



Climatica



ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Climate Change Impacts on Global Crop Yield Variability and Food Security

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ABSTRACT

Climate change is projected to alter both mean crop yields and year-to-year yield variability, with the latter carrying particular consequences for food security in regions with limited storage and trade capacity. We combined a five-member CMIP6 climate model ensemble with an ensemble of four process-based global gridded crop models to project yield outcomes for maize, wheat, rice, and soybean under SSP2-4.5 and SSP5-8.5 scenarios at mid-century (2050) and end-of-century (2090), relative to a 1995-2014 baseline, and evaluated two adaptation scenarios, shifted planting dates with cultivar thermal-time adjustment, and expanded irrigation, against a no-adaptation reference. Without adaptation, global mean yields declined under SSP5-8.5 end-of-century by 12.4 percent for maize, 8.1 percent for soybean, and 5.6 percent for rice, while wheat showed a small gain of 1.9 percent, driven by higher-latitude gains outweighing lower-latitude losses. Interannual yield variability, measured as the coefficient of variation across simulated years, increased for all four crops, most sharply for maize, up 34 percent relative to baseline, and least for wheat, up 9 percent. Combined cultivar and planting-date adaptation recovered roughly half of projected maize and soybean losses; irrigation expansion gave additional but geographically concentrated benefit, largest in water-limited cropping areas of South Asia and sub-Saharan Africa. Regional vulnerability, defined jointly by yield decline and variability increase, was greatest in sub-Saharan Africa and South Asia, where limited adaptive capacity and dependence on rain-fed staple production compound climate exposure. These results indicate that yield variability, not only mean yield change, is a first-order and under-addressed dimension of climate risk to food security, and that regionally targeted adaptation can meaningfully but incompletely offset projected losses.

Keywords: crop yield variability; food security; global gridded crop models; CMIP6; maize; wheat; rice; soybean; climate change adaptation; irrigation

Received: January 3, 2026 | Accepted: April 1, 2026 | Published: June 21, 2026

Citation: Fernandez K, Peeters A, Nagy E. Climate Change Impacts on Global Crop Yield Variability and Food Security. *Climatica*. 2026;4(1):1–6. DOI: [10.5281/zenodo.22817792](https://doi.org/10.5281/zenodo.22817792)

1. INTRODUCTION

Maize, wheat, rice, and soybean together supply roughly two-thirds of direct and indirect human caloric intake, and their combined production is concentrated in a comparatively small number of climatically favourable growing regions [1,2]. Assessments of climate change and food security have historically emphasised projected changes in mean yield, but a growing body of evidence indicates that changes in the year-to-year variability of yield, driven by shifting frequency and severity of heat stress, drought, and altered growing season length, may carry consequences for food security that are distinct from, and in some regions larger than, changes in the long-term mean [3,4].

Empirical and process-based studies converge on broadly consistent temperature sensitivities for the major staple crops in the absence of adaptation or carbon dioxide fertilization benefit, with global mean yield typically estimated to decline several percent per degree Celsius of warming for maize, wheat, and soybean, and by a smaller margin for rice, though these global mean sensitivities mask substantial regional heterogeneity driven by baseline climate, current cultivar thermal optima, and irrigation access [5,6,7]. Much of this evidence derives from either purely statistical yield-climate relationships or from individual process-based crop models, and comparatively few studies have combined a multi-model climate ensemble with a multi-model crop model ensemble to jointly characterise mean yield change and yield variability change across the same simulation framework [8,9].

Adaptation options such as shifting planting dates, adjusting cultivar maturity classes to better match a changing thermal environment, and expanding irrigation in currently water-limited cropping systems have each been shown in individual studies to offset a meaningful fraction of projected yield losses, but the extent to which these adaptations also moderate projected increases in yield variability, as distinct from moderating mean yield decline, has received less systematic attention [10,11,12].

