



# Contribution of improved varieties to maize productivity under climate change in Uganda

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## Abstract

One of the most promising pathways to enhance food security for smallholder farmers is the use of improved crop varieties to increase productivity and minimize climate risks. However, assessing the performance of improved crop varieties under climate change is difficult because of limited long-term empirical data from on-station- and farmer field trials and because future climate could be different from what has been experienced. In this study, the climate change adaptation potential of hybrid maize as an improved variety using the Decision Support System for Agrotechnology Transfer (DSSAT) model applied on grid-scale across Uganda was analysed. The DSSAT model was calibrated with observed weather data and analysed the impact of climate change on maize yield under low (SSP1-RCP2.6) and high (SSP3-RCP7.0) emission scenarios. At the national level, it is projected that a yield reduction of 9.6% (low emission scenario) and 11.8% (high emission scenario) by 2030 will occur under climate change. A yield reduction of 11.2% (low emission scenario) and 19.6% (high emission scenario) is projected by 2050, and 13.3% (low emission scenario) and 29.4% (high emission scenario) by 2090. Comparing the effect of climate change between both varieties shows that it is always better to use the hybrid variety, especially under high emission climatic conditions (8.2% and 24.6% yield buffering by 2090 under low emission and high emission scenarios, respectively) at national level. This positive yield effect is realized across all grids, but substantially varies between sites. However, in order to increase adoption of hybrid maize varieties by smallholder farmers in Uganda, adoption barriers, like access to input markets and financial services, have to be overcome. We identify some of these barriers and discuss opportunities to attenuate them and implications on the modelling results. It is concluded that hybrid maize varieties can potentially be a suitable adaptation measure against climate change-related declines in maize production in Uganda.

**Keywords** Maize production · Breeding · Spatialized modelling · Smallholder agriculture · Landraces

## 1 Introduction

Climate change is one of the most significant global challenges of our time with its impacts on food security becoming increasingly evident across many parts of the world. As temperatures rise, rainfall patterns and magnitudes shift, and extreme weather events become more frequent, severe and widely distributed, crop yields are impacted (Campbell, 2022; Ortiz-Bobea et al., 2021; Shukla et al., 2019). Such climate change impacts on crop yields can have severe consequences for food security, economies and livelihoods in agriculture-dependent contexts. Maize is one of the most important staple crops globally, providing food and livelihoods for millions of people, while being highly sensitive to climate variability and change (Falconnier et al., 2020;

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Stuch et al., 2021). Impacts on maize yields are projected to increase under climate change threatening food security (Chemura et al., 2022; Zizinga et al., 2022), and among the suggested adaptation measures for farmers is to adjust their crop varieties to increase productivity per land area and minimize climate risks (Prasanna et al., 2021; Zabel et al., 2021).

An improved or modern variety is a new breed variety of a plant species which produces higher yields, quality, and/or provides better resistance to plant pathogens and pests while minimizing the pressure on the natural environment (Anderson et al., 2020). These characteristics can be reached by all breeding techniques, however, often hybrid varieties are seen as improved variety (Smale et al., 2018). The term “improved variety” is widely used in the literature, but it lacks a clear, standardized definition. As a result, the specific breeding techniques underlying these varieties are not always clear. Hybrid varieties are a cross-pollination of two genetically diverse varieties which make use of the heterosis effect – enhanced characteristic of the offspring in comparison to the parents’ characteristics. These varieties can therefore contribute to adaptation to climate variability and offer advantages compared to their predecessors, such as uniformity, higher tolerance to stress factors such as drought, heat, flooding, or salinity, and provide easier management and/or shorter growing cycles (Martey et al., 2020; Nawaz et al., 2023; Simtowe et al., 2019a).

Despite the huge potential of hybrid seeds to increase maize yields, there are many factors limiting their widespread adoption, in particular by smallholder farmers. Obvious factors that hamper the use of hybrid varieties by smallholder farmers are often the high cost of new seeds combined with low incomes. Hybrid varieties have to be purchased regularly, which poses financial challenges for those farmers. Traditionally, smallholder farmers in particular save some of their seed for the next season. Besides this, costs are not always the decisive factor. Other barriers include lack of technical knowledge and other resources (labour, land, and financial capital for mechanization (Atube et al., 2021; Feliciano et al., 2022; Lamichhane et al., 2022). Simtowe et al. (2019b) and Abdulai (2023) note heterogeneous seed access and information asymmetry as leading factors limiting adoption of improved varieties. As a case study based on observational data on improved potato varieties from Ethiopia shows that the frequency with which technical support is utilized and access to credit also influences adoption of improved varieties (Feliciano et al., 2022; Gemeda et al., 2023). In addition, factors like secure land ownership and market access (Abdulai, 2023) or factors associated with gender and/or the ethnic group can explain differences in access to improved varieties by farmers (Mastenbroek et al., 2020; Simtowe et al., 2019a; Teklewold et

al., 2020). On the farmer’s side, income status and behavioural traits, such as risk aversion, are influential. A study across six African countries found that insufficient information, high seed prices, limited resources, and undesirable traits in new varieties are negatively associated with their adoption (Lamichhane et al., 2022). The combined impact of these factors often leads to a relatively low adoption of improved seeds, with varying significance in empirical studies depending on the specific context.

As in many African countries, maize is productivity is important for food security in Uganda, providing over 40% of a Ugandan’s daily calorie intake and reported that only 6% of farmers use improved varieties in Uganda (MoAAF, 2010), meaning that most of the farmers use local maize landraces. According to Longley et al. (2021), up to 89% of seeds planted by smallholder maize farmers in Uganda are informally sourced through self-saving, or sourcing from family, friends, or local markets. Bold et al. (2017) find that hybrid maize seeds in Uganda contain less than 50% of the promised seeds. In addition to this, the quality of other inputs is also very low e.g. with 30% of nutrients missing in fertilizers. This discrepancy between promised benefits and actual outcomes on farmers’ field may be a reason for low acceptance.

Information for the selection of suitable varieties are usually obtained from breeding and agronomic trials, but these are often limited to a number of centralized research stations or selected on-farm sites because of the costs and logistics needed to increase the density of such trials (Rotili et al., 2020; Seyoum et al., 2019) and can limitedly mimic future climate conditions. Therefore, information about the potential of new varieties under future climatic conditions is needed to inform information campaigns on the benefits of improved varieties, political decisions and accelerate investments in breeding (Afzal et al., 2023; Xiong et al., 2022).

In this study, a process-based crop model to address this research and data gap is used. Crop models can simulate potential impacts of climate change on yield and evaluate the effectiveness of adaptation strategies such as the use of different crop varieties. These models are widely used to quantify the potential increase in crop production under both present and future climatic conditions. They offer crucial insights at scale, aiding in local cropping decisions by providing essential information (Challinor et al., 2018). Specifically, a simulation approach is applied to (i) model the current maize yield distribution in Uganda, (ii) project the impact of climate change on maize yields, and (iii) compare how the adoption of hybrid maize varieties could affect yields under current and projected climate change scenarios at both grid and sub-regional level in Uganda, and identify the socio-economic barriers that constrain a widespread adoption of hybrid varieties. The simulation approach allows

for isolating the effects of hybrid maize varieties from other factors that could influence maize production. Our findings have important implications for farmers, development programs and stakeholders interested in the resilience of maize production systems to climate change. Overall, this article seeks to enhance our understanding of how switching crop varieties can mitigate the adverse effects of climate change on agriculture, addressing complexities that empirical studies or point-based modelling alone may not fully capture. Uganda is particularly an interesting case study because maize is an important food and cash crop cultivated by over 85% of the agricultural households and yet yield gaps and climate risks for the crop are high (Okoboi, 2010).

