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Climate change impact and adaptation of rainfed cereal crops in sub-Saharan Africa

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ABSTRACT

Sub-Saharan Africa's (SSA) demand for cereals is projected to more than double by 2050. Climate change is generally assumed to add to the future challenges of the needed productivity increase. This study aimed to assess (i) the potential climate change impact on four key rainfed cereals (maize, millet, sorghum and wheat) in ten SSA countries namely Burkina Faso, Ghana, Mali, Niger, Nigeria, Ethiopia, Kenya, Tanzania, Uganda, and Zambia using local data and national expertise, and (ii) the potential of cultivar adaptation to climate change for the four crops. We assessed effects on rainfed potential cereal yields per crop and aggregated these to regional level in West (WA), East and Southern Africa (ESA). We made use of a rigorous agronomic dataset for 120 locations in the ten countries and performed simulations of rainfed potential yield (Yw) using bias-corrected climate data from five GCMs, three time periods (1995–2014 as baseline, 2040–2059, and 2080–2099) and two scenarios (SSP3–7.0 as business as usual and SSP5–8.5 as pessimistic). We tested whether better adapted cultivars (taken from the pool of cultivars currently employed in the ten countries) could compensate for climate change. Results showed that climate change decreased aggregated Yw of cereals by around 6% in ESA by 2050, whereas projected impacts in WA were not significant. In 2090, however, the projected impact of climate change in both WA (−24%) and ESA (−9%). was significant. Cultivar adaptation partially compensated the negative impact of climate change. With the adaptation approach, 87% and 82% of potential production in ESA was estimated to occur with higher average Yw and lower variability in, respectively, 2050 and 2090, compared to the baseline period. In WA 67% and 43% of the potential production was estimated to experience such positive effects in 2050 and 2090, respectively. These results highlight remaining adaptation challenges for 13% (2050) and 18% (2090) in ESA and 33% (2050) and 57% (2090) in WA for potential production. In the context of the large yield gaps in SSA, this is likely to further increase challenges to meet cereal self-sufficiency for SSA, especially in WA.

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1. Introduction

Cereals are the most important source of dietary energy in sub-Saharan Africa (SSA), as they account for ca. 50% of daily calorie intake (FAOSTAT, 2023). Demand for cereals in SSA is projected to increase more than twofold in the coming decades, while yields are progressing at a slow pace and yield gaps (i.e., the difference between potential and actual yield) remain very large (van Ittersum et al., 2016).

Products from rainfed cropping systems make up more than 95% of farm output in SSA (Abrams, 2018) and the main cultivated rainfed cereal crops are maize, millet, sorghum, and wheat (FAOSTAT, 2023; https://www.yieldgap.org). Risks of loss of food production from crops are increasing due to climate change, particularly in rainfed cropping systems, which are more sensitive to climate change than irrigated cropping systems (Kurukulasuriya et al., 2006). Temperatures in Africa are increasing more rapidly than the global average (Ranasinghe et al., 2021). In addition, precipitation reductions are projected for Southern Africa and the western part of West Africa, while increased annual rainfall is projected for the eastern part of West Africa, Eastern Sahel, East Africa and Central Africa (Trisos et al., 2022).

Several studies investigated the effect of climate change impact and risk assessment on cereal yield in SSA. Most of these were part of global studies relying on coarse assumptions, such as using a single cultivar for simulations across the sub-continent (e.g., Jägermeyr et al., 2021; Stuch et al., 2021; Rosenzweig et al., 2014; Parry et al., 2004). Case studies at local level in SSA were mainly carried out to evaluate climate change impact on a few crops or in a limited number of geographies (e.g., Siatwiinda et al., 2021; Amouzou et al., 2019; Faye et al., 2018; Traore et al., 2017; Ahmed et al., 2015; Sultan et al., 2014). Most of these studies point to large yield reductions due to climate change, both in the near and far future, especially in West and Central Africa. However, climate change impact on cereal yields was positive in some areas in West Africa where rainfall is projected to increase in the near future (Amouzou et al., 2019).

While some studies focused their climate change analysis on potential yields (Stuch et al., 2021; Siatwiinda et al., 2021; Faye et al., 2018) others assessed effects on actual yields (Akumaga et al., 2018; Ahmed et al., 2015). There are several reasons why we advocate to focus on potential yields when conducting climate change impact assessments for SSA. First, actual yields in the region are only 10–30% of their potential (Silva et al., 2023; Assefa et al., 2020; van Ittersum et al., 2016). Hence, actual yields are very low and at the same they must increase by a factor of two to three in just 30 years to keep up with the steep demand increase due to projected population growth and dietary change (van Ittersum et al., 2016). Even substantial effects of climate change by 2050 on actual yields in the order of 10–20% would imply only a fraction of the needed yield changes in SSA. The potential yield (corrected for climate change) is an informative, strategic indicator for research and development in SSA. Second, crop growth models are not well equipped to simulate the impact of key yield constraints to actual yields in the region (e.g., plant density, nutrient inputs, and biotic factors), certainly not in interaction with climate change (Silva and Giller, 2020). Furthermore, negative climate change impacts on potential yield provide an upper bound estimate in comparison to, for example, nutrient-limited yield (Falconnier et al., 2020).

Agricultural systems in low- or middle-income countries and in the (sub-)tropics, including in SSA, are projected to suffer most in economic growth due to global warming because climate conditions are already harsh and because agriculture takes a dominant position in their economies (IPCC, 2018). Thus, it is essential to find effective ways to adapt to climate change in SSA, through shifts in sowing dates and changes in growing season duration (Traore et al., 2017; MacCarthy et al., 2017; Tatjana et al., 2014) or through switches in crop types or abandonment of agricultural activities (Rippke et al., 2016). One affordable means of adaptation could be through shifting cultivars that are already employed in one part of SSA to another part such that these fit the new growing conditions better (Zabel et al., 2021). There is a large variation in current cereal cultivars in SSA in terms of total thermal time requirement to reach maturity (https://www.yieldgap.org). Previous studies on cultivar adaptation are based on hypothetical cultivars which bear a limited relationship to the potential of cultivars which were already employed elsewhere in the region (Akumaga et al., 2018; Singh et al., 2017; Srivastava et al., 2016, Sultan et al., 2014).

This study aims to assess (i) the projected climate change impact on the four key rainfed cereals (maize, millet, sorghum and wheat) in ten SSA countries namely Burkina Faso, Ghana, Mali, Niger, Nigeria (all in West Africa, WA), Ethiopia, Kenya, Tanzania, Uganda, and Zambia (in East and Southern Africa, ESA) using a dataset with local weather and agronomic data, and (ii) the potential of cultivar adaptation for the four crops in the ten countries. We estimate effects on individual crops as well as aggregated effects, the latter to more directly offer insight on the potential impact on total cereal production at systems level.

2. Methods

2.1. Study sites

The Spatial Production Allocation Model layers (SPAM version 2017; Yu et al., 2020), together with expert knowledge from agronomists and experts from the focus countries, were used to identify the harvested area of the four target crops (maize, millet sorghum and wheat). The reference weather stations for the key production areas of these crops were extracted from the Global Yield Gap Atlas (GYGA) for the ten countries (https://www.yieldgap.org). The GYGA protocol selects the key climate zones (designated climate zones, DCZ) for each country and crop combination based on harvested area and information from local agronomists. Within those DCZs local weather stations are identified. Next, a 100-km radius ‘buffer’ surrounding each weather station is created and clipped by the borders of the DCZ and the country to ensure that the buffer zone is located within a unique CZ and a unique country (van Bussel et al., 2015). Following this method for the ten countries resulted in a total of 87 weather stations for maize, 72 for millet, 77 for sorghum, and 18 for wheat selected for the crop model simulations (Table S1). The weather stations represent the climate of the key climate zones covering most of the cultivated area of the four cereal crops in the ten countries (Table S1).

2.2. Crop modelling

In this study, we used the Python Crop Simulation Environment of the crop growth model WOFOST (de Wit et al., 2019; https://pcse.readthedocs.io/en/stable/) to perform simulations for millet (pearl millet in West and South Africa and finger millet in East Africa), sorghum, and wheat, and the Hybrid-Maize crop model for maize (Yang et al., 2004). The descriptions of the two models are provided in the section "Crop Models Description" in the SI.

