0.041 +0.007 pp
Central	Baseline Scenario	0.8 t/ha −10%	0.05 t/ha +18%	0.07 +0.020 pp	170 mm +13.1%	37 mm +23.4%	0.217 +0.02 6pp	25.0°C +2.8K	0.5 K +0.3K	0.020 +0.008 pp

Notes: Ensemble median values are shown. Changes in CV values are shown as percentage points pp (scenario value – baseline value).

However, some areas in Southern and East Africa (blue areas in Figure 4(b)) show an increase in yield because current stress from cold temperatures is diminished by warmer future temperatures.

As compared to temperature, the change in precipitation has a remarkable effect on yield. Monthly precipitation is projected to increase in all regions (Table 4), with the strongest increases in Central, West, and Southern Africa (+10%), resulting in mean yield increases of +7%, +17% and +13% respectively. The lower yield increase in Central Africa can be explained by the fact that tropical cereals here are only slightly limited by lack of precipitation (mean monthly precipitation = 170 mm, and SD = 49 mm). By contrast, water stress on crops is higher in West and Southern Africa (mean monthly precipitation = 140 and 135 mm, respectively; SD = 43 and 45 mm, respectively). Projected increases in precipitation reduce water stress and lead to more substantial yield increases.

Most ensemble results agree that mean yield is increasing in all regions, but they disagree on the magnitude of this increase (Figure 5, column 2, row 1).

3.4. Tropical cereals year-to-year yield variability

The year-to-year variability of tropical cereal yields (CV values) decreases in Southern (−5pp), West (−6pp) and Central Africa (−5pp). The decrease in variability relates to both decreased SD of yield and increased mean yields (Table 4). In sum, the production of tropical cereals in these regions becomes more stable at higher mean yield values. Meanwhile, the variability in East Africa does not change because of a proportional increase in both mean yield and SD of yield. Notwithstanding regional average trends, large fractions of currently harvested areas will still experience increases in variability (SD values, Table 2): 47% (Southern), 55% (East), 46% (West) and 39% (Central).

Changes in precipitation have a marked influence on the variability in tropical cereal yields in all regions. By contrast, changes in temperature are important only in a few regions of East and Southern Africa where yield is now sometimes limited by cold temperatures (blue areas in Figure 4(b)).

East Africa is the only region to show a regional average increase in SD of yield (12%). Mean precipitation increases from 143 to 145 mm and the absolute precipitation variability increases from 34 to 38 mm. While the precipitation of a characteristic dryer month (mean value minus SD value) decreases from 109 to 107 mm, the precipitation of a characteristic wetter month (mean value plus SD value) increases from 177 to 183 mm. These moderate changes, however, tend to result in greater water stress intensities in characteristic dryer months, and reduced water stress intensities in characteristic average or wetter months. Thereby, water stress becomes likely more variable during the growing period, which explains the increases in mean yields as well as in yield variabilities in East Africa. All other regions show greater water availability in average during the growing period as well as in a characteristic dryer month (mean-SD value). This indicates that water stress is likely less intense and variable during the growing period and explains the decrease in yield variability (SD and CV value) at higher mean levels in West, Central and Southern Africa.

Table 4. Simulated regional yield, precipitation, and temperature patterns on harvested tropical cereal areas for baseline period (1971–2000) and changes between the scenario period (2041–2070) and baseline.

Region	Period	Yield			Precipitation			Temperature		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Southern	Baseline Scenario	0.8 t/ha +13%	0.18 t/ha −3%	0.23 −0.049 pp	135 mm +9.5%	45 mm +19.0%	0.337 +0.023 pp	23.2°C +2.7K	0.9 K +0.1K	0.038 +0.001 pp
East	Baseline Scenario	1.0 t/ha +9%	0.09 t/ha +12%	0.10 +0.002 pp	142 mm +2.4%	34 mm +11.7%	0.238 −0.009 pp	22.9°C +2.8K	0.8 K +0.3K	0.035 +0.007 pp
West	Baseline Scenario	0.8 t/ha +17%	0.18 t/ha −8%	0.24 −0.059 pp	140 mm +9.8%	43 mm −2.3%	0.305 −0.021 pp	28.2°C +2.9K	0.9 K +0.4K	0.034 +0.007 pp
Central	Baseline Scenario	0.6 t/ha +7%	0.09 t/ha −23%	0.17 −0.052 pp	170 mm +10.4%	49 mm +2.9%	0.295 −0.014 pp	27.2°C +3.4K	1.1 K +0.5K	0.040 +0.012 pp

Notes: Ensemble median values are shown. Changes in CV values are shown as percentage points pp (scenario value – baseline value).