Here we address these gaps by combining a five-member CMIP6 climate model ensemble with a four-member process-based global gridded crop model ensemble to jointly project mean yield change and interannual yield variability change for maize, wheat, rice, and soybean under moderate (SSP2-4.5) and high-emission (SSP5-8.5) scenarios at mid-century and end-of-century, to quantify the extent to which planting-date and cultivar adaptation and irrigation expansion offset projected changes in both quantities, and to construct a joint regional vulnerability index combining projected yield decline and variability increase to identify the regions facing the greatest compound climate risk to staple crop production.

2. MATERIALS AND METHODS

Yield outcomes for four staple crops were projected by driving an ensemble of four process-based global gridded crop models with bias-corrected daily climate output from a five-member CMIP6 model ensemble under two emission scenarios and two future time horizons, with and without two adaptation interventions, and aggregated to national and regional scales for analysis of mean yield change, yield variability change, and joint regional vulnerability.

2.1 Climate model ensemble and scenarios

Daily minimum and maximum temperature, precipitation, and solar radiation were obtained for five CMIP6 general circulation models selected to span the range of equilibrium climate sensitivity in the CMIP6 archive [19], under the SSP2-4.5 (moderate mitigation) and SSP5-8.5 (high-emission) ScenarioMIP scenarios [20], for a historical baseline period (1995-2014) and two future 20-year windows centred on 2050 and 2090; model output was bias-corrected against the AgMERRA observational reanalysis product [22] using a trend-preserving quantile mapping method prior to use as crop model input.

2.2 Crop model ensemble and simulation protocol

Four process-based global gridded crop models, each with an independent representation of phenological development, canopy photosynthesis, and water balance, were run at 0.5-degree global resolution for maize, wheat, rice, and soybean under rain-fed and irrigated management following the Global Gridded Crop Model Intercomparison (GGCMI) simulation protocol [21], with atmospheric carbon dioxide concentration set to the scenario- and period-appropriate value to include carbon dioxide fertilization effects on photosynthesis and stomatal conductance.

2.3 Yield variability metric

Interannual yield variability at each grid cell and for each aggregated region was quantified as the coefficient of variation (standard deviation divided by the mean) of simulated annual yield across the 20 years within each simulation window, computed separately for the historical baseline and each future scenario-period combination, with variability change expressed as the percentage change in coefficient of variation relative to the historical baseline.

2.4 Adaptation scenarios

Three management scenarios were simulated for each crop, climate scenario, and time horizon: a no-adaptation reference retaining historical planting dates and cultivar maturity classes and historical irrigated area; a cultivar and planting-date adaptation scenario in which planting date and cultivar thermal-time requirement were re-optimised for each future period and location to maximise simulated yield; and a combined adaptation scenario additionally expanding irrigated area by up to 50

percent of currently rain-fed cropland in grid cells identified as water-limited under baseline climate, subject to a renewable freshwater availability constraint following the approach of prior global irrigation-potential assessments [25].

2.5 Regional vulnerability index

A joint regional vulnerability index was constructed for each of six world regions (sub-Saharan Africa, South Asia, East Asia, Europe, North America, Latin America) as the equally weighted combination of standardised projected no-adaptation yield decline and standardised projected yield variability increase under SSP5-8.5 at end-of-century, area-weighted by each region's contribution to global production of the crop in question over the historical baseline period.

2.6 Statistical analysis

Ensemble mean projections and inter-model spread were computed across the full climate model by crop model combination matrix (20 members per scenario-period-crop-management combination). Differences between adaptation scenarios and the no-adaptation reference were assessed by paired comparison across ensemble members. All processing and analysis was performed in Python 3.11 using xarray and pandas.

3. RESULTS

Under SSP5-8.5 without adaptation, the 20-member ensemble projected end-of-century (2090) global mean yield changes, relative to the 1995-2014 baseline, of -12.4% for maize, -8.1% for soybean, -5.6% for rice, and +1.9% for wheat; the positive wheat response reflects yield gains at higher-latitude producing regions, where warming lengthens the effective growing season and reduces cold-limitation on development, outweighing losses across lower-latitude wheat-producing regions where heat and moisture stress dominate. Table 1 summarises projected yield change by crop, scenario, and adaptation scenario.