## 2 Data and methods

### 2.1 Study area description

Uganda is a landlocked country located in East Africa between latitudes 4°12' N and 1°29' S and longitudes 29°34' E and 35°0' E at an average elevation of about 1,100 m above mean sea level. It has a total land area of 241,038 km<sup>2</sup> and a population of over 45 million (2020 estimate) (Ngoma et al., 2021a). The country has an equatorial climate with most parts of the country experiencing two rainy seasons (March to May and September to November). In the northern part, rains occur between April and October, while the period from November to March is the dry season (Ngoma et al., 2021b). Mean annual rainfall is around 1,500 mm. Mean annual temperatures range from about 16 °C in the southwestern highlands to 25 °C in the northwest, while in the northeast, temperatures exceed 30 °C in the dry season. Major cereals crops produced in Uganda in order of importance include maize, finger millet, sorghum, rice, pearl millet and wheat. Other key crops are bananas, common beans, cassava and rice (Longley et al., 2021; Nakanwagi, 2021).

## 2.2 Model parameterization and evaluation

### 2.2.1 DSSAT CERES-Maize model

The process-based crop simulation model Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model v4.8 (Hoogenboom et al., 2019, 2024; Jones et al., 2003) was used to simulate maize yield. DSSAT is a generic cropping-system model developed to simulate several crops under a set of management, genetic potential, soil and weather conditions, which define, limit, or reduce crop growth and yields. The DSSAT-CERES-Maize is part of the DSSAT cropping system model and simulates phenological events, reproductive development, dry matter accumulation throughout the growing season, and yield as a function of different soil, weather, and crop management conditions. DSSAT CERES-Maize model calculates plant and soil water, nitrogen, phosphorus, and carbon balances, as well as the vegetative and reproductive development of crops at daily time scales. The model requires daily weather data, soil profile information, detailed crop management information, and genetic coefficients of varieties as inputs to simulate crop growth and yield. We adopted the “Seasonal” module in CERES-Maize model which is appropriate for continuous cropping over many seasons and resets the soils status after every harvest. Information on previous crop, including root biomass, residue and its quality, was obtained from our local understanding of the cropping systems for various parts of Uganda and t default values from the literature (Table 1).

### 2.2.2 Crop management data

For the assessment, various data sources for parameterising and calibrating the model was used (Table 2). Maize yield under rain-fed conditions as this is the dominant system for maize production in Uganda was modelled. Planting

**Table 1** Genetic parameters of the DSSAT-CERES-Maize for local landraces (baseline) and the selected hybrid varieties

Parameter	Description	Baseline		Hybrid	
		Longe5	Local	H628	Longe10H
P1	Thermal time from seedling emergence to the end of the juvenile (degree days > 8 °C) phase during which the plant is not responsive to changes in photoperiod	208.6	238.6	458.0	208.6
P2	Extent to which development (expressed as days) is delayed for each one hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (days)	0.50	0.50	0.50	0.50
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)	508.5	654.0	429.0	554.0
G2	Maximum possible number of kernels per plant.	450	450	450	460
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)	10.5	10.5	10.5	10.5
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	45.6	75.0	75.0	45.0

**Table 2** Data sources used for model parameterisation over Uganda

Parameter	Units	Source
Planting Dates	DOY	MoAAF (2019), Local knowledge
Harvest Dates	DOY	MoAAF (2019), Local knowledge
Planting Depth	Cm	MoAAF (2019), Local knowledge
Row Spacing	Cm	MoAAF (2019), Local knowledge
Plant Density	Count	MoAAF (2019), Local knowledge
Maize varieties	Name	MoAAF (2019), FAO, USAID
Soil profiles	Various	The Harvest Choice Soils, ISRIC, WISE, HWSD, Local
N & P fertilizers	Kg/ha	SEDAC
Weather	mm and °C	ERA5, CHIRPS
Climate	mm and °C	ISIMIP3b (Low emission scenario, High emission scenario)
Validation	Kg/ha	MAPSPAM by IFPRI (2005, 2010, 2017)

dates, harvest dates, planting depth, row spacing and plant density were obtained from the Maize Training Manual for Extension Workers by the Ugandan Ministry of Agriculture, Animal Industry and Fisheries (MoAAF, 2019) and local expert knowledge of maize farming systems. The Harvest Choice Soils HC27 Generic Soil Profile Database (Han et al., 2015), ISRIC – World Soil information soils (Hengl et al., 2014) and the World Inventory of Soil Emission Potentials (WISE) Soil Database (Batjes & Bridges, 1995) were used as soil profiles for each grid (Supplementary Information 1). Fertilizer applications (N and P) were obtained from SEDAC estimates of fertilizer use at grid level (Potter et al., 2010, 2012). In the model, sowing dates were automatically determined when a field meets at least 10% of soil moisture, and the temperature reaches between 10 and 40 °C after the beginning of a sowing window as these allow for seed germination (Gupta & Van Staden, 2021). Similarly, harvest dates are automatically calculated when the crop has reached maturity.

To assess climate change impacts, specific open-pollinated and hybrid varieties were selected from the most common varieties among the many maize varieties that are grown in Uganda. These mainly vary with agro-ecological region as influenced by altitudinal gradient. The baseline maize variety was set as either a local variety Longe 5 (from 1,500 m.a.s.l.) or local landraces (represented by a local open-pollinated variety) in the model (up to 1,500 m.a.s.l.), depending on the altitude of the grid. First, the model was run with the current OPV variety. In a next step, the OPV variety was replaced with the hybrid maize for that zone. As hybrid maize Longe 10 H (up to 1,500 m.a.s.l.) and H628 (from 1,500 m.a.s.l.) as recommended by MoAAF (2019) were used in the modelling. The choice of these two hybrid varieties was to make sure that the hybrids selected are appropriate for the areas that they are selected for and readily available for use by the farmers instead of being

futuristic or hypothetical. The genetic parameters of the local landraces and hybrid varieties that were used in the modelling are shown in Table 1.

In a study in Eastern Uganda, Murken et al. (2024) use a mental model approach to study the decision-making process of investing in improved seeds from the perspective of farmers. Out of 15 factors that were presented to farmers, the most frequently chosen factors were financial capital, input costs, and the expected benefit of improved seeds. The least chosen factors were possession of a land certificate, household size, labour availability, and tenure security. To study the extent of potential barriers to improved (maize) variety uptake in Uganda, we analysed nationally representative household data. The data are from the Uganda National Panel Survey (UNPS), which was collected by the Uganda Bureau of Statistics (UBOS) in 2019–2020 and includes responses from 2,214 households.

### 2.2.3 Observational weather data

For model calibration climate hazards infrared precipitation with stations (CHIRPS) was used for precipitation while ERA5 was used for temperature. The CHIRPS datasets are blended products that combine global climatology, on-station data, satellite observations and rainfall observations from Global Telecommunications Systems (Chisanga et al., 2025). This dataset spans from 50°S to 50°N with a 0.05° spatial resolution satellite rainfall estimates with in-situ station data to produce a quasi-global rainfall dataset covering a long period from the early eighties at daily time step (Funk et al., 2015; Gebremicael et al., 2017). The ERA5-Land temperature data was released in 2019 is an improved version of ERA5 that was created by forcing the terrestrial component of ERA5 reanalysis, covering the same period for land only (Hersbach et al., 2020). Radiation data is required for the modelling and it was therefore derived from the maximum and minimum temperature values from ERA5, latitude, day of the year and derived temperature amplitude values using the *sirad* package of R (Bojanowski et al., 2016) according to Mahmood and Hubbard (2002).