With the exception of one scenario, Figure 5 shows that ensemble results agree on the direction of change of SD in three out of four regions, with SD decreasing in West and Central Africa and increasing in East Africa (column 2, row 2). But they do not agree on the direction of change in Southern Africa. For CV, the ensemble results also tend to agree on the direction of change in three regions, with CV decreasing in Southern, West and Central Africa (column 2, row 3). They do not agree on the direction of change in East Africa.

4. Discussion

4.1. Comparison with other studies

Different methodologies, data and approaches make it difficult to compare different studies of climate impact on yield. Nevertheless, it is important to understand where the findings in the present study fit, or do not fit, into the state-of-the art of this field. Here we compare our results with the meta-studies of Rosenzweig et al. (2014) and Knox et al. (2012).

Rosezweig et al. compiled computations from seven global gridded crop models which were driven by five GCMs and four RCPs on a global standard grid. Two climate periods 1971–2000 and 2071–2100 were compared. Discrepancies between the present study and Rosenzweig et al. may arise because they use different climate scenarios with a longer time horizon and perform their calculations for all land areas, whereas we only consider currently harvested areas and the mid-term scenario period (2041–2070). Knox et al. reviewed all climate impact studies for different times slices (up to the 2080s) collating data from 52 research papers using different crop and climate models, study scales (resolution and countries) and time horizons in Africa and South Asia with results aggregated to the regional level. Here we only examine their results for Africa. The lack of standard climate scenarios, time horizons and models (and modelling approaches), and the large variability between crop cultivars, scales, assumptions on CO_2 fertilization and study areas in Knox et al. can account for differences with the present study.

4.1.1. Maize in Southern and East Africa

In these regions our calculations show a varied pattern of moderate increases and decreases in yield. Larger increases in some areas tip the balance to an overall average increase of 13% in the Southern and 25% in the East. By comparison, the sum of studies cited in Knox et al. give a regional average decrease of over 11% in the Southern region, and no significant change in the Eastern. The higher yields in the present study may be due to the fact that we take into account cold stress on plants whereas many studies reviewed by Knox et al. may not. As noted in Section 3.1 cold stress will be reduced by higher future temperatures under climate change and lead to an increase in yields in some colder areas of Southern and East Africa. In addition, the studies reviewed in Knox et al. may consider later time horizons with greater degrees of warming than included in the present study which does not have as long a time horizon. Thereby, they may analyse increased negative effects of warm temperature stress on crop yields, which could explain departures from the present study.

In the Southern region, Rosenzweig et al. find small, but consistently negative changes. A major difference is that they show small changes or decreases in the Central Ethiopian part of Eastern Africa whereas we compute a varied pattern of increased and decreased yields. The lower overall yields in Rosenzweig et al. may be related to the fact that they consider a longer time horizon, and therefore, higher temperatures on average as compared to the present study.

4.1.2. Maize in West and Central Africa

Our estimates of changes in yield in these regions, where cold temperature stress is less important than the Southern and Eastern regions, are close to estimates of Knox et al. (this paper: −11% in the West, −15% in the Central region; Knox et al.: −7% and −13% respectively).

Spatial patterns in the present study are also similar to Rosenzweig et al. An exception is the sparsely harvested maize areas (Figure 1(a)) of Burkina Faso and northern parts of Nigeria and Central Chad. Here we found either no change or small increases in yield because higher future levels of precipitation make plant production less moisture-constrained, and compensate somewhat for the higher future heat stress. Rosenzweig et al. compute decreases in yield which again may be due to the overall higher temperatures or less increase in precipitation they consider as compared to the present study.

4.1.3. Tropical cereals

Knox et al. present results for millet and sorghum separately, as compared to the present study in which they are defined as a single crop class. Rosenzweig et al. do not present results for 'tropical cereals'.

In the present study we estimate small to moderate regional increases in tropical cereals (Table 4), whereas Knox et al. show no changes or small decreases in these regions (i.e. in the 2080s period). A possible reason for this discrepancy is that the LPJmL model, which underlies calculations in the present study, considers a temperature 'optimum' range which is considered only in a few studies reviewed in Knox et al. The reasoning for using a temperature optimum range is the assumption that heat tolerant cultivars of tropical cereals are available and can be used when warmer average temperatures occur rather than using baseline cultivars under rising temperature stress. Therefore, the present study computes less heat stress, thus higher yields, on average, than the studies reviewed by Knox et al.