Daily weather data, soil parameters, crop parameters, and management data are needed to run the models. WOFOST and Hybrid-Maize have previously been calibrated on a broad range of experiments from diverse environments (De Wit et al., 2019; Yang et al., 2004). For the application in GYGA additional calibration was performed following Grassini et al. (2015). The phenology and water-limited (rainfed) potential yield (Yw) have been verified and deemed plausible by the country agronomists of the ten countries for all the reference weather stations and the four crops (https://www.yieldgap.org; Rattalino Edreira et al., 2021). In addition, in the section "Evaluation of crop models" (Supplementary Information, SI), the crop models were evaluated against the highest yielding treatments from rainfed field experiments conducted in SSA under diverse climatic conditions, sourced from a collection of 43 published articles. This analysis indicates a robust simulation of Yw of the four crops in SSA.

2.2.1. Climate change weather data and atmospheric CO_2 concentration

The baseline weather data (1995–2014) and future climate data for 2050 (2040–2059) and 2090 (2080–2099) of five General Circulation Models (GCMs) from the Coordinated Modelling Intercomparison Project-Phase 6 (CMIP6) including GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1–2-HR, MRI-ESM2–0, and UKESM1–0-LL were prepared from the Inter-Sectoral Impact Model Intercomparison project (ISIMIP). Two future scenarios were employed, i.e. SSP3–7.0 as business as usual scenario, and SSP5–8.5 as the pessimistic scenario to give an upper bound of the effect of climate change.

ISIMIP provides daily datasets with a resolution of $0.5^\circ\times0.5^\circ$ (~55×55 km pixel size). ISIMIP uses a downscaling and bias-adjustment method based on a quantile mapping approach and the observational W5E5 v.1.0 dataset (Cucchi, et al., 2020). The bias in the ISIMIP temperatures data was enormous in areas with elevation exceeding 1000 m in SSA. Thus, we applied the Delta method as a second bias correction step to reduce the mean bias in the data of both the historical and future ISIMIP weather data for SSA, which is particularly prominent in areas with substantial topographical variation (see the section "ISIMIP weather data bias correction" in the SI). Monthly correction (delta) factors of climate variables (minimum and maximum temperatures, precipitation and radiation) were calculated for each GCM, such that the monthly climate variables of the historical GCM weather data matched the measured GYGA weather data set for the reference weather stations in the ten countries for the period from 1995 to 2014.

2.2.2. Soil information

Soil data were obtained from the Africa Soil Information Service (AfSIS; Leenaars et al., 2018). Soil moisture content at field capacity and wilting point, not infiltrating fraction of rainfall, initial soil water content, and maximum rootable depth of the soil were obtained as soil parameters for each weather station. The method to select the dominant soils within the weather station buffer zones (100 km diameter around the location of each weather station, clipped by the climate zones) is explained on the GYGA website (http://www.yieldgap.org/web/guest/methods-soil-series; van Bussel et al., 2015). The water balance simulation was started two months before the sowing date, with an initial soil water content of 0.03 $cm^3\ cm^{-3}$, in order to estimate the soil water content at sowing time for each simulated growing season. Following from the number of weather stations and the dominant soil types within the weather stations' buffer zones (100 km radius), the number of simulation units was 289 for maize, 275 for millet, 304 for sorghum, and 63 for wheat for the ten countries for each GCM and scenario (i.e., historical, or SSP-by-period) combination.

2.2.3. Management data

The simulations were performed for water-limited (rainfed) conditions, assuming no limitation of nutrients and full control of weeds, pests, and diseases. Hence, the sowing date and the maturity type of the cultivars used within the buffers of the weather stations were the required management input data to run the crop growth models. For this purpose, the common sowing windows of the target crop for each buffer zone were provided by agronomists from each of the countries (van Ittersum et al., 2016; https://www.yieldgap.org). These sowing windows were used in combination with an algorithm to estimate the sowing date for each year of each weather station. The algorithm calculates the amount of cumulative rainfall for seven consecutive days within the sowing window. The last day of this period resulting in more than 20 mm cumulative rainfall was considered the sowing date. If there were no consecutive seven days with at least 20 mm rainfall within the sowing window, the last day of the sowing window was assumed the sowing date (van Loon et al., 2018). Country agronomists verified whether the average of sowing dates estimated by the algorithm were correct for each weather station under the current climate conditions. All estimated sowing dates for the current climate, using the algorithm, were evaluated by the local agronomists. Sowing windows and sowing date algorithm were the same for historical and future climate simulations. In the tropics, growing periods are largely driven by precipitation seasonality, with sowing dates occurring at the onset of the main rainy season (Minoli et al., 2022). The region may expect only small changes in sowing dates to adapt to climate change (Minoli et al., 2022). Insufficient soil moisture at earlier sowing dates prevents emergence, while a delayed sowing may come with a risk of water stress during the grain filling period, unless cultivars with shorter growing seasons are selected. It is important to note that selecting later sowing dates, in combination with shorter duration cultivars, results in a shorter growing period.

2.2.4. Crop parameters without adaptation

The crop parameters consist of crop-specific values regarding phenology, assimilation, respiration, and biomass partitioning to crop organs. For each crop, the same crop parameters were used for the simulations in all the weather stations except for those controlling crop development (Table 1). The phenological parameters without adaptation, including the thermal time requirement from emergence to flowering, and from flowering to maturity, were calculated based on the observed sowing, emergence, flowering and maturity dates collected from the local agronomists, and using the cardinal temperatures of the four crops and the observed weather data for each reference weather station (https://www.yieldgap.org).

2.3. Analysis of environmental conditions during the growing season

We divided the growing season of the four crops into four periods including 1: early vegetative growth stage, 2: late vegetative growth stage, 3: early reproductive growth stage, and 4: late reproductive growth stage. For this purpose, the period from sowing to flowering was divided into two equal periods using calendar days (#stage1, #stage2). The same was done for the period from flowering to maturity (#stage3, #stage4). Average temperature, sum of rainfall, and number of days with maximum temperature of more than 32̊C were calculated for each period during the growing season for each crop-location-year simulation. Maximum temperatures of more than 32̊C were considered extreme for the growth and development of the four crops (Ramirez-Villegas et al., 2013), while we acknowledge that the precise temperatures that cause heat stress depend on the crop and the target mechanism in the crop model (e.g., heat stress temperatures are different for phenology, leaf growth and senescence, CO_2 assimilation and respiration of a given crop).

Table 1
The number of reference weather stations of the four crops in ten countries in sub-Saharan Africa with different growing season thermal time requirements of current cultivars. Source: GYGA.

Thermal time range of cultivars (Degree Days)	Number of reference weather stations			
	Maize	Millet	Sorghum	Wheat
880–950	1	2	3	0
950–1050	2	2	2	0
1050–1150	2	7	5	0
1150–1250	5	12	14	0
1250–1350	6	12	8	0
1350–1450	17	10	3	0
1450–1550	7	11	5	0
1550–1650	11	9	10	0
1650–1750	8	4	5	1
1750–1850	9	0	2	0
1850–1950	19	0	9	0
1950–2050	0	3	1	2
2050–2150	0	0	0	1
2150–2250	0	0	3	7
2250–2350	0	0	2	2
2350–2450	0	0	1	0
2450–2550	0	0	2	5
2550–2650	0	0	2	0

2.4. Crop parameters employed to determine adaptation to climate change

The reduction factor for reduced transpiration rate (RF) is a parameter in WOFOST indicating the daily water stress throughout the growing season, being calculated a follows:

$$RF = \frac{Transpiration_{act}}{Transpiration_{max}} \quad (1)$$

RF: reduction factor for reduced transpiration rates (unitless)

$Transpiration_{act}$: actual transpiration (cm d^{-1})

$Transpiration_{max}$: maximum transpiration for given crop status as derived from the crop leaf area index and the reference evapotranspiration (cm d^{-1})

The quantification of the extension of the growing season for cultivars under future climate conditions was carried out through a four-step analysis. First, all weather stations were classified according to aridity index. The aridity index of climate zones, in which the reference weather stations were located, was extracted from the climate zonation scheme of GYGA. This index shows the ratio between the mean annual precipitation and the mean annual potential evapotranspiration of each climate zone (http://www.yieldgap.org/web/guest/climate-zones). Second, the growing season of the four crops was divided into the same four periods as detailed in Section 2.3. Third, the frequency distribution of the daily water stress index, simulated by model, was studied for each of the four stages under both the current and future climates. Finally, the water stress pattern during the growing season was analyzed in relation to both the current and future climates (Fig. S5).

Generally, we did not find large differences in the water stress index between the historical conditions and the future climates during the first three stages of the growing season. However, the last stage of the growing season was often wetter under future climates than under the historical conditions (Fig. S5). The analysis revealed that for most weather stations there might be an opportunity to use new cultivars with a longer growing season duration, i.e., cultivars with around 10–15 percent longer thermal time compared to the current cultivars. When the length of the growing season exceeded this limit, crop growth was significantly affected by water stress towards the end of the growing season.