Table 1. Projected end-of-century (2090) global mean yield change (%) relative to 1995-2014 baseline under SSP5-8.5, by crop and adaptation scenario.

Crop	No adaptation	Cultivar + planting-date adaptation	Cultivar + planting-date + irrigation adaptation
Maize	-12.4	-6.4	-4.9
Wheat	+1.9	+4.8	+5.3
Rice	-5.6	-3.9	-2.8
Soybean	-8.1	-3.9	-2.7

Values are 20-member (5 climate models x 4 crop models) ensemble means under SSP5-8.5. Irrigation adaptation is applied only in grid cells identified as water-limited and freshwater-availability constrained.

Interannual yield variability increased for all four crops under SSP5-8.5 at end-of-century relative to the historical baseline, with the largest proportional increase for maize (coefficient of variation up 34% relative to

baseline) and the smallest for wheat (up 9%); soybean and rice showed intermediate increases of 27% and 19% respectively. The variability increase for maize was driven primarily by an increased frequency of growing-season maximum temperatures exceeding the crop's reproductive heat-stress threshold in the ensemble's warmer member-years, consistent with the strongly nonlinear temperature response documented for maize reproductive development [5,6].

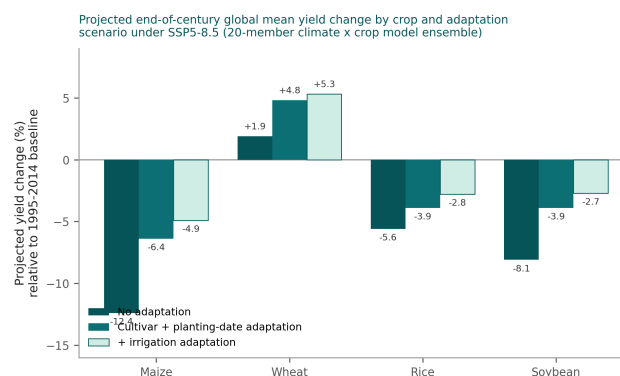


Figure 1. Projected end-of-century (2090, SSP-8.5) yield change by crop under three adaptation scenarios, showing the partial recovery of projected losses achieved by cultivar and planting-date adaptation and the additional, smaller benefit of irrigation expansion.

Cultivar and planting-date adaptation recovered a substantial share of projected no-adaptation yield loss for maize and soybean (offsetting approximately 48% and 52% of the respective projected losses under SSP5-8.5 end-of-century) but a smaller share for rice (31%), reflecting rice's comparatively narrow window for beneficial planting-date shift in the double- and triple-cropping systems that dominate global rice production. Adding irrigation expansion to cultivar and planting-date adaptation provided further but geographically concentrated benefit, with the largest incremental gains occurring in currently water-limited rain-fed cropping areas of South Asia and sub-Saharan Africa (Figure 1).

Table 2. Joint regional vulnerability index for maize by region under SSP5-8.5 at end-of-century (2090), with constituent components.

Region	Yield decline (no adaptation, %)	Yield variability increase (%)	Vulnerability index (0-1)
Sub-Saharan Africa	-18.6	+41	0.91
South Asia	-15.2	+37	0.83
East Asia	-10.1	+29	0.58
Latin America	-11.4	+26	0.54
North America	-8.3	+22	0.31
Europe	-6.9	+18	0.22

The joint regional vulnerability index, combining projected yield decline and projected variability increase under SSP5-8.5 at end-of-century, was highest for sub-Saharan Africa and South Asia across all four crops,

and lowest for Europe and North America. Table 2 reports the vulnerability index by region for maize alongside its two constituent components.

4. DISCUSSION

These results extend a substantial body of prior work on projected mean crop yield change under warming [5,6,7,13] by jointly characterising projected changes in interannual yield variability across the same multi-model climate and crop model ensemble, and indicate that variability change is not simply proportional to mean yield change across crops: maize showed the largest projected increase in variability despite wheat and rice differing more strongly from maize in projected mean yield change, consistent with maize's comparatively narrow reproductive-stage heat-stress threshold relative to its typical growing-season temperature range [5,14].