### 2.2.4 Model calibration

In order to have confidence in the performance of the DSSAT CERES-Maize crop model for application in Uganda, experimental field data from sites was used. Experimental data on maize yield was obtained from the National Agricultural Research Organization (NARO)'s three research sites in Central (three years: 2017–2019), Southern (two years: 2018–2019) and Western (two years: 2017–2019) Uganda, giving a total of seven data points. The model was calibrated for these sites to determine the best parameters

that influence maize yield and make these close to the ground. All the experiments used for point-based calibration were laid out in a randomized complete block design (RCBD) with different treatments replicated three times. Planting arrangements (rows, spacing and planting depth), basal fertilizer and top dressing varied and were adjusted for each experimental site. Measurements considered from the experimental plots were maize biomass and yield at harvest, and other parameters were used as they were not consistent across the sites and seasons.

The root mean square error (RMSE), percent bias (pBias in %) and index of agreement (d) and coefficient of determination ( $R^2$ ) were used to assess the performance of the model compared to the experimental results across sites and seasons.

### 2.2.5 Model evaluation

After model calibration, the performance of the model across the country was independently assessed. To do this, the Spatial Production Allocation Model (SPAM) 2017 yield data (Yu et al., 2020) was used. The SPAM data has been widely used in gridded modelling studies in many parts of the world including in tropical Africa such as by Zhai et al. (2021) and Alimaghani et al. (2024) across Africa, van Dijk et al. (2023) in Southern Africa, Grever et al. (2025) in Ghana and Bekere (2021) in Ethiopia. It provides farming system specific yields from a collection of sub-national statistical data integrating ancillary information such as crop prices, population density and crop-specific biophysical suitability to distribute sub-national statistics within the cropland extent using cross entropy (Luo et al., 2022). The final parameterized and calibrated model to independently simulate the maize yield for the period 2006 to 2019 with the observational data was applied. To evaluate the model, its correspondence with the 2017 MAPSPAM maize yields was checked using the same assessment parameters as those in the calibration.

## 2.3 Climate projections and climate change impact assessment

Future climate projections were obtained from 5 GCMs of the ISIMIP3b (Lange, 2019), which provides bias-adjusted and downscaled CMIP6 data. The GCMs used are GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. These 5 GCMs were selected because they are consistent in terms of climatic variables that they have, cover the diversity of potential futures and ensure comparability with similar impact studies that commonly use the same GCMs (Lange, 2019, 2021). Historical simulations of ISIMIP3b cover the period 1850–2014, and future

projections cover the period 2015–2100 at daily temporal resolution at a  $0.25^\circ \times 0.25^\circ$  spatial grid. These were down-scaled from the original  $0.5^\circ \times 0.5^\circ$  grid using the ISIMIP-3BASD statistical downscaling method (Lange, 2021). Two scenarios were selected, a low emission scenario (SSP1-RCP2.6) and a high emission scenario (SSP3-RCP7.0) to represent the range of future possibilities depending on climate ambition. The low emission scenario forecasts a sustainable future where global warming is likely to be well below  $2^\circ\text{C}$  and thus in line with the Paris Agreement. Meanwhile, the high emission scenario depicts high challenges for mitigation and adaptation in a world with no or little climate policy interventions (Hausfather, 2018). The analysis focuses on the periods 1995–2014 (baseline) as the reference period and the three future periods 2021–2040 (Short-term), 2041–2060 (Medium-term), and 2081–2100 (Long-term). The ISIMIP3b  $\text{CO}_2$  concentration data were used for the future and the model-inherent default for the current period (380 ppm) (Lange, 2019) to follow the trends associated with each emission scenario.

The impact of climate change for each grid cell was assessed as the difference between the baseline yield and the projected future yield. The adaptation effect is defined as the percentage difference in yield between the climate change impact when using a hybrid maize compared to utilizing an open-pollinated variety. The results were summarized according to administrative sub-regions as well as nationally, using spatially weighted means.

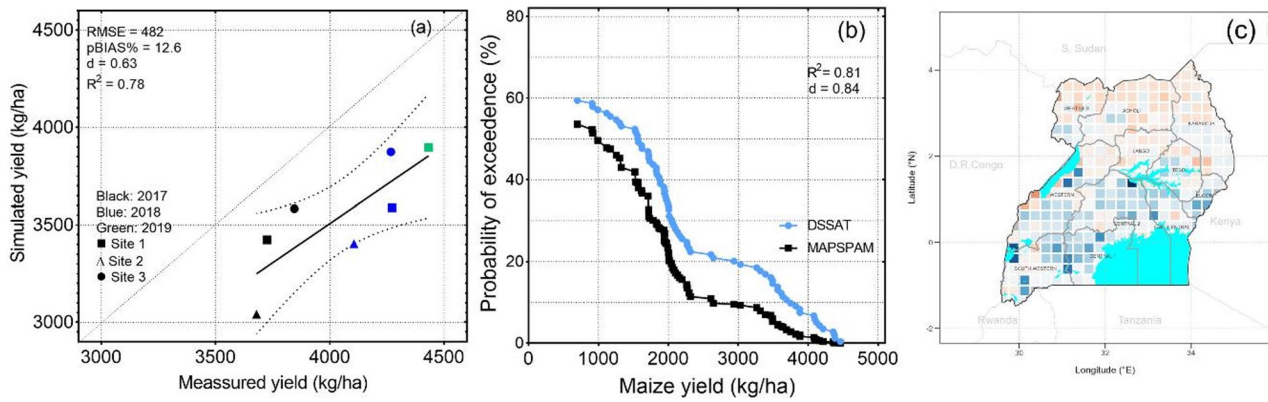
## 3 Results

### 3.1 Model calibration and evaluation

The calibration of the model achieved relative fit between measured yield and simulated yield in Uganda ( $R^2 = 0.78$ ,  $d = 0.63$ ). This performance varied depending on seasons and sites. Overall, the DSSAT CERES-Maize model overestimated maize yields across all sites, as expected (Fig. 1a). In terms of model evaluation, model performance was satisfactory compared to reference data for the 2017 season and also spatially across the country with  $R^2 = 0.81$ , and  $d = 0.84$  (Fig. 1b). The model was able to represent major maize producing areas in the western and eastern parts of the country and also the low maize yield areas in the north and north-eastern parts.