It should be noted that it was possible to perform this analysis using the daily outputs for millet, sorghum, and wheat from the Python version of WOFOST (Fig. S5). Since the Hybrid-Maize crop model software does not readily provide daily results as output for scenario-year combinations, for maize we studied only total rainfall during the four growth stages to assess opportunities to shift the growing season using new cultivars.

For each reference weather station, we selected a cultivar from our database of SSA (Table 1), ensuring a 10–15 percent longer growing season duration in terms of thermal time requirement from emergence to maturity. In other words, for a given weather station we looked at other locations to find cultivars (Table 1) with a longer growing season duration compared to the current cultivar in the given weather station, and we re-ran the model with these 'new' cultivars. If under the future climate Yw increased with this 'new' cultivar compared to the current cultivar, we kept that 'new' cultivar as the climate change adapted cultivar for the given station. For the stations for which Yw decreased with new (longer duration) cultivars, we selected cultivars with a shorter growing season duration, that is cultivars with a lower thermal time requirement to reach maturity compared to the current cultivars, also from the existing cultivars in our database. In this case, the new cultivars had ca. 10–15 percent shorter growing season duration in terms of thermal time requirement. For weather stations where neither cultivars with 10–15% longer nor shorter growing season duration improved Yw under climate change conditions compared to the current cultivars, we used the same cultivars for both current and future climates.

For those weather stations where cultivars with the highest thermal time requirement are already used, it was not possible to select cultivars with a longer duration of the growing season. Therefore, if a longer growing season still resulted in higher yields, hypothetical cultivars with a 15% longer growing season duration than existing cultivars were employed for these stations.

2.5. Aggregating cereal rainfed potential yields

For calculating the maize equivalent Yw of the crops we first calculated Yw of each of the cereals in each country (see above). The harvested area of each crop was extracted from SPAM2017 (Yu et al., 2020). Finally, the equivalent maize yield was calculated for each country using Eqs. 2 and 3:

$$\mathbf{eq\quad Maize} = \frac{\sum(\mathbf{Yw_c} * \mathbf{area_c} * \mathbf{EnCoef_c})}{\sum(\mathbf{area_c})} \quad (2)$$

$$\mathbf{EnCoef_c} = \frac{\boldsymbol{EnCon_c}}{\boldsymbol{EnCon_{maize}}} \quad (3)$$

eq Maize: Equivalent maize yield (ton ha^{-1}) of all cereals (c) including maize, millet, sorghum and wheat at a country level.

Yw: simulated water-limited yield of the crop c at the country level (ton dry grain ha^{-1}).

area: annual harvested area of the crop c in the country (ha)

EnCoef: energy coefficient of the crop c

$EnCon_c$: dry grain energy content of crop c (kcal kg^{-1})

$EnCon_{maize}$: maize dry grain energy content (kcal kg^{-1})

To calculate the equivalents of maize yield for each crop we used as energy content the average of three different data sources (FAO, INRAE, and USDA; Table S4). The GYGA protocol was applied to upscale results from weather station level to climate zone and then to country level (van Bussel et al., 2015). This protocol first uses crop area-weighted averages to upscale results from station level to climate zone level. The SPAM version 2017 data was used for this calculation. Second, the same method was used to upscale results from climate zone level to country level. Van Bussel et al. (2015) demonstrated that national Yw estimations using this protocol were robust if data could be collected that are representative for approximately 50% of the national harvested area of a crop (Table S1).

2.6. Relative rainfed potential yield change

Relative Yw change was calculated to quantify the impact of climate change on Yw (Eq. 4). It was calculated for each GCM, climate change scenario, and time horizon separately as follows:

$$\mathbf{Relative\quad yield\quad change}(\%) = \frac{\mathbf{Yw_f} - \mathbf{Yw_b}}{\boldsymbol{Yw_b}} * \mathbf{100} \quad (4)$$

Yw_f: Average of yearly simulated yields under future climates (f) with or without adaptation

Yw_b: Average of yearly simulated yields under current climate (b)

2.7. Spatial distribution of climate change impacts

In this study, two impacts of climate change on the four crops were studied, including (i) average Yw, and (ii) Yw variability using the coefficient of variation for the aggregated cereal yields (CV). The first effect was analyzed using Eq. 4 for each crop separately and for the aggregated yields using maize equivalents. The CV was calculated for each combination of climate zone, GCM, climate change scenario and time horizon. Thus, there were ten values of CV (combination of 5 GCMs and two climate change scenarios) for each climate zone and time horizon. Finally, the calculated CVs for future and current climates were statistically compared per climate zone using a paired t-test. Note, that the CV was employed in this study to assess the stability of Yw and thus in this paper the terms "high stability" and "low coefficient of variation" (or vice versa) are considered to be interchangeable.

3. Results

3.1. Environmental conditions during the growing seasons

Average temperature over the growing seasons of the four crops were lower in East and Southern Africa (ESA) than in West Africa (WA) both under the current and future climates (Fig S5). The temperatures are projected to remain in the optimum or sub-optimum ranges for all four crops in Ethiopia and Kenya in 2050, while cereal crops are projected to face high temperatures more frequently (maximum daily temperature higher than 32̊C) in the other three countries in ESA by 2050 and 2090 (Fig. S6 and S7). Environmental conditions are projected to become harsher in WA under climate change when maize, millet and sorghum (note that wheat is a marginal crop in WA) will likely experience more days with maximum temperatures higher than 32̊C throughout the growing season in 2050 and 2090 (Fig. S7). Current sowing windows have been set by farmers such that the flowering time of these three crops occurs during the coldest period of the growing season, with the lowest possibility of extreme temperatures in WA (see anthesis time between #stage2 and #stage3 in Fig. S7). Taking into consideration the projected temperature increase throughout the entire growing season, altering the sowing date is unlikely to be a successful strategy for avoiding high temperatures during around anthesis, under future climate conditions. The reason is that extreme temperatures are expected to occur consistently throughout the entire growing season, rather than during specific periods of the growing season.

Generally, climate change impact on rainfall distribution during the growing season of the four crops was not significant (Fig. S8). A small increase in rainfall occurred for wheat in ESA. In WA, rainfall was higher during the growing season of millet and sorghum in Niger and Nigeria under the future climate compared to the current climate (Fig. S8).

3.2. Rainfed potential yield of cereals under current climate

In ESA and under historical climate conditions, the highest Yw for all four crops was simulated in ESA, particularly in Ethiopia and Zambia (Fig. 1). In ESA, the Yw were simulated in Tanzania and Uganda, where there is a relatively lower rainfall during the growing season of the four crops compared to the other three countries in ESA (Fig. 1 and S7). Amongst all ten countries, the lowest simulated Yw of millet and sorghum were in Niger (Fig. 1). The difference in Yw across countries in ESA can be attributed to a difference in severity of water stress during the growing season. However, both water stress and heat stress were the main factors determining cereal Yw in WA (Fig. S7 and Fig. S8). In general, environmental conditions during the cereal growing season in WA were much harsher than in the ESA.

3.3. Climate change impact on phenology and rainfed potential yield

Climate change shortened the growing season of all crops, with larger reductions in ESA than in WA. In ESA, the growing season reductions were between 8 and 18 days in 2050 and 19–34 days in 2090 compared to the baseline. In WA, growing season length of the four crops decreased between 2 and 8 days in 2050 and 2–17 days in 2090 (Fig. 2).

Climate change is projected to decrease the overall Yw, expressed in maize equivalent weight, by around 6% in ESA, while aggregated yields were not significantly affected in WA (−3%) (Fig. 3). In 2090, however, the negative effect of climate change was projected to be larger in WA (−24%), and slightly larger in ESA (−9%), compared to 2050 (Fig. 3). While the regional weighted average reveals some important challenges (e.g., large Yw reductions in WA by the end of the century), it also masks country- and crop-specific results. In other words, the positive impact of climate change in some regions and crops (e.g., millet and sorghum in Niger and Nigeria, which are projected to experience higher rainfall during the growing season in the future; Fig. S8) compensated for the negative impact for the other regions and crops particularly in Ghana and Mali in 2050 (Fig. 4). Niger and Nigeria have the greatest harvested area for sorghum and millet among the five countries in WA (Fig. S9). Thus, these two crops in Niger and Nigeria played a key role in offsetting the negative impact of climate change on the aggregated cereal yield in WA in 2050. In ESA, aggregated yield calculations were dominated by maize due to its larger harvested area and higher Yw in all five countries (Fig. 1; Fig. S9). Moreover, in ESA the positive effect of climate change on wheat yield offset the negative effect on sorghum and millet yield (Fig. 4; Fig. S9).