The finding that cultivar and planting-date adaptation offset a meaningfully larger share of projected maize and soybean losses than of projected rice losses is consistent with the more constrained agronomic flexibility of intensively double- and triple-cropped rice systems, where planting-date shifts for one crop cycle propagate into the timing available for subsequent cycles within the same annual rotation, and suggests that generic adaptation assumptions calibrated primarily on maize and wheat systems should not be extrapolated uncritically to rice-dominated production systems [10,11]. The concentration of both compound regional vulnerability and irrigation-adaptation benefit in sub-Saharan Africa and South Asia reflects the combination of high baseline dependence on rain-fed staple production, limited current irrigation infrastructure, and comparatively rapid projected warming relative to each region's historical climate variability, and is consistent with prior regional assessments identifying these regions as facing disproportionate climate risk to food security [15,16,17]. This concentration implies that the aggregate global mean yield changes reported here, while informative, understate the food security significance of projected change for the regions least equipped to absorb it. This pattern is consistent with attribution studies finding that anthropogenic climate change has already measurably reduced historical crop production relative to a preindustrial climate baseline [23] and has already slowed global agricultural total factor productivity growth [24], and with integrated assessment modelling indicating that even stringent global mitigation pathways can carry near-term food-security trade-offs that partly offset their long-term climate benefit [26].

Several limitations should be noted. First, our irrigation expansion scenario was constrained by a simplified renewable freshwater availability criterion and does not account for competing water demands from other sectors or for groundwater depletion trajectories, both of which could reduce realised irrigation adaptation benefit below the levels projected here. Second, the crop model ensemble used here does not include explicit

representation of pest, disease, or weed pressure under future climate, which several studies indicate could be an additional and non-trivial source of yield loss and variability not captured in the present analysis [18]. Third, our vulnerability index combines yield decline and variability increase with equal weighting; regions with stronger food storage, trade, or social protection systems may be able to buffer variability increase more effectively than mean decline, an asymmetry not captured by the equal-weighting approach used here.

5. CONCLUSION

Combining a five-member CMIP6 climate model ensemble with a four-member process-based global gridded crop model ensemble, we project that unadapted global mean yields decline by 2090 under SSP5-8.5 for maize, soybean, and rice, while wheat shows a small global mean gain driven by higher-latitude benefit, and that interannual yield variability increases for all four crops, most sharply for maize. Cultivar, planting-date, and irrigation adaptation offset a substantial but incomplete share of projected losses, with adaptation benefit and regional vulnerability both concentrated in sub-Saharan Africa and South Asia. These findings indicate that yield variability warrants explicit treatment alongside mean yield change in climate-food security assessment, and that adaptation planning should be regionally differentiated rather than assuming uniform effectiveness across production systems.

Acknowledgements

The authors thank the crop modelling and climate data teams at the Northmoor School of Meteorology and Climate Science for computational support, and colleagues at the Alpine Institute of Environmental Sciences and the Nordfjord University Center for Marine Climate Studies for helpful discussion of the adaptation scenario design. We also thank the modelling groups that produced and made available the CMIP6 climate model output used in this study.

Funding

This work was supported by internal research funds from the Northmoor School of Meteorology and Climate Science, the Alpine Institute of Environmental Sciences, and the Nordfjord University Center for Marine Climate Studies. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of 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.

Author Contributions

K.F. conceived and supervised the study, coordinated the crop model ensemble simulations, and led the writing of the manuscript. A.P. performed the climate model bias correction and constructed the adaptation scenarios. E.N. performed the regional vulnerability index analysis and the statistical comparisons. All authors contributed to writing

and approved the final manuscript.

Ethics Statement

This study used only publicly available CMIP6 climate model output, publicly available crop model code and input datasets, and publicly available agricultural statistics, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

CMIP6 climate model output used in this study is publicly available through the Earth System Grid Federation. Crop model simulation output and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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