### 3.2 Current distribution of maize yields

The national long-term average maize yield for Uganda from FAOSTAT between 2007 and 2017 is 2,362 kg/ha and our model estimates this at 2,751 kg/ha. The distribution

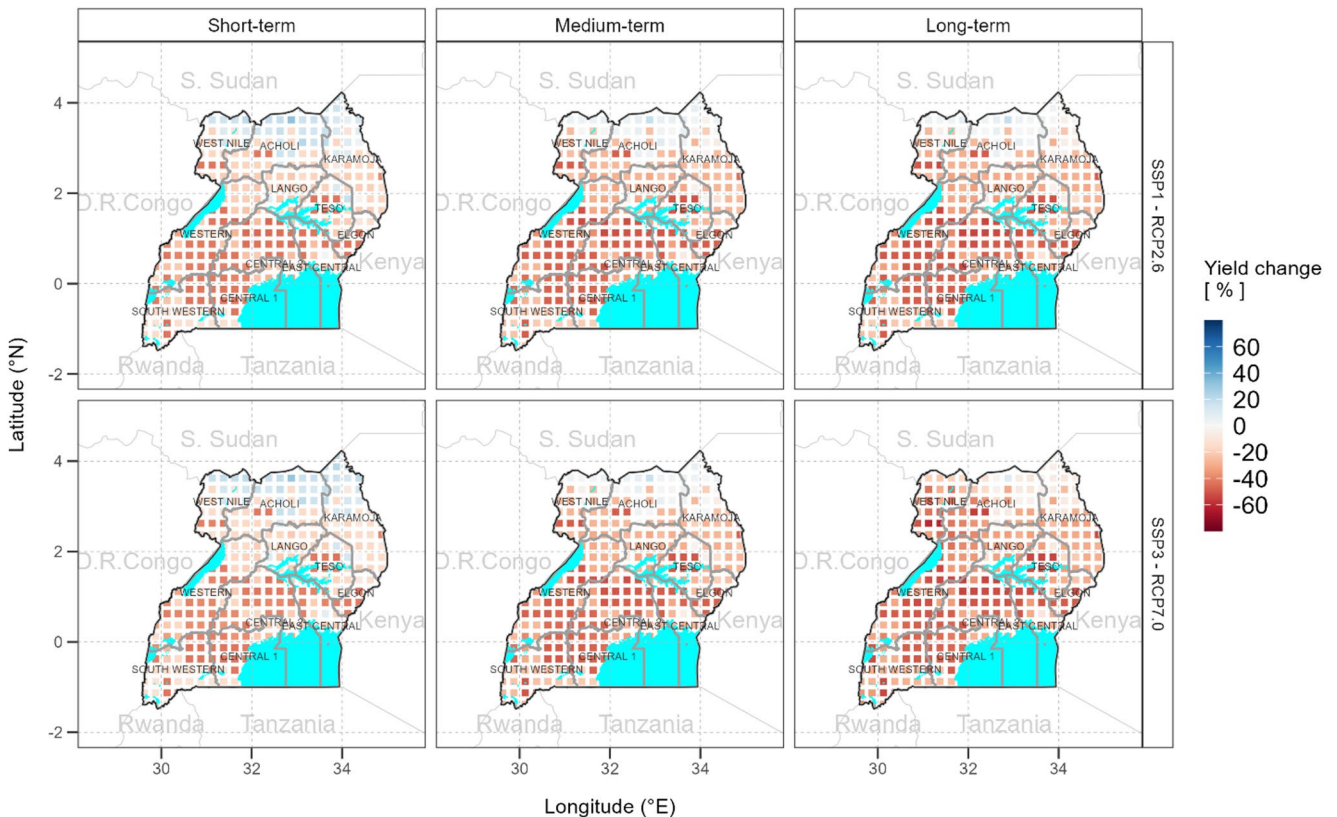


**Fig. 1** Maps of (a) performance of the DSSAT CERES Maize model in relation to experimental data from 3 sites (b) comparison of simulated maize yield and reference MAPSPAM yield for 2017 and (c) simulated maize yield in Uganda at 0.25° grid spacing

of maize from the model is shown in Fig. 1c. The major maize-producing zones are in Elgon, East Central and Teso in the East and at the intersection of the Western, Central 1 and Central 2 subregions, while parts of the West Nile sub region also see high maize yields. Two maize yield distribution zones in Uganda were identified from the model; i.e. around 1.5 t/ha and around 3,500 kg/ha (Fig. 1c). There is a general northward decrease in yields, except for patches in the West Nile subregion (Fig. 1c).

### 3.3 Climate change impacts on maize yields

Figure 2a shows the current maize yield distribution and Fig. 2b shows the projected future percentage changes in maize yields across Uganda for short-term (first column), medium term (second column), and long-term (third column) under the low emission scenario (upper row) and the high emission scenario (lower row). The impact of climate change on maize yields shows spatial and temporal



**Fig. 2** Projected future maize yield changes (%) in Uganda at 0.25° grid spacing under the low emission scenario (top row) and the high emission scenario (bottom row) for the short-term (around 2030), medium-term (around 2050), and long-term (around 2090)

disparities, with a general worsening trend over time (2030–2090) and scenario (low emission scenario to high emission scenario). At the national level, a yield reduction of 9.6% (low emission scenario) and 11.8% (high emission scenario) around 2030, 11.2% (low emission scenario) and 19.6% (high emission scenario) by medium term, and 13.3% (low emission scenario) and 29.4% (high emission scenario) in the long-term are projected (Fig. 2). Maize yield reductions of up to 45% (low emission scenario) and 46.6% (high emission scenario) are projected in the central and southern parts of the country in the short-term while maximum reductions of up to 55% are projected in the long-term, especially in the West Nile sub-region. Positive impacts of climate change on yield are projected for very limited areas in Northern Uganda region in the short-term with a projected 13.2% increase (low emission scenario) and a projected 9.6% increase (high emission scenario) (Fig. 2b).

Of the three high potential maize zones, the West Nile and the Elgon regions are projected to experience the most severe climate change impacts on maize yields. The sub-regional distribution of yield reductions is shown in Fig. 3.

From the sub-regional distribution of projected maize yield reduction trend, it is observable that yield reductions progressively worsen under high emission scenario in all regions while they remain relatively stable under the low emission scenario (Fig. 4). In the medium term, the highest yield reductions of over 40% are projected for the Teso, Lango and Western sub-regions under the high emission scenario. The lowest yield reductions are projected for the northern parts in all scenarios and periods, which happen to be low maize yield areas.

### 3.4 Yield buffering potential of hybrid maize varieties

Next, the adaptation effect of using a hybrid maize variety compared to an open-pollinated variety were simulated (Fig. 5). Using a hybrid maize results in at almost double the maize yield under current climatic conditions (94.6%) compared to the current varieties, with maize yield exceeding 10 t/ha in the south-western and eastern parts of the country (Fig. 6). This yield benefit is realized in almost all