On average, Yw decreased by 6% for maize, 27% for millet and 16% for sorghum in ESA by 2050 (Table S5). The negative effect of climate change on these crops was larger in 2090. However, wheat benefited from climate change conditions and its Yw increased by around 13% in 2050 and 15% in 2090 (Fig. 4; Table S5). A sharp reduction in maize, millet and sorghum Yw was found for WA in 2090 compared to the

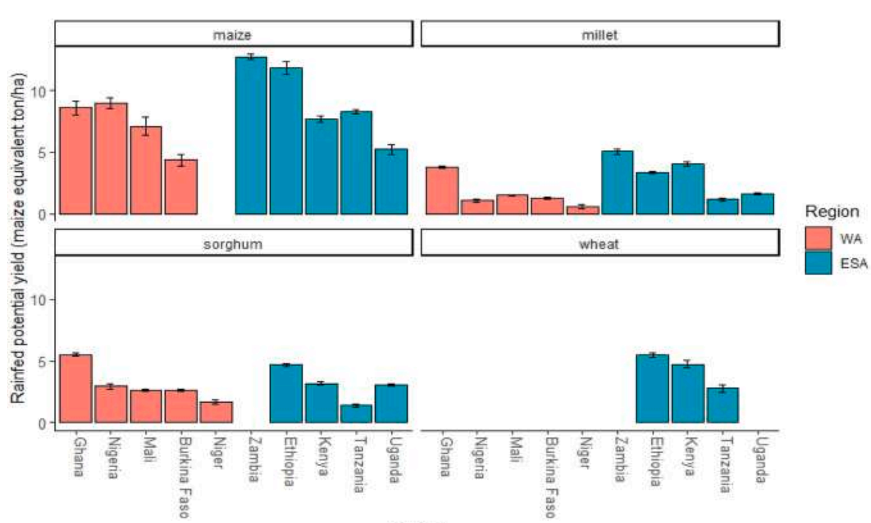

Fig. 1. Rainfed potential yield (Yw) of maize, millet, sorghum and wheat, expressed in maize equivalent weight, for ten sub-Saharan African countries during the period 1995–2014 (baseline). Yields are with 0% moisture content. The historical weather data of five GCMs were used for the simulations for each country. The standard errors of the mean illustrate the variability of simulated outcomes derived from different GCMs.

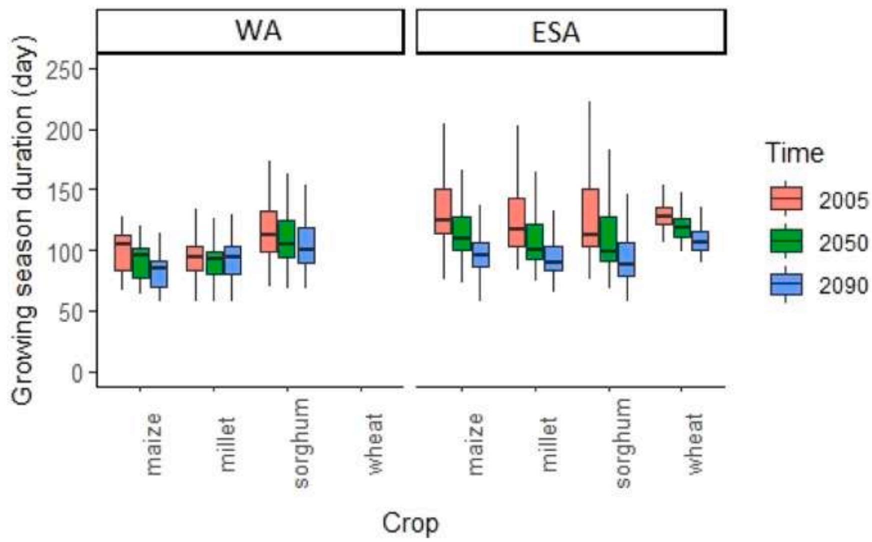

Fig. 2. Climate change impact on the growing season duration of cereal crops in WA (West Africa) and ESA (East and Southern Africa). Each box-plot contains the results of combinations of reference weather stations, two climate change scenarios, five GCMs, and 20 years.

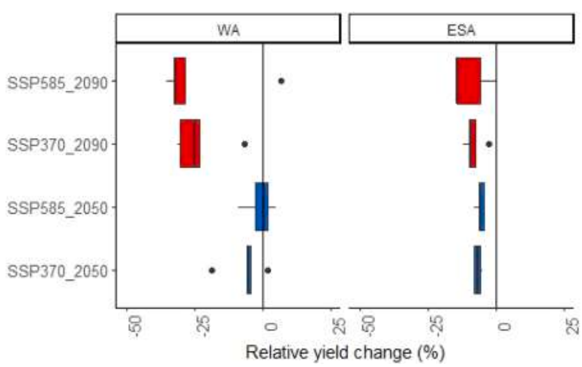

Fig. 3. Climate change impact on cereal rainfed potential yield (no adaptation) for two climate change scenarios (SSP370 and SSP585), five GCMs, and two time horizons (2040–2059 labelled 2050 and 2080–2099 labelled 2090) relative to historical climate (1995–2014) in sub-Saharan Africa, aggregated for all four cereal crops in WA (West Africa) and ESA (East and Southern Africa).

baseline (Fig. 4; Table S5). Maize Yw were lower for both 2050 (−11%) and 2090 (−27%) compared to the historical climate conditions in WA.

Climate change will not only affect the average Yw, but it will also change Yw variability, i.e., the temporal aspect of productivity (Fig. S10e). Both in WA and ESA ca. 40% of the rainfed potential production of cereal crops will likely benefit from climate change, i.e., higher average Yw yields and a lower coefficient of variation in 2050 compared to the baseline (Fig. 5). Around 44% of the cereals' rainfed potential production in ESA and 45% in WA are projected to face a lower average Yw and a higher coefficient of variation in 2050 compared to the baseline (Fig. 5). Our results show that ca. 10% of the cereals' rainfed potential production in ESA and ca. 15% in WA was with a lower average Yw and the same or lower coefficient of variation in 2050 compared to the baseline. The remaining 6% of the cereals' rainfed potential production in ESA was with a lower stability and the same or higher average Yw (Fig. 5). Thus, similar patterns for effects on Yw and its stability are projected for ESA and WA in 2050. However, by 2090, a smaller share of rainfed potential production will benefit from climate change in WA (29%) compared to ESA (45%) (Fig. 5). About 31% of rainfed potential production in ESA and 41% in WA were under a lower average Yw and lower stability in 2090 compared to the baseline (Fig. 5). Thus, by 2090 cereals' rainfed potential production is projected to be under more robust conditions in ESA than in WA.

3.4. Effects of cultivar adaptation

Fig. 6 shows the types of cultivars that are most appropriate for adapting cereal crops in both WA and ESA by 2050. Overall, 58%, 96%, 49% and 100% of, respectively, maize, millet, sorghum, and wheat harvested areas within the buffer zones of the reference weather stations of these crops in SSA would benefit from a new cultivar with a longer growing season duration to adapt to the climate change conditions. Cultivars with a shorter growing season duration are suitable for adaptation in 1% of millet and 49% of sorghum harvested areas located in the reference weather stations' buffer zones (Fig. 6). The remaining 42% of the maize area, 3% of the millet area, and 2% of sorghum harvested areas did not show a benefit from adjusting the growing season duration of these crops' cultivars. Notably, almost all harvested areas in Ethiopia, Kenya, Tanzania, Uganda, and Zambia located in ESA would need cultivars with a longer growing season duration regardless of the crop type, apart from maize in Kenya and Tanzania where adaptation of the growing season was not effective (Fig. 6). In contrast, there is more variation in the maturity groups of the adapted cultivars in WA (Fig. 6). It is important to note that we found no better performing cultivar among the existing cultivars for 22% of the wheat area, 3% of the sorghum area, and 0% for maize and millet harvested areas. Thus, we used new hypothetical cultivars for adaptation for part of the wheat area in ESA and sorghum area in WA.

Yw of the four crops in all countries benefited from climate change adaptation by using new cultivars under climate change conditions (cf. Figs. 7 and 4; Fig. S11). The relative average Yw change in maize equivalents (departure from the baseline) across the two regions became positive (+3 to +9%) in all SSP scenarios and periods, except for WA in 2090 (–14% in SSP3–7.0, and –18% in SSP5–8.5; Fig. 7). For 2090 in WA, adaptation did decrease the negative impact of climate change, but the impact on Yw remained negative (in particular for sorghum and millet).