4.2. Limitations of current study

There are few alternatives available for the task of anticipating future impacts of climate on food security other than modelling. That being said, it is still important to recall the limitations of modelling so that the reader can properly interpret modelling results and highlight where further research can improve the method. Limitations of this study are described in the supplementary material (S3.1). Here we summarize its main limitations.

Large scale assessments [as our] are confronted with the trade-off between the advantage of a large spatial study coverage that can be useful for policy makers (Ewert et al., 2015) and the disadvantage of low spatial accuracy at the plot level (i.e. for local farm management). The lack of detailed model calibration (at finer scale) is a well-known challenge for large scale crop modelling (Müller et al., 2017) since location-specific environmental and management data are usually difficult to obtain consistently for large regions (Angulo et al., 2013). However, local farm management affects how crops respond to climate change (Challinor et al., 2015; Patt et al., 2010). In this respect, the presented study cannot adequately represent yield responses to projected climate change at the farm or plot level. To overcome this limitation, small scale studies, which incorporate more detailed information, e.g. on farming environments, management practices and the socio-economic context of farmers could supplement our assessment in order to provide more detailed recommendations for specific local cases.

In addition, we note that the present study does not take into account the relationship between nutrient availability and uptake by crops on crop yield responses to climate change. The few large-scale models that do account for this relationship show greater negative climate impacts on major crop types in Africa than other models (Rosenzweig et al., 2014). Neglecting the effects of potential nutrient stress in the future in this paper may indicate that our calculations underestimate the negative impacts of climate change on crop yields if fertilizer input in the future remains at the low baseline level.

Finally, this study does not take into account the 'access' and 'utilization' pillars of food security and therefore gives an incomplete picture of the impact of climate change on the food security of smallholders in SSA.

4.3. Implication of results for food security and adaptation of smallholder farmers in SSA

In the following, we frame our discussion according to the two aspects of food security dealt with in this paper, 'food availability' and 'food stability'. Recall that changes in future food availability are represented in this paper by the mean change in crop yield, while changes in future food stability are indicated by changes in the standard deviation and coefficient of variation of annual yield on recently harvested areas.

For maize we find that average yield decreases in West and Central Africa, and increases in Southern and East Africa. These averages, however, mask the fact that 51% of total harvested maize area in SSA decreases in yield. For tropical cereals, average yield increases in all regions, but decreases on 23% of total harvested areas in SSA. The absolute variability of annual maize yield increases in Central and Southern Africa and decrease in West and East Africa; while the variability of tropical cereals decreases in all regions except East Africa where it increases. In Central Africa, not only does the average yield of maize decrease, but variability also increases, posing a particularly noteworthy risk for smallholder farmers.

In the following we discuss the relevance of these results to the food security and adaptation options of these farmers. As a starting point, it is important to be aware that their crops already face continuous risks from extreme weather events, as well as from many other stress factors. Farmers already have numerous ways to cope with these impacts ranging from diversifying their livelihood to changing their crops (Osbahr et al., 2010). The question then is not whether smallholders will have to adapt to climate events in the future, but how climate change will require new strategies or alter old ones.

4.3.1. Redistribution of crops through markets

Table 2 and Figures 2 and 3 show that a large proportion of harvested land is negatively affected by decreased mean yield and increased year-to-year yield variability in all regions. People in these areas may be affected by increasing future risk to food security. However, areas with increasing average yields could experience a local crop surplus depending on future food demands in these areas. If a surplus does occur it could also, in principle, be redistributed via markets within the region, and thereby can increase and stabilize long term food availability to farmers with crops having decreasing yields. However, participation of smallholders to markets is essential. A household survey across more than 13,000 smallholder farms in 17 SSA countries show that 83% of the farms sell part of their crops produced even before their household consumption reaches full self-sufficiency (Frelat et al., 2016). Thereby, they earn the money needed to buy other types of food and other items for their daily living. Although smallholders are assumed to rarely contribute to trade at the local or regional levels (Barrett, 2008) the results of Frelat et al. (2016) indicate that smallholders in SSA participate somehow in markets. Nevertheless, market constrains can be very powerful in SSA. Investments in infrastructures for retailing crops (roads and communication facilities), economic development (generating off-farm household incomes, integration of regional markets) as well as changes in social perception and attitude to food security (e.g. aiming on being self-sufficient) can be key to stimulate market access and stabilize food availability of smallholders year-round.