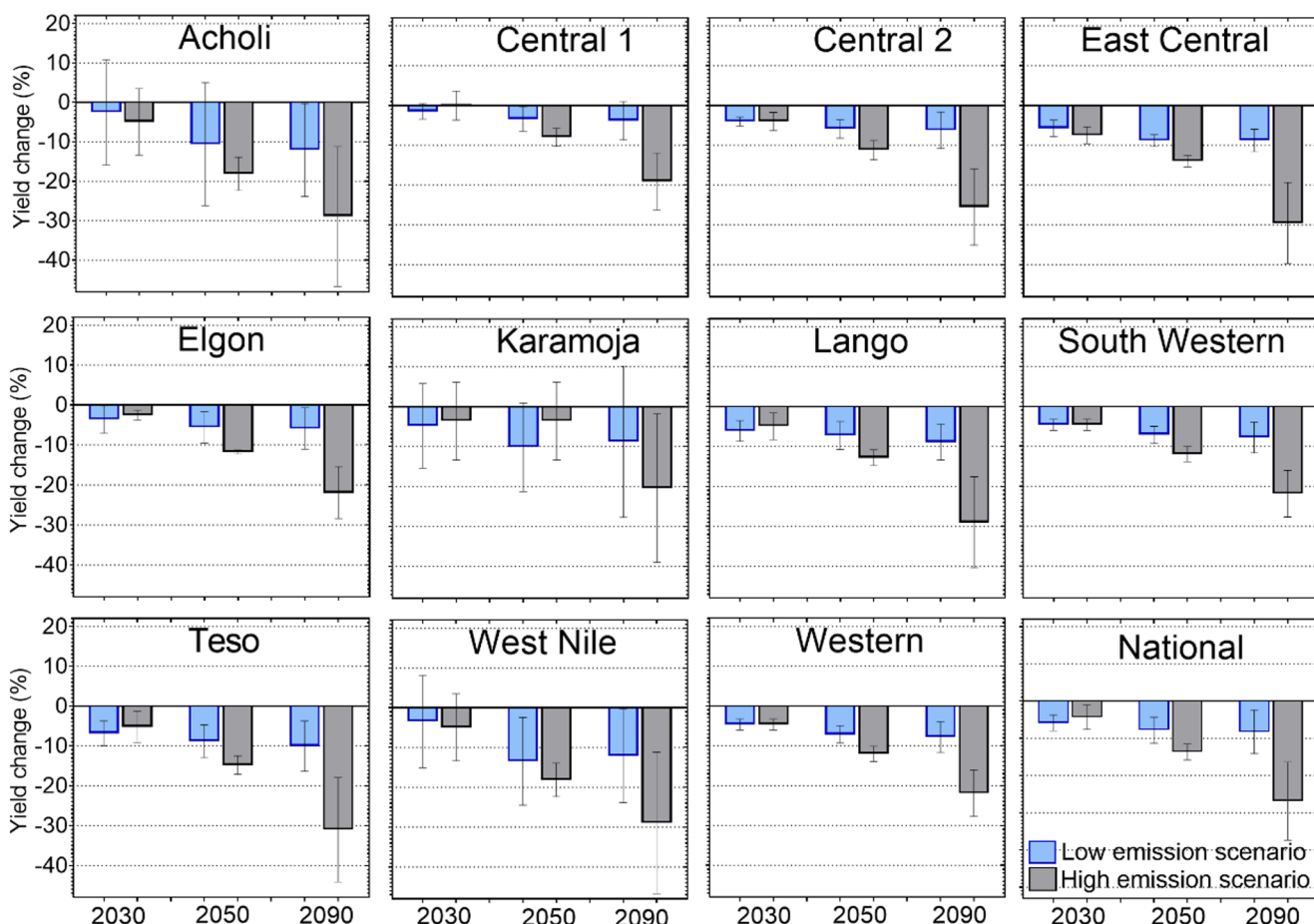


Fig. 3 Simulated climate change impacts on maize yield at sub-regional level in Uganda for the short-term (around 2030), medium-term (around 2050), and long-term (around 2090) under the low emission scenario and the high emission scenario with the open-pollinated variety

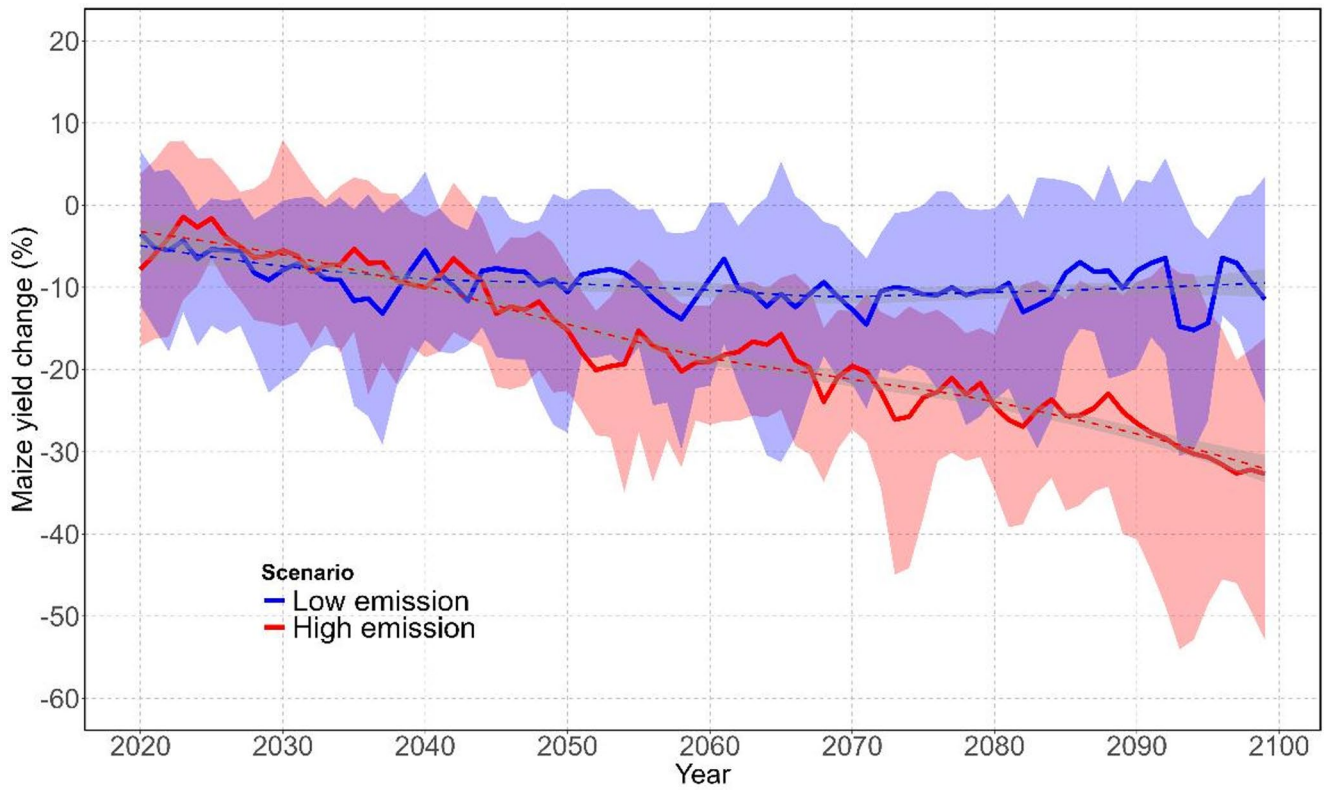


Fig. 4 The national level projected maize yield change under climate change for the high and low emission scenarios in Uganda