Thus, adapting cultivars in region A through the use of cultivars from region B which currently already has the range of temperatures of the future of region A, can help offset the negative climate change impact on maize equivalent yields of cereals. Comparing the relative changes of the aggregated Yw with adaptation to Yw without adaptation for each time horizon illustrated that the adaptation impact was larger for both future time horizons, 2050 and 2090, than the effect of the same cultivar

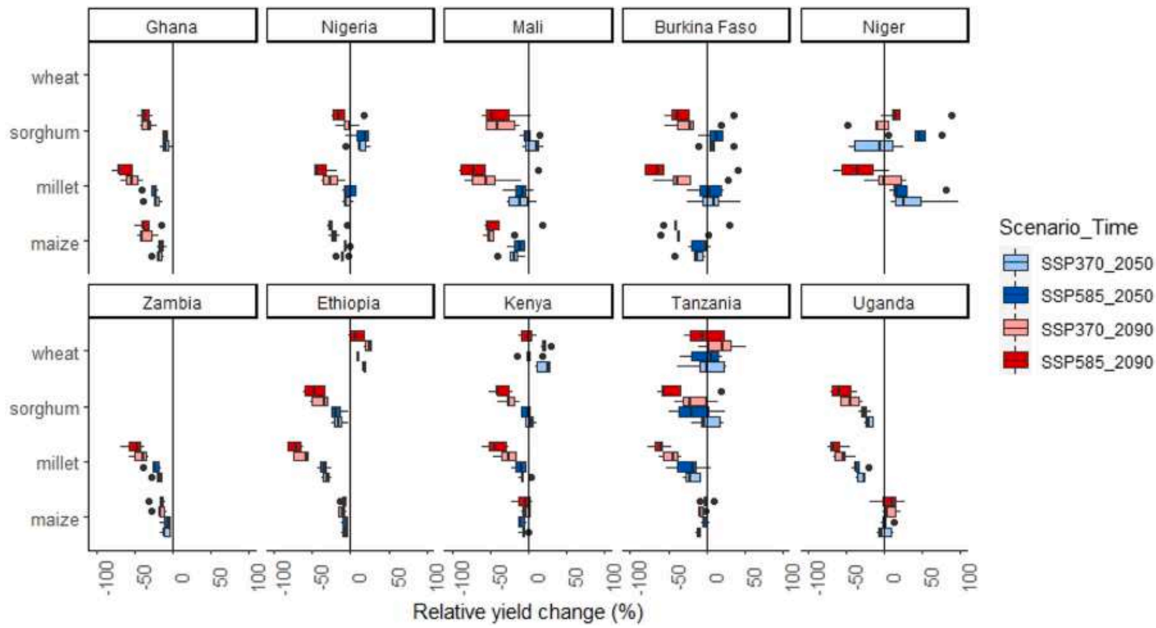

Fig. 4. Country- and crop-level climate change impact on rainfed potential yield (no adaptation) for two scenarios (SSP370 and SSP585), five GCMs, and two time horizons (2040–2059 labelled 2050 and 2080–2099 labelled 2090) relative to historical climate (1995–2014) in sub-Saharan Africa.

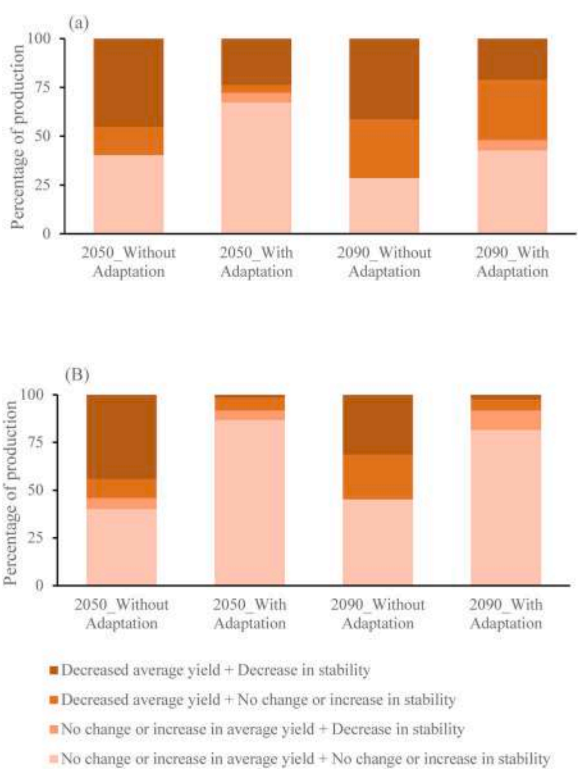

Fig. 5. The effect of climate change on the average rainfed potential yield change and its stability (CV), for the four cereals, expressed in maize equivalents, in (a) West Africa and (b) East and Southern Africa. The y-axis represents the percentage of total potential cereal production volumes in the different categories of yield and CV change, for each time horizon and adaptation option. Each bar is based on the average of the results for two SSPs and five GCMs. In Fig. S12, the same results are illustrated for each country separately. In this figure, the terms "decrease in stability" and "increase in CV" (or reverse) can be used interchangeably.

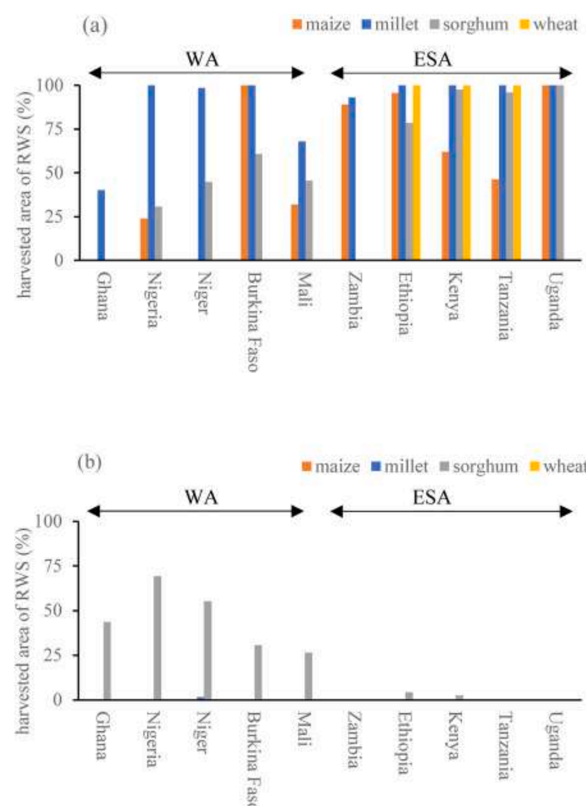

Fig. 6. Share of each crop's harvested area in buffer zones of reference weather stations (RWS) for which cultivars (a) with a longer growing season duration due to a larger thermal time requirement and (b) with a shorter duration due to a smaller thermal time requirement will be needed to adapt to climate change in ten countries of sub-Saharan Africa by 2050. The sum of the bars in the two charts does not reach 100% in some countries since some regions in these countries did not benefit from adjusting the growing season duration. WA = West Africa, ESA = East and Southern Africa.