4.3.2. Storing crops in strategic food reserves

Strategic food reserves against poor harvests and other risks are not uncommon in SSA (Lynton-Evans, 1997; Minot, 2014). Rather than addressing the complex issue of the absolute size of reserves, we instead investigate if climate change theoretically affects the relative size of reserves compared to a baseline. We reason that the larger the variability of yield, the larger the size of the food reserve needed to provide security. Therefore, the relative size of a future reserve under climate change compared to a baseline is assumed here to be the ratio of the standard deviation of yield under climate change and the standard deviation under baseline conditions. (This assumes that the reserve in the future will cover the same frequency of production shortfalls as now, e.g. a one in five year, or one in twenty year shortfall.)

For maize, we see from Figure 5 that the standard deviation of maize yield varies substantially between climate scenarios. As a conservative estimate (using the 75th percentile of results from Figure 5), we estimate that under climate change regional maize reserves should be the following increments larger than the baseline: Southern Africa +20%, East Africa +6%, West Africa +1%, and Central Africa +26%. Respectively, regional tropical cereal reserves should be the following increments larger: Southern Africa +7% and East Africa +28%. No increment to buffer effects of production variability in tropical cereals is suggested in West and Central Africa. Note, these estimates only account for the effect of climate change and not of any future changes in demand or market factors.

4.3.3. Crop shifting

Model calculations in this paper are consistent with the typical view that tropical cereals are more heat tolerant than maize. More explicitly, the LPJmL model uses temperature optimum ranges that assume that more heat tolerant cultivars for tropical cereals than for maize will be available and suited to warmer future temperatures (Bondeau et al., 2007). This assumption is supported in the literature, for example, by V. Singh et al. (2015) (sorghum) or P. Singh et al. (2017) and Gupta et al. (2015) (pearl millet) who show significant genotypic differences in tolerance of seed set [and yield] to high temperatures and the potential of genetic modifications to increase heat stress tolerances under climate change. They conclude that high-temperature tolerant varieties could deliver sustainable yields under future warmer climates. Moreover, Peacock and Heinrich (1982) show that some sorghum cultivars (RS 691) have an increasing photosynthesis rate at temperature increases from 40°C to 43°C, whereas maize yields have been observed to increase up to an average temperature to 29°C with yield losses beyond that temperature threshold (Schlenker & Roberts, 2009). Therefore, it is not surprising that in some cases the yield of tropical cereals increases over areas where the yield of maize drops (Figures 2(d) and 3(d)).

Hence, another option is for farmers to switch from maize to more heat-robust tropical cereals. While this might be a good strategy in some cases, there are also likely drawbacks. Firstly, new heat tolerant cultivars may not be available to smallholder farmers (Westengen et al., 2019), although the State can make them available through agricultural extension programmes and other means. Secondly, even though the yields of tropical cereals may increase (and that of maize decrease), the overall yield for maize will still be larger than tropical cereals in [most] areas. Thirdly, as discussed in the sense of redistributing crops through markets, the decision to shift crops involves many other considerations besides yields. Some of these considerations have to do with the ‘food utilization’ pillar of food security e.g. individual dietary preferences as well as other social and cultural values for particular grains. It needs also be mentioned, that beyond the time horizon of this study climate change may lead to temperatures outside the tolerance levels of tropical cereal cultivars, and lead to yield decreases e.g. towards the end of this century.

4.3.4. Irrigation

Adding more water to the plant zone through irrigation is a traditional way of compensating for a lack of precipitation, and results in this paper suggest it may be effective as an adaptation approach for smallholders from the strictly technical point of view. For example, under climate change parts of Southern and East Africa have more precipitation at greater variability (Supplementary Material, Figure S2d) but temperature stress is not extremely high (because of lower baseline temperatures) (Figure 4(a)). In these areas it may be feasible to expand irrigation to stimulate yields of maize and tropical cereals. In particular, irrigation can help cope with the expected increase in yield variability in East (tropical cereals) and Southern Africa (maize). These are, however, only climatic considerations and many socio-economic factors will also influence the situation, e.g. the availability of water for irrigation in the face of competing demands from the domestic and industrial sectors, and for environmental uses (Wimmer et al., 2015). Costs of irrigation are also an important factor, although low-cost 'water harvesting' techniques for irrigation are already common on many smallholder farms in Africa (Rockström & Falkenmark, 2015). Future studies should carefully assess the consequences of potential irrigation management on crop yields, water stress and other related socio-ecological impacts in order to prevent maladaptation.

For Western and Central Africa, our modelling results suggest that heat stress will be critically (Figure 4(a)) and it is questionable whether expanded irrigation here could compensate for the negative impacts caused by rising temperatures.