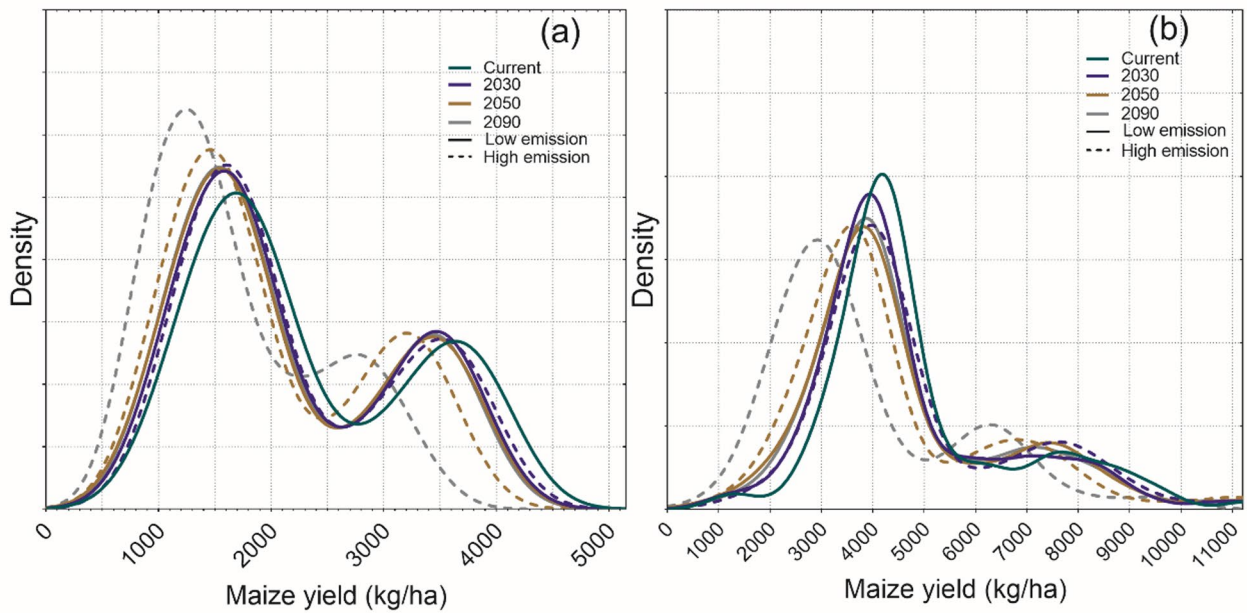
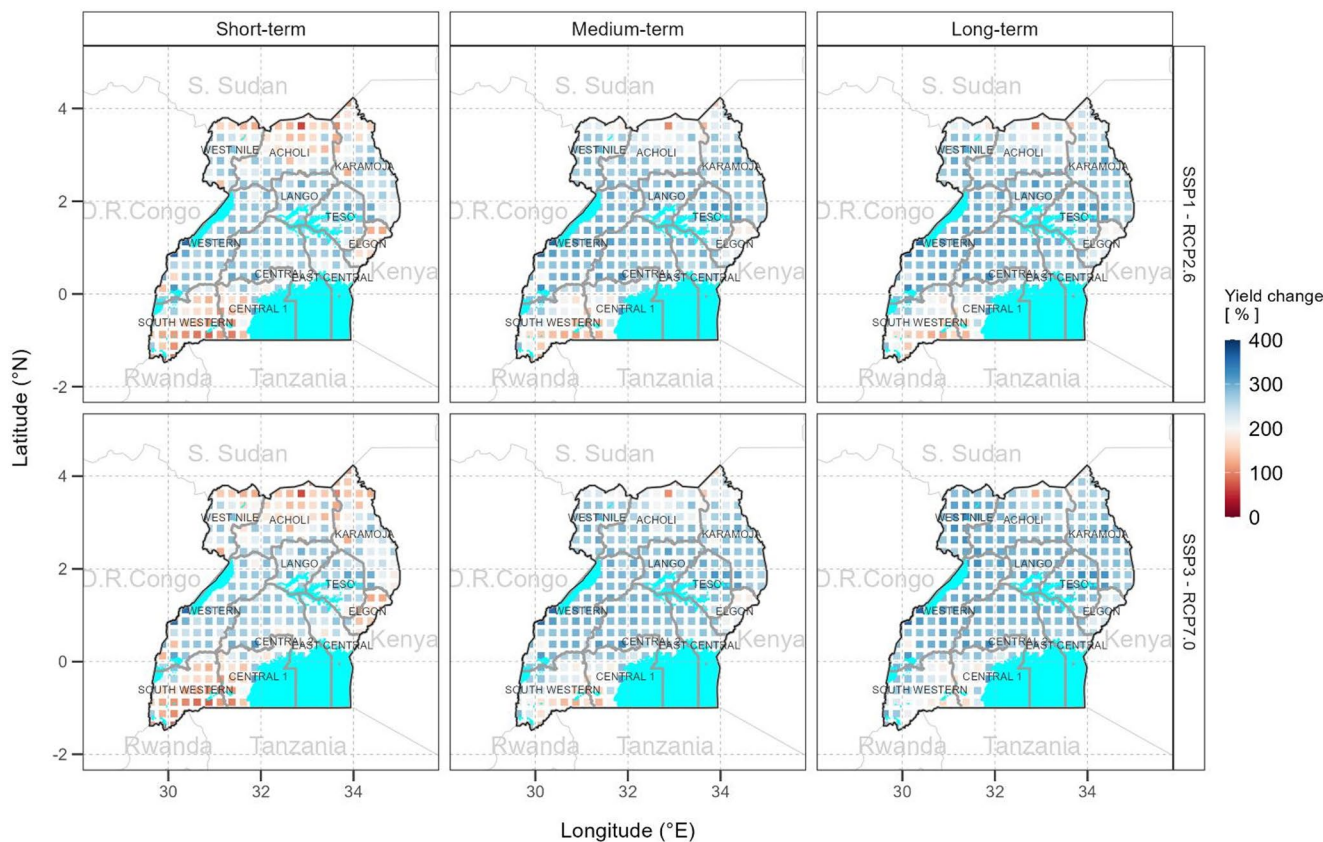


Fig. 5 The national level maize yield probability density under current and projected climatic conditions with (a) traditional variety and (b) hybrid maize in Uganda



**Fig. 6** Grid-level spatial distribution map for the projected adaptation effect of the hybrid maize in Uganda for the short-term (around 2030), medium-term (around 2050), and long-term (around 2090)

grids but substantially varies from around  $-8-340\%$ . The most positive yield responses from using the hybrid maize under current climate conditions are projected to occur in the South-western sub-region (284%) and the south-western sub-region (212%), while the least positive yield effects are projected to occur in Teso (60%) and the West Nile (85%).