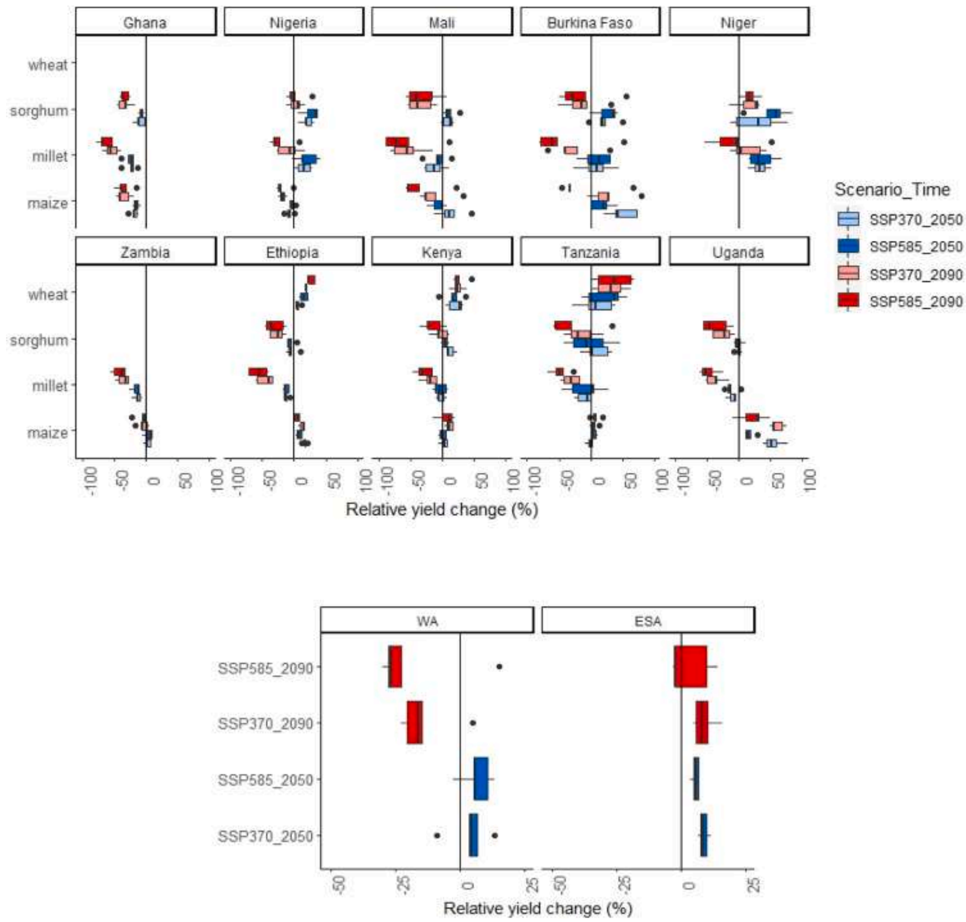

Fig. 7. Climate change impact on rainfed potential yield (with adapted crop cultivars) for two climate change scenarios (SSP370 and SSP585) and two time horizons (2040–2059 labelled 2050 and 2080–2099 labelled 2090) relative to the current climate (1995–2014) in sub-Saharan Africa. (a) the climate change impact on each crop in each country; (b) the climate change impact on the aggregated yield of all four crops in West Africa (WA) and East and Southern Africa (ESA).

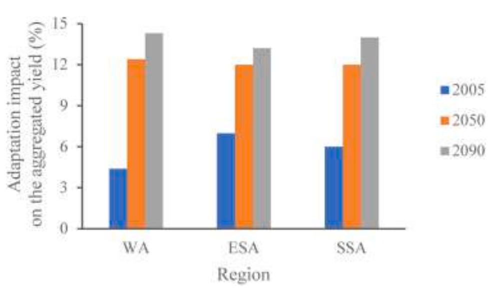

Fig. 8. The adaptation effect on the aggregated rainfed potential yield in WA, ESA and all ten countries (SSA) for each time horizon separately. Each bar is based on the average of the results for two SSPs and five GCMs.

changes for the current climate (Fig. 8). This suggests a true adaptation effect of changing cultivars under climate change.

In terms of aggregated average Yw and stability, the positive effect of adaptation was higher in ESA than in WA (Fig. S10 and S11). With the adaptation approach, in ESA around 87% of potential production was estimated to occur with a higher average Yw and higher stability in 2050 compared to the baseline while in WA ca. 67% of the production was estimated to experience this in 2050 (Fig. 5). In 2090 (compared to the baseline), adaptation was estimated to lead to more stable cereal potential production, especially in ESA where ca. 82% (ca. 43% in WA) of the cereal production was with higher average Yw and stability (Fig. 5).

3.5. Climate change and cereal production gap

The average annual rainfed potential production was 136 million tons of maize equivalents (with 0% water content) for the five countries

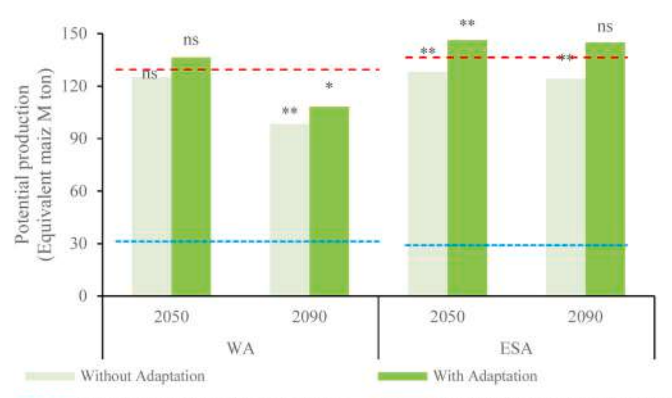

Fig. 9. The impact of climate change, without and with adaptation, on the aggregated rainfed potential production of the four crops, expressed in maize equivalents, in West (WA) and East and South (ESA) Africa and in 2050 and 2090. Each column is the average of the results for two SSPs and five GCMs and for each time horizon. The signs indicate whether the difference with the amount of production under current climate (red dashed line) is statistically significant or not, where * and ** mean significant difference at respectively 95 and 99% confidence level, ns: no significant difference.

in ESA, and 129 million tons of maize equivalents for the five countries in WA under the current climate (Fig. 9). In ESA, climate change without adaptation is projected to significantly decrease (compared to the baseline production) the potential production by ca. 8 million tons of maize equivalents in 2050 and 12 million tons of maize equivalents in 2090 (Fig. 9). A sharp reduction, i.e. 31 maize equivalent million tons, is projected for 2090 compared to the baseline in WA (Fig. 9). In ESA, climate change adaptation is estimated to significantly increase potential production from 128 to 146 million tons of maize equivalents in 2050, and from 124 to 145 million tons in 2090 (Fig. 9). In WA, potential production with and without adaptation did not significantly differ in 2050, while adaptation could compensate for 10 of the 31 million tons of maize equivalents reduction of rainfed potential production by 2090 (Fig. 9).

Given the low actual yields and the large yield gaps of today, and the relatively small effects of climate change (certainly with adaptation and until 2050) on rainfed yield potential, it is evident that the climate and available soil water are unlikely to restrict a strong increase in cereal production in SSA (Fig. 7). Moreover, the further increase in potential yield resulting from adaptation suggests that addressing yield gaps through management is needed if adaptation benefits are to be fully realized. Given current rainfed cereal areas in the ten countries, the highest rainfed cereal production gap is prevalent in Nigeria, Ethiopia, and Tanzania, both with and without adaptation in 2050 and 2090 (Fig. 10). The cereal production gap was similar for the remaining seven countries with adaptation in 2050 (Fig. 10b). In 2090, however, this gap was larger for ESA countries compared to WA countries because of the significant negative impact of climate change on the aggregated cereal yield for countries in WA (Fig. 7b; Fig. 10d).

4. Discussion

4.1. Strengths and limitations of the study

A key added value of our work is the use of the agronomically robust GYGA data set (https://www.yieldgap.org/) and bias-corrected weather data to perform crop model simulations for the present and future climatic conditions. All crop model input data and results were checked at a local scale by country experts. For instance, GCMs project that rainfall will increase in Niger (IPCC et al., 2021) and our results demonstrated that new cultivars with a longer growing season can improve sorghum and millet yields at some of reference weather stations located in this