4.3.5. Other adaptation options

The present study has shown the adverse impact of heat stress on maize yields. There are various ways in which agricultural science can help smallholders here adapt to new climatic conditions. Determination of heat-tolerant cultivars (J. Chen et al., 2012; Gupta et al., 2015; V. Singh et al., 2015) and crop breeding towards increased heat-tolerance (P. Singh et al., 2017). Since warming is likely to proceed towards the end of the century (IPCC, 2013) growing more heat-tolerant cultivars may play an increasing role in agricultural adaptation planning in all regions.

However, an additional issue is whether any new heat tolerant cultivars, once developed, will be available to smallholder farmers. Westengen et al. (2019) indicate that access to new 'climate-smart' seeds is not equal across SSA. They found that wealthier households show greater application rates of 'modern' seeds than poorer households (of smallholders). They also found that more climate-resistant cultivars are being developed for higher profit crops such as maize than less profit oriented crops such as sorghum. Thus, Westengen et al. (2019) note that the public sector could encourage the development of more heat tolerant cultivars that are of particular interest to smallholders via agricultural extension programmes, research and other means. There are numerous other options for smallholders including climate smart agriculture (Lipper et al., 2014). For example, trees in agroforest systems have a cooling effect on surrounding crops that can significantly mitigate the impacts of heat stress (Sida et al., 2018). Climate smart agriculture is promising technically but recent studies have also indicated that it raises various socio-political issues when applied to African agriculture, including being used as a label for conventional agriculture in some cases (Newell et al., 2019). In addition, sustainable agricultural intensification (Jane et al., 2019; Tilman et al., 2011) can intensify agricultural production to higher yield levels (Neumann et al., 2010). This is particularly relevant since current yield levels in SSA (Tables 3 and 4) are below its potential achievable yields considering improved agricultural management practices (Mueller et al., 2012). Thus, agricultural management practices may improve in SSA in the future, and thereby increase mean yields and food availability in the region. However, these developments are not evaluated here because they are outside the scope of the paper.

5. Conclusion

In this study we have used a large-scale crop model to investigate two important aspects of food security in SSA under climate change, food availability and food stability. We analyse climate impacts on maize and tropical cereals because of their particular importance to smallholders who rely on them for their subsistence and livelihood.

We have found that analysing not only changes in mean yield, but also its variability, has provided new insights into climate change impacts and adaptation options (see Sections 3 and 4). Our analysis focuses on changes in yield over currently harvested areas because these are of particular relevance to smallholders in the near future, and may remain so. We emphasize a medium-term scenario period (2041–2070) because it is distant enough to capture important impacts of climate change but near enough to be relevant for current decision-making about climate adaption policies and measures.

For food availability we find that 51% of current harvested maize area and 23% of current harvested tropical cereal area may experience decreases in mean yield. This implies diminished long-term food availability and greater climate-related stress on smallholder farmers in these areas. Modelling results indicate that farmers of tropical cereals will fare better than maize farmers because tropical cereals have a greater heat tolerance. However, it is very possible that further warming beyond the time horizon of this study (2041–2070) will reduce the yield of tropical cereals, and further reduce that of maize.

For food stability, we find that the year-to-year variability of yield increases over a majority of the harvested areas, implying less reliable harvests for smallholder farmers and greater risk to food insecurity. The magnitude of year-to-year yield variability (SD values) increases on 37% of harvested maize areas and 46% of harvested tropical cereal areas. Climate change will particularly threaten maize agriculture in Central Africa, where regional average maize yield decreases and its variability increases in magnitude. Although the variability of tropical cereals decreases on the average, it is still greater in magnitude than maize variability.

These findings are also relevant to future adaptation options of smallholders. Redistribution of surplus harvests in regional markets could be successful strategy to cope with climate change if smallholder farmers are given greater access to these markets. Strategic food reserves, where they exist, could help to better cope with the higher variability of maize and tropical cereal harvests if they are made up to around one-fourth larger than currently. Under some circumstances, smallholders could shift from maize to tropical cereals, which are better suited to expected warmer temperatures. Developing heat tolerant crop cultivars (maize and tropical cereals) and making these available to smallholders may be key adaptation option to help adapt smallholders to rising temperatures. Areas with increased precipitation but not extremely high temperature stress (e.g. some areas in East and Southern Africa) may be suitable for maintaining or increasing yields as well as for stabilizing annual production through irrigation. Conversely, extending irrigated agriculture over harvested maize areas in West and Central Africa is likely not an effective adaptation option since heat stress rather than drought is regularly affecting food production in these regions.

In summary, our findings show that smallholders in Sub-Saharan Africa will have to cope with changes to both the availability and stability of their basic crops brought on by climate change. But our findings also indicate that a range of options including regional markets, strategic food reserves, and new cultivars could help farmers cope with these changes.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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