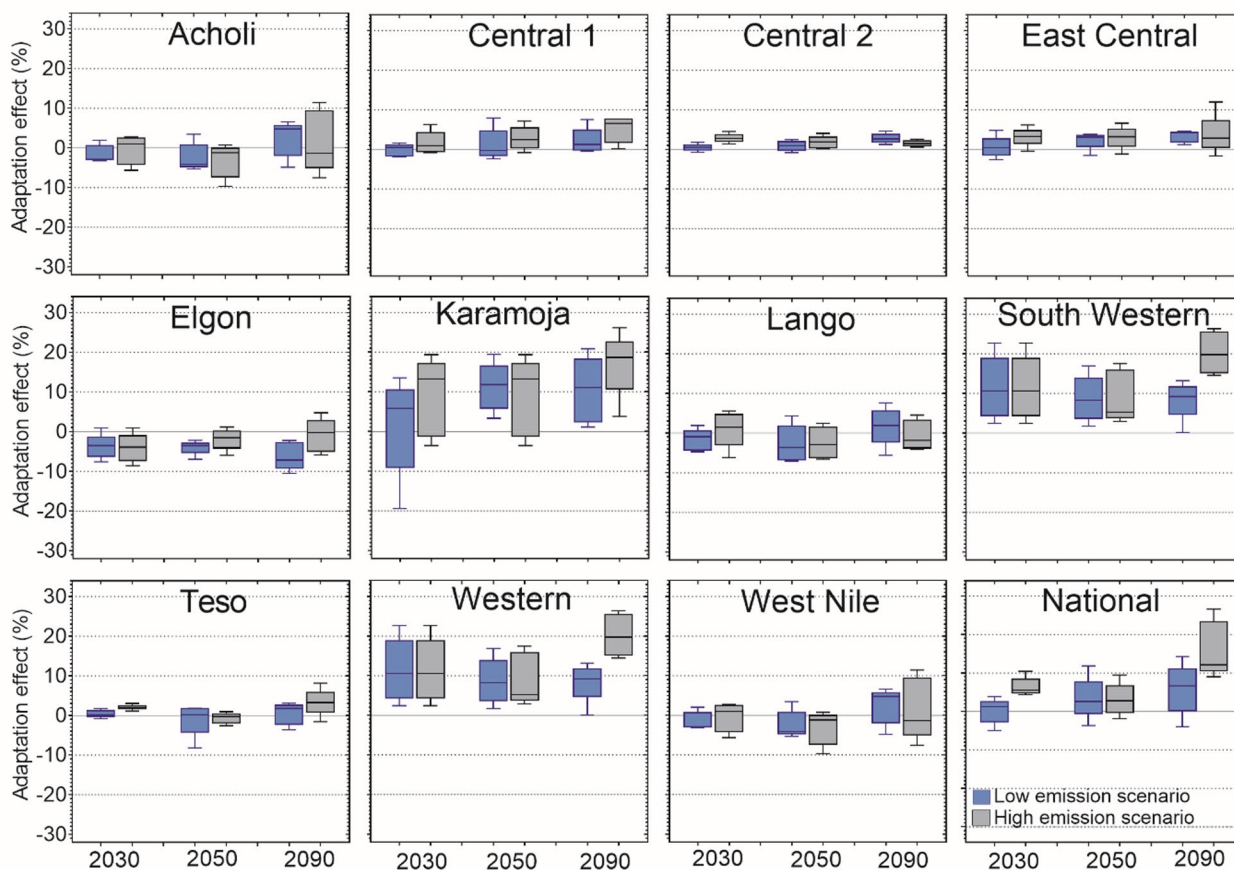
Using the hybrid maize can fully offset projected negative climate change impacts and even surpass current production levels. Results show that it is always better to use the hybrid variety, especially under high emission climatic conditions (8.2% and 24.6% yield buffering in the long-term under low emission and high emission scenarios, respectively) at national level (Fig. 7). The highest adaptation effect of the hybrid maize will be realized in the Karamoja sub-region progressively with time and scenario, being highest under the high emission scenario by 2090 (36%) and lowest under the low emission scenario in the short-term (12.4%, Figs. 6 and 7). Other sub-regions with high adaptation effects of the hybrid maize is the South-Western, East Central, Teso and Western sub-regions.

The yield reductions projected with the hybrid maize for Acholi, Elgon and West Nile sub-region are in the same range (Figs. 5 and 6), indicating that in these regions using the hybrid maize is a good agronomic practice that will

increase yield but does not buffer climate change impacts. Since the climate change buffering potential of the hybrid maize is positive for the majority of regions and at national level, the results support the use of hybrid maize varieties as a climate change adaptation strategy in Uganda.

### 3.5 Socio-economic barriers to hybrid maize variety adoption in Uganda

Table 3 presents nationally representative descriptive statistics on key indicators for socio-economic adoption barriers to hybrids from households who reported to grow crops in the 2019/2020 season. The choice of indicators was informed by the literature on improved variety adoption. With regard to use of improved maize seeds, 43% of agricultural households in the sample reported to grow maize, 9% of households purchase their maize seeds and 3% of all agricultural households reported to use improved maize seeds. On average, households paid ca. 1,500 Uganda shillings for maize seeds in the 2019/2020 agricultural season. While about 1/3 of farmers was able to borrow money during the reference period and hence had access to credit, only few farmers received extension advice. However, 44% of agricultural households in the sample reported to be informed



**Fig. 7** Yield impacts of using the hybrid maize across sub-regions over different scenarios and periods. The adaptation effect refers to the difference in yield between scenarios with and without the implementation of an adaptation measure. This comparison is made as difference between both projected and current periods, relative to the current situation without the adaptation measure

about agricultural training opportunities offered by the National Agricultural Advisory Services of Uganda. Lack of financial means to afford improved varieties is often cited as an important barrier to adoption. Within the UNPS sample, 14% of agricultural households are considered poor as determined by the national poverty line. The mean monthly consumption expenditure stands at 337,481 Uganda Shillings, which amounts to ca. 86 USD as of February 2024. In contrast, households reported to pay on average 1,555 USh for maize seeds in a given season, which amounts to ca. 40 US Cents – the price for the hybrid maize Longe10H per hectare (for 25 kg of seeds) is approximately 50 to 75 USD (250,000–320,000 Uganda Shillings).

Given that the cost of improved seeds approaches the level of an average monthly household expenditure (Table 3), combined with limited access to credits (Murken et al., 2024) and the frequent mismatch between promised and actual input quality (Bold et al., 2017), it is understandable that uptake of hybrids remains very low among smallholder

farmers. As a result, the yield gains projected under ideal conditions are, in practice, unlikely to be realized within the existing agricultural and institutional context. This highlights the need for not only technological innovations but also systemic reforms that improve access to input markets and financial services, and enhance farmers' confidence in the quality of hybrid seeds.

## 4 Discussion

In this study, the impact of climate change on maize yield and investigate the potential of improved maize varieties in buffering the negative impacts of climate change on maize production systems in Uganda was assessed. The spatialized DSSAT CERES-Maize model and a simulation approach to assess climate impacts on yield and isolate the effects of hybrid maize varieties across the country was used. Three advancements in this approach which are identified (i)

**Table 3** Descriptive statistics of potential barriers to improved variety uptake in Uganda

Statistic	Mean	SD	Min	Max	N
	(1)	(2)	(3)	(4)	(5)
Seed characteristics:					
Household grows maize	0.43	0.50	0.00	1.00	2,214
Household uses improved maize seeds	0.03	0.18	0.00	1.00	2,214
Certified	0.01	0.12	0.00	1.00	2,214
Quality declared	0.02	0.12	0.00	1.00	2,214
Household purchased maize seeds	0.09	0.28	0.00	1.00	2,214
Amount paid for maize seeds (in US\$)	1,555	10,476	0	216,000	2,214
Potential barriers to improved variety uptake:					
Household borrowed money in the last 12 months	0.30	0.46	0.00	1.00	2,191
Extension advice received in last 12 months:					
From national agr. advisory services	0.03	0.18	0.00	1.00	2,209
From input supplier	0.01	0.08	0.00	1.00	2,207
From NGO	0.01	0.12	0.00	1.00	2,204
Household is informed about agr. training programs	0.44	0.50	0.00	1.00	2,213
Household size	5.10	2.53	1.00	18.00	2,212
Monthly household expenditure (in US\$) <sup>1</sup>	337,481	262,853	0	3,047,965	2,212
Household is poor	0.14	0.35	0.00	1.00	2,212

<sup>1</sup> In 2009/10 constant prices.

Data source: UNPS wave 7 from 2019/2020. Note that the sample is restricted to households that grow crops in the 2019/2020 agricultural season

providing a national level assessment of climate change on maize yield using a model calibrated with local knowledge, local crop management data and regional biophysical information, (ii) an assessment of sub-regional climate impacts adaptation and (iii) a robust assessment based on multiple scenarios and time periods for both short, medium and long-term climate planning for an important food crop for Uganda. The results are relevant for breeders, farmers, policymaker, and other stakeholders interested in mitigating the negative impacts of climate change on agriculture.