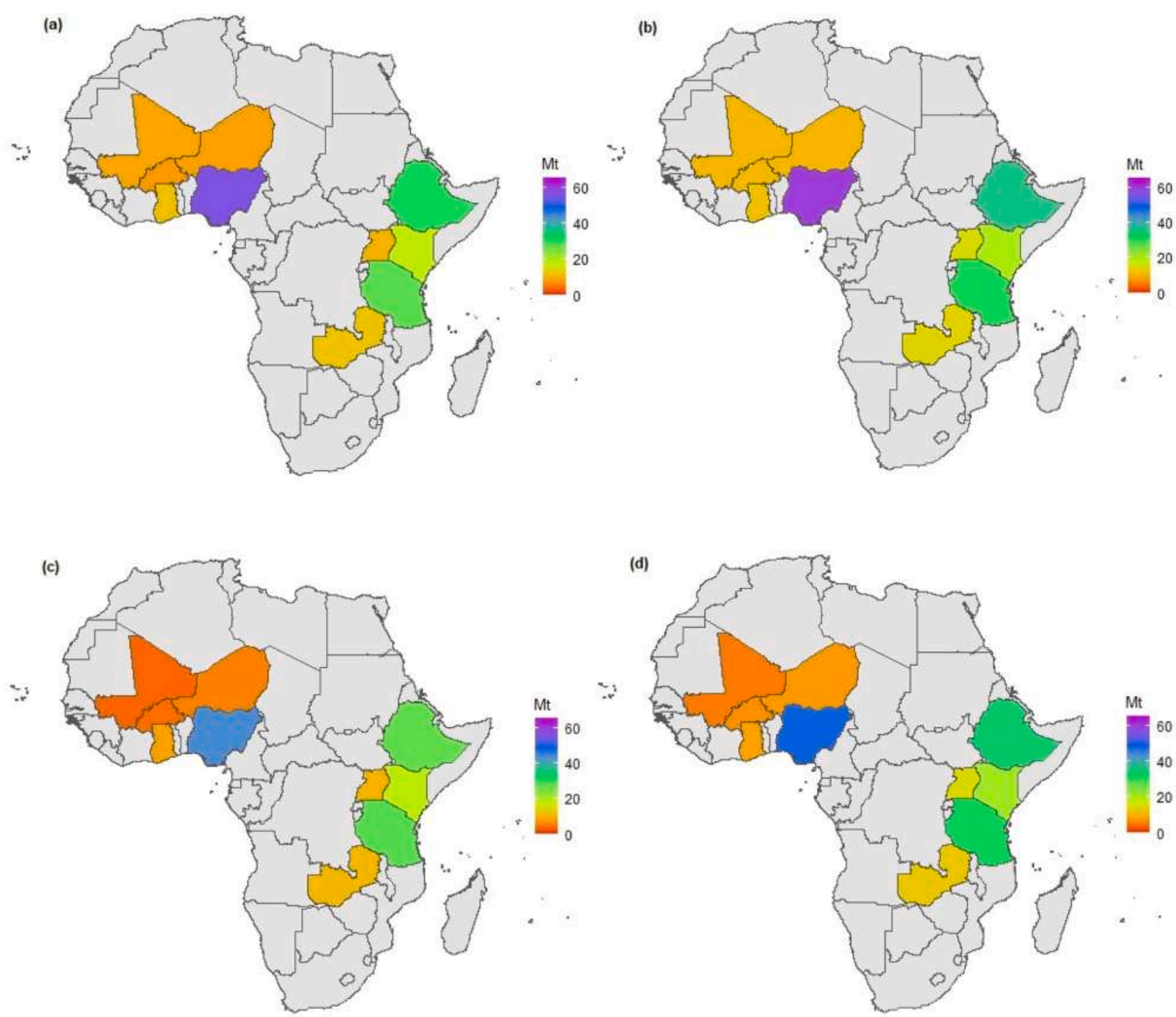

Fig. 10. The aggregated rainfed cereal production gap (the potential production minus the actual production) for each country (a) without adaptation in 2050, (b) with adaptation in 2050, (c) without adaptation in 2090, (d) with adaptation in 2090. The actual rainfed cereal production was kept constant at historical levels. The actual production was extracted from the GYGA (https://www.yieldgap.org). Production data are expressed with 0% moisture content.

country in future. These results were consistent with the local agronomist's observations in this region where rainfall amount was indeed higher in recent years compared to previous decades (Ado, et al., 2020) and consequently there is a tendency for farmers to use cultivars with longer growing season in this region. The evaluation of climate change impact on the aggregated cereal yield instead of the yield of each crop separately is another strength of this study as it provides insight into the potential climate change impact on rainfed cereal cropping systems of SSA. It also facilitates the comparison of impacts of climate change on cereal production across countries with different shares of cereal crop areas in SSA. These results can thus help designing scenarios to evaluate future pathways of food self-sufficiency in SSA (e.g., van Ittersum et al., 2016).

The reliability of simulated results in rainfed systems under current and future climate relies heavily on the ability of the crop models to simulate the water balance during the growing season. Through evaluation in different studies, it has been demonstrated that both the WOFOST and Hybrid-Maize model can simulate soil water balances in field conditions throughout the growing season (Dewenam et al., 2021; Yang et al., 2017). The adequate match between the simulated and observed results indicated that the models perform reasonably well in simulating cereal yields across varying temperature and water stress conditions (Fig. S2 and S3). Furthermore, Bassu et al. (2014) compared the responses of several crop models to climate change factors, including Hybrid-Maize and WOFOST. The study reported substantial consistency in simulated outputs between our two models and the remaining 21 models, as well as a reasonable performance at both 'low' and 'high' information levels (for further details the reader is referred to Bassu et al., 2014). Like for any modelling study, there is no guarantee that all factors and interactions will be well captured in this study, but given the fact that both models were calibrated for phenology for each station separately and evaluated for very diverse conditions in SSA (Table S2), the rigorous protocol employing local and measured data (Grassini et al., 2015; van Bussel et al., 2015) and the involvement of national experts, we argue that the present study is a rigorous and robust assessment of climate change impact and adaptation options for SSA compared to more coarse continental and global studies with little agronomic detail and model evaluation (Jägermeyr et al., 2021; Zabel et al., 2021; Rosenzweig et al., 2014).

In the future, extreme weather events such as heat waves, large storms, prolonged droughts, or floods are likely to become more frequent or more intense (Trisos et al., 2022; Fig. S7). However, modelling the effects of these events on crop growth, and their interaction with future climate change, is challenging (Webber et al., 2020; Rötter et al., 2018). Crop models are not ready to simulate all such events (Silva and Giller, 2020), and furthermore the prevalence of such events under climate change is difficult to project. Therefore, our results are probably somewhat optimistic from this perspective. It is worth mentioning that the negative effect of extreme events (e.g., high temperatures and drought) may be mitigated by introducing new cultivars using breeding techniques (Tesfaye et al., 2018; Fita et al., 2015). Second, we assumed that the spatial distribution of the four crops under future climate will remain similar to that under the historical climate. However, we do acknowledge that climate change can affect the spatial distribution of harvested areas of crops in the future (Nidumolu et al., 2022). Third, we tried to estimate the adaptation potential of existing cultivars in terms of growing season duration. Crop traits related to tolerance to drought stress and high temperatures can also play an important role in increasing yield and yield stability of the four crops under climate change, particularly in West Africa (Tesfaye et al., 2018; Cairns et al., 2013). Thus, the adaptation potential of new cultivars with these kinds of traits, in addition to the adjustment of the growing season duration, can be greater than what we have investigated in this study.

4.2. Regional differences of climate change impacts

In this study, we found a different response of cereals to climate change in ESA compared to WA, which also depended on the time horizon. For 2050, in ESA a modest impact was found (−6% in maize equivalents), while the impact was virtually absent (−3%) in WA. In 2090, however, the negative effect of climate change was much higher in WA (−24%) compared to ESA (−9%). Hasegawa et al. (2022) reported similar results for maize using a meta-analysis study for the entire globe. They indicated that by the middle of the century negative effects of climate change on maize yield were higher in the regions with current annual temperatures around 20℃ (like ESA, Fig. S6) compared to regions with current annual temperature around 25℃ (like WA, Fig. S6). However, by the end of the century, the negative impacts of climate change on maize yield in the warmer regions were larger than in the cooler regions (Hasegawa et al., 2022). The difference in the temperature of the two regions is related to the topography. The total area with an elevation above 1000 m above sea level is 1025 thousand km^2 throughout East Africa while it is only 22 thousand km^2 throughout West Africa (Romeo et al., 2020; Fig. S13). This difference in topography between West and East Africa creates different environmental and climatic conditions in these regions. The annual temperature at the weather stations located in West Africa is up to 10°C warmer than those located in East Africa (Le Houérou, 2009).

Daily temperatures under historical climatic conditions are generally sub-optimal or optimal for crops in ESA, while they are optimum or beyond optimum for the three crops planted in WA (Fig. S6 and S7). It is projected that annual temperatures will increase by 2.6℃ based on SSP3–7.0 and 3℃ based on the SSP5–8.5 climate scenario in 2050 and by 4.6℃ (SSP3–7.0) and 5.7℃ (SSP5–8.5) in 2090 compared to the current climate (IPCC et al., 2021; Fig. S6). With climate change, temperatures will generally shift from sub-optimal to optimal for crops in ESA. On the one hand, this will have a positive effect of increased temperature and CO_2 on crop yield by increasing daily photosynthesis, especially for C_3 crops like wheat (Jägermeyr et al., 2021; Wang et al., 2017; Kiirats et al., 2002). On the other hand, crop biomass accumulation and yield can be reduced due to the shortening of the growing season and hence less intercepted radiation during the growing season (Asseng et al., 2015; Thornton et al., 2011). Yields of C_4 crops, including maize, millet, and sorghum, decreased because of a reduction in growing season duration particularly in ESA, where there was not an environment with severe water stress and high temperatures during the late growing season of the crops in the future (Fig, S4; Fig. S7; Fig. S8).

4.3. Adaptation of the growing season with existing cultivars from the region

Cultivars with a longer growing season duration can improve crop yield if they do not face a severe drought stress during the late growing season in ESA. Our results showed that such severe drought conditions are not projected under climate change conditions, but rather in some areas, such as Ethiopia, an increase in rainfall is projected for the end of the growing season of the four crops under climate change in ESA (Fig. S8).

The situation will likely become more complicated under climate change for cereals in WA. Cereal crops are projected to face two main challenges simultaneously, namely high temperatures and drought stress. Thus, the effects of both high temperatures and drought stress will determine whether cereal crops can adapt to the new climate. The adaptation can be either with a shorter growing season duration to escape the harsh conditions at the end of the growing season or with a longer growing season duration to benefit from the wetter conditions during the late growing season.

Previous case studies in WA demonstrated ambiguous outcomes as to using new cultivars with a shorter or longer growing season for adaptation (Carr et al., 2022; Akinseye et al., 2020; Singh et al., 2017; Sultan et al., 2013 and 2014). Our results for WA confirm that the response of new cultivars to climate change depends on the crop and (sub-) country (Fig. 6). In WA, millet cultivars with a longer growing season showed a positive impact on yield (Yw) under future climate change in substantial areas, while a shorter growing season never had a positive impact on yield (Fig. 6). For maize, cultivars with a longer growing season showed some adaptation potential in some countries (Burkina Faso, Mali and Nigeria), while shorter growing season cultivars were never beneficial. For sorghum, both cultivars with a shorter or longer growing season could offset the negative effect of climate change under future climates in different regions in WA (Fig. 6).

The selection of cereals (in particular maize, sorghum, or millet) in SSA is usually determined by the severity of water stress. Maize is the preferred crop in regions with lower water stress, while sorghum or millet dominate in areas with higher water stress. Sorghum is well-known for its tolerance to water stress (Prasad et al., 2021) and its ability to achieve high rainfed yields in wet years. It is therefore typically observed that sorghum cultivars have a longer growing season duration in comparison to millet (Table 1) to take advantage of the likely available water late in the growing season in wet years in WA. Due to the low frequency of wet years, it is more common for sorghum to experience drought stress compared to millet during later stages of the growing season in WA. The more severe water stress at stage #4 for sorghum, compared to millet, in dry regions (areas with aridity index less than 300) in Fig. S5 illustrates this finding. Furthermore, for such areas, farmers prioritize millet cultivars that have very short growing seasons (Table 1) to advance food production (this information was obtained from the local agronomists). The implementation of new sorghum cultivars with shorter growing season durations may help in avoiding the late season water stress in some regions in WA.

Sing et al. (2017) also reported that new cultivars with a longer growing season could offset the negative impact of climate change on millet in Sadore, Niger, and Cinazan, Mali. Carr et al. (2022) conducted a meta-analysis for WA to identify the most effective traits for climate change adaptation. They indicated that, in general, cereal (maize, millet, sorghum and rice) cultivars with a longer growing season can be more effective for climate change adaptation in WA than cultivars with a shorter growing season. Akinseye et al. (2020) also reported that a later maturing variety increased yield of sorghum in Bamako, Mali, and Kano, Nigeria, in 2050 compared to the baseline. In contrast, sorghum cultivars with a shorter growing season were shown to perform better under climate change in some selected weather stations located in Senegal (3 stations), Mali (2 stations), Burkina Faso (3 stations) and Niger (1 station) (Sultan et al., 2014).

We demonstrated that planting new cultivars with a longer growing season duration may compensate for the negative effect of climate change on cereal yields in ESA (Fig. 6). However, Zabel et al. (2021) showed cereal yields did not benefit from an extended growing period, due to the occurrence of water stress at the end of the growing season in Kenya. Zabel et al. (2021) investigated the effects of new cultivars adaptation on global cereal (maize, rice, wheat) and soybean production under future climate change scenarios. The difference in reported findings between our study and Zabel et al. (2021) can be attributed to the secondary bias correction of the weather data we performed. For some reference weather stations of the four crops in ESA, the bias was up to ±5°C for historical temperature data from the GCMs compared to observed weather data. Additionally, there was a bias in GCMs rainfall data (Fig. S4). These biases in GCM data had a significant effect on the simulated growing season duration and yield. Thus, we corrected for these biases using a secondary bias method and the available observed weather data for each weather station (Section 3.2 in the SI). A second reason for differences between our study and those from the literature is that we rely on a robust agronomic dataset with local data for phenology and sowing dates of the crops at each reference weather station. In contrast, Zabel et al. (2021) used information from just one cultivar of each crop for doing simulations throughout Kenya. As to the sowing date, Zabel et al. (2021) used a global level dataset for finding sowing windows and sowing dates, which is much coarser than the data we employed.

Our results suggest that planting adapted cultivars not only compensates for the reduction in cereal production in ESA, but the rainfed potential production could even be increased by 10 million tons maize equivalents (0% water content) in 2050, compared to the baseline. To illustrate the significance of this result, we note that the total amount of grains consumed as food in Tanzania with its 58 million population was 7.5 million tons in 2019 (FAOSTAT, 2023). Thus, the suggested adaptation in ESA for 2050 may result in a considerable increase in cereal production.

4.4. *Climate change and cereal production potential in SSA*

Overall, we found a negligible negative effect of climate change on aggregated water-limited cereal yield in SSA by 2050 using adapted cultivars. Evidently, narrowing the yield gaps is the most important challenge to maintain or increase cereal self-sufficiency in SSA by 2050 (van Ittersum et al., 2016). However, climate change will add to the challenge, as we found negative effects of climate change on rainfed potential yield stability in 2050, and negative effects on both average rainfed potential yield and stability of yields in 2090 when adaptation measures were not considered. For WA, we projected that ca. 28% of cereal potential production in 2050 and ca. 52% in 2090 will experience negative effects of climate change (lower average rainfed potential yields and/or stability) even with adaptation using new cultivars. Furthermore, climate change will also have an impact on actual yields and affect the extent to which agronomic gains can be attained by any given technology. We thus argue that in the context of the steep cereal demand increases in SSA, this is likely to further increase food self-sufficiency challenges, especially in the western part of the sub-continent.

The average relative yield gap of the cereal crops was estimated to be 78% of the water-limited yield (Yw) in ESA and 78% of the water-limited yield in WA (https://www.yieldgap.org). Although there is an enormous yield gap in cereals in the ten countries in SSA, the self-sufficiency for these crops was estimated to be 0.83 for the ten countries in 2010 (van Ittersum et al., 2016). According to the projections, the countries' total population is projected to increase between 74% (with a low fertility rate assumption) and 104% (with a high fertility rate assumption) in 2050 compared to 2020 (https://data.un.org). The ten countries are thus in urgent need to narrow yield gaps in the future to maintain and/or increase cereal self-sufficiency rates.

5. Conclusion

We quantified the potential impact of climate change on the water-limited potential yield (Yw) for the main cereals cultivated in SSA. We also assessed the potential of existing cultivars in SSA to adapt to climate change. For the total production in the ten countries, the negative impact of climate change on Yw was projected to be small in 2050, particularly in WA, but varied significantly among regions (e.g., climate zones). In 2090, however, the negative impact of climate change on Yw was projected to be significant in SSA. Adaptation to climate change with existing cultivars from the ten countries could partially compensate the negative climate change impact on Yw in WA by 2090 (−16% instead of −24%) and may increase Yw by 2050 and 2090 in ESA (respectively +7% and +6% compared to baseline) and in 2050 in WA (+5%). Adaptation of cultivars can also result in a more stable cereal production both in ESA and WA. Overall, the potential production of cereals was more stable in ESA than in WA, both in 2050 and 2090, with adaptation of existing cultivars. Selecting new cereal cultivars from the existing pool of cultivars for each region and narrowing cereal yield gaps will remain the key challenge to achieve cereal self-sufficiency in ESA in the coming decades. In WA, however, the path to self-sufficiency will likely require, in addition to yield gap closure, exploring other adaptation options than cultivar maturity class.

CRediT authorship contribution statement

Seyyedmajid Alimagham: Writing – original draft, Software, Methodology, Conceptualization. **Marloes P van Loon:** Writing – original draft, Methodology, Data curation. **Julian Ramirez-Villegas:** Writing – original draft, Validation, Conceptualization. **Samuel Adjei-Nsiah:** Writing – review & editing, Validation. **Freddy Baijukya:** Writing – review & editing, Validation. **Abdullahi Bala:** Writing – review & editing, Validation. **Regis Chikowo:** Writing – review & editing, Validation. **João Vasco Silva:** Writing – review & editing, Validation. **Abdelkader Mahamane Soulé:** Writing – review & editing, Validation. **Godfrey Taulya:** Writing – review & editing, Validation. **Fatima Amor Tenorio:** Writing – review & editing, Methodology. **Kindie Tesfaye:** Writing – review & editing, Validation. **Martin van Ittersum:** Writing – original draft, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127137.

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