It was observed from this assessment that climate change will have an overall negative impact on maize yield in Uganda especially in high maize potential areas, and this is projected to worsen with time and emission scenario. Our findings concur with previous studies that projected

decreases in maize yield in some parts of Uganda under climate change (Bwambale & Mourad, 2022; Zizinga et al., 2022). Three climate change pathways are distinct in Uganda with a clear trend of increasing temperatures, but a mixed precipitation signal with precipitation projections ranging from dryer, unchanged to wetter conditions. This means that assessing climate change impacts and adaptation options have to be spatially specific to cover the trends that are distributed across the country. Because of this, this study provides a spatialized modelling framework to capture the whole range of climate change impacts on maize yield in the country.

It is suggested that the projected yield reductions are mostly driven by the warming trend in the country rather than by precipitation changes. This is because projections show an overall warming trend and variability in rainfall (Bwambale & Mourad, 2022; Ngoma et al., 2021b), and yet results predominantly show a decrease in yields. Increases in temperatures are more important for maize development compared to precipitation changes, because they affect both metabolic processes such as photosynthesis and nutrient assimilation, plant water demand and reduced water use efficiency (Ayub et al., 2021; Chemura et al., 2022; Chukwudi et al., 2021; Teng et al., 2022). The projected declines in maize yield may lead to looming food and nutrition insecurity (as maize is an important source of calories across the country) and may also influence land expansion and its consequences on biodiversity as farmers attempt to compensate for reduced yield (Mulunch, 2021; Raven & Wagner, 2021; Twongyirwe et al., 2018).

Our study further shows that using currently available hybrid varieties has the potential to increase maize yields in Uganda under current climatic conditions and also buffer climate change-induced yield reductions. The results show that using these varieties is a viable climate change adaptation method in two principal ways. First, increasing yield means that any projected reduction will be happening on higher baseline yield, meaning that farmers may remain with higher yields compared to when a low baseline yield is impacted. Second, and more importantly, the results indicate that an improved variety assessed in this study perform equally well under projected future climatic conditions as it does under current conditions. This shows that improved varieties are a climate impact reducing measure in most parts of the country, for most periods and under all scenarios. These results confirm that new maize varieties can make an important contribution to adapting maize systems to climate change (Afzal et al., 2023; Gosal & Wani, 2020; Prasanna et al., 2021).

The potential doubling of yield with hybrid varieties is due to the higher genetic potential of the hybrid varieties (potential yield 9-12t/ha) compared to current varieties

(potential yield 3–4t/ha) (MoAAF, 2019). Therefore, while keeping other agronomic management constant, changing the variety can potentially double yields in many areas across the country. Due to the heterosis effect, the hybrid maize has significant advantages over open-pollinated varieties, as shown in various research articles (Khatibi et al., 2022; Masuka et al., 2017; Silva et al., 2022). Hybrid varieties have also been shown to have better quality such as water use efficiency (Su et al., 2022), heat tolerance (Dong et al., 2021; Salika & Riffat, 2021), and shorter growth periods that avoid some stress windows (Abendroth et al., 2021; Buhiniček et al., 2021). However, it is questionable whether these yields will be achieved at field level as the lack of high-quality seeds and other inputs at local markets pose a challenge (Lee, 2020; Nakanwagi, 2021). This substantially reduces the productivity and the expected economic return of such investments. Nevertheless, as these hybrid varieties are already available in the country it is important to improve the access to and acceptability of these varieties by smallholder farmers (Lee, 2020; Longley et al., 2021; Simtowe et al., 2019b). This finding highlights the need for ongoing investment in maize breeding and seed systems research, especially in low-income countries where farmers are particularly vulnerable to climate change impacts. In addition, governments can fund breeding programmes to have more and better suited hybrid varieties and inform about the benefits of hybrids and improved management due to extension services (Izumi et al., 2025). While subsidize improved varieties and other inputs is considered as costly and the effectiveness is often not clear (Burke et al., 2022) boosting the adoption of hybrids and provide farmers with credit access can have positive effects. Finally, the private sector seed companies play an important role when it comes to increase outreach and expands markets for hybrid seeds.

Results from this study also underscores the need for a coordinated effort between breeder policy programmes and farmers to ensure that in general improved maize varieties are effectively disseminated and adopted to promote sustainable agriculture and food security in the face of climate change (Prasanna et al., 2021). However, maize breeding alone will not address all agricultural production challenges, as other factors such as agronomic decisions, performance of recycled seeds, preferences of farmers, and markets are also important for the actual yield improvements under climate change (Lee, 2020; Nakanwagi, 2021; Simtowe et al., 2019b). Our approach provides insights into the potential impacts of climate change on crop production as well as identifies strategies to reduce these impacts. Further research should explore the potential of other improved crop varieties, as well as other adaptation strategies, such as changes in planting dates (Ahmad et al., 2020; Baum et al., 2019), crop rotation (Kodzwa et al., 2020; O'Dell et al.,

2020), agroforestry (Chemura et al., 2021), and soil management (Fahad et al., 2021; Zizinga et al., 2022), in the face of climate change.

There are many potential limitations of modelling studies such as these in climate change impact assessment and food security studies. One limitation is that they do not explicitly consider the socio-economic factors that may influence the adoption of improved varieties. These factors, such as access to credit, market opportunities, institutional support, or the behaviour of farmers, are crucial in determining the uptake of improved crop varieties or other new agricultural technologies (Lee, 2020; Martey et al., 2020; Teklewold et al., 2020). Additionally, our models use the same agronomic management information and apply the same amount of fertilizer for both varieties. These assumptions have limitations in the long run, as higher yields may require higher soil nutrient amounts (Prasanna et al., 2021; Xiong et al., 2022). The model is also not able to simulate the effect of pests, weeds and pathogens, hence there might be a bias between attainable yield level simulated in the model and the actual yields observed at farm or trial level. The study also relied on some gridded data, some of which may not be close to local conditions being modelled, even as shown in modelling performance. Also, and importantly, hybrid maize is not a panacea to food security and climate change challenges in Uganda and should be considered as part of a suite of adaptation measures. These include shifting planting dates, implementing agronomic techniques like mulching, agroforestry, irrigation and crop diversification to buffer climate impacts. Future research could explore the potential of other crops to improve agricultural resilience to climate change, as maize is only one part of the food basket in Uganda, albeit an important one, which has the highest nutritional value in combination with other crops.

## 5 Conclusions

In this study the climate change impacts on maize yield on a grid scale in Uganda was modelled and assessed the potential of a hybrid maize to buffer the projected yield reductions under climate change. From the findings of this study, it is concluded that climate change impacts on maize yield vary across the country, being larger in the northern and western parts of the country (West Nile and Elgon regions). These impacts are projected to worsen with time and emission scenario. In addition, the hybrid maize variety has the potential to buffer the negative impacts of climate change on maize yields in all parts of Uganda, but the projected increase varies strongly across the country. Therefore, stakeholders in the maize seed value chain should prioritize the regions with the largest projected potential for hybrid or other improved

varieties. It should be considered that farmers' adoption is often low and their interest is not only in increasing crop yields as grain quality and nutritional value are also important. In addition, strengthening of breeding systems and seed supply systems are required as climate change already affects maize yields, while breeding processes take a long time until new varieties are released.

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**Author contributions** AC and CG conceptualized and designed the research. AC, PA, and PR assembled required data, parameterized and ran the crop models. EAK, LM and SL collected, analysed and curated local maize production data used for the modelling. AC, PA, SL wrote draft manuscript. CG, EAK, and LM reviewed and fine-tuned the manuscript.

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## Declarations

**Conflict of interest** Authors declare no competing interests.

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