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Impact of Climate Change on Cereal Crop Production: Current Trends and Future Challenges

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ABSTRACT

Climate change is increasingly affecting cereal crop production through rising temperatures, altered rainfall patterns, drought, floods, and increasing pest and disease pressures. This abstract reviews current trends and future challenges associated with climate-induced changes in major cereal crops, including wheat, rice, maize, and barley. Temperature and moisture stresses can reduce crop growth, yield, grain quality, and nutritional value, threatening global food security. Adaptive approaches such as climate-resilient varieties, precision agriculture, improved irrigation, conservation agriculture, integrated nutrient management, and stress-tolerant cropping systems offer promising solutions. Future research should prioritize sustainable technologies, resilient farming systems, and integrated climate adaptation strategies to ensure stable cereal production under changing environmental conditions.

Keywords: *Climate change; Cereal crops; Yield loss; Heat stress; Adaptation.*

INTRODUCTION

Cereal grains are the foundation of the global food system. Wheat, rice and maize alone accounted for approximately 91% of total cereal production in 2023, and cereals as a group supply the largest single share of human dietary energy and a substantial proportion of dietary protein, particularly in low- and middle-income countries (FAO, 2023a).

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Over the six decades from 1961 to 2023, global cereal production expanded from roughly 877 million tonnes to 3,126 million tonnes, an increase achieved overwhelmingly through yield intensification rather than area expansion (Ritchie et al., 2023). This achievement of the Green Revolution era is now unfolding against a rapidly changing climatic backdrop that threatens both the level and the stability of cereal supply.

The physical evidence for that change is unambiguous. Global surface temperature in the decade 2011–2020 was approximately 1.1 °C above the 1850–1900 baseline, with land areas warming roughly twice as fast as the ocean, and the best estimate of total human-caused warming from 1850–1900 to 2010–2019 is 1.07 °C (IPCC, 2023). Atmospheric carbon dioxide concentration exceeded 410 ppm by 2019, higher than at any time in at least two million years (IPCC, 2021). Extreme events of direct agronomic relevance have intensified in parallel: a heat extreme that occurred once per decade in the pre-industrial climate now occurs roughly twice as often and is about 1.2 °C hotter, while decadal droughts and heavy-precipitation events have become 1.7 to 2.0 times and 1.3 times more frequent, respectively (IPCC, 2021).

Cereals are exposed to these changes through several interacting pathways. Warming accelerates phenological development and shortens the grain-filling period; heat episodes coinciding with anthesis impair pollen viability and grain set; shifting rainfall alters water availability and the frequency of terminal drought and waterlogging; elevated carbon dioxide stimulates photosynthesis in C3 species such as wheat, rice and barley while leaving C4 species such as maize, sorghum and millets largely unresponsive; and rising temperature expands the range and metabolic demand of insect pests and pathogens (Hatfield & Prueger, 2015; Long et al., 2006; & Bebber et al., 2013). Because the net outcome is crop-, region- and management-specific, aggregate statements about climate change and food security obscure operationally important detail.

Current Trends in Global Cereal Production

The long-run trajectory of global cereal supply remains upward. Production rose from 876.9 million tonnes in 1961 to 2,057.9 million tonnes in 2000 and 3,126.3 million tonnes in 2023, while average cereal yield increased from 1.35 to 4.23 tonnes per hectare over the same interval (Ritchie et al., 2023). Harvested area, by contrast, expanded only marginally, fluctuating within a band of roughly 650 to 740 million hectares (Figure 1). Growth in output has therefore been almost entirely a function of yield, driven by improved germplasm, fertiliser and irrigation use, and mechanisation.

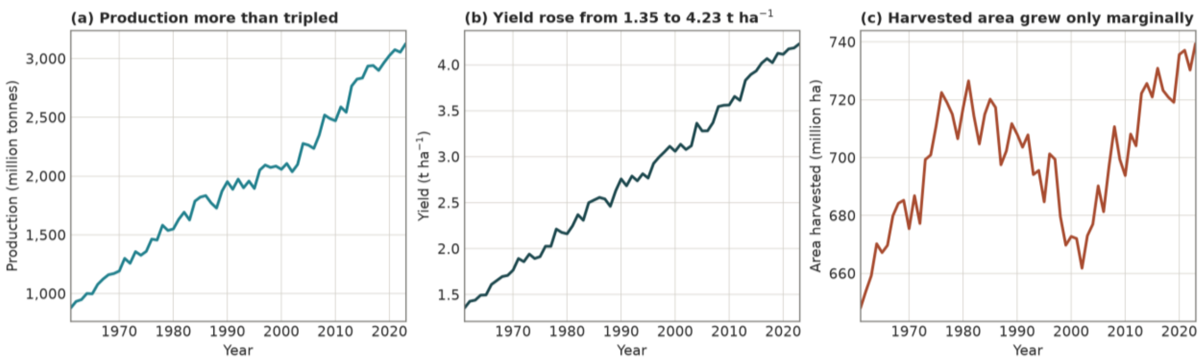

Figure1. Global cereal production, yield and harvested area, 1961–2023. Production has more than tripled while harvested area has changed little, indicating that virtually all growth derives from yield intensification. Data: FAOSTAT, processed by Our World in Data (Ritchie et al., 2023)

Disaggregation by crop reveals divergent trajectories (Figure 2). Maize yield rose from 1.94 to 5.87 tonnes per hectare between 1961 and 2023 and maize output reached 1,238.6 million tonnes in 2023, making it the largest single cereal by volume. Rice yield advanced from 1.87 to 4.76 tonnes per hectare, with 2023 paddy production of 804.7 million tonnes, while wheat yield rose from 1.09 to 3.63 tonnes per hectare (Ritchie et al., 2023). Two features of the recent record are notable. First, growth rates have decelerated: between 2000 and 2020, global yields rose by 33% for maize, 28% for wheat and 19% for rice, a slower pace than in preceding decades, and African rice yields actually declined by 5% over that period (FAO, 2021). Second, interannual variability is conspicuous. Wheat production peaked at 808.0 million tonnes in 2022 before falling to 794.6 million tonnes in 2023, and FAO's marketing-year accounts recorded a 3.0% contraction from the 2022 record (FAO, 2023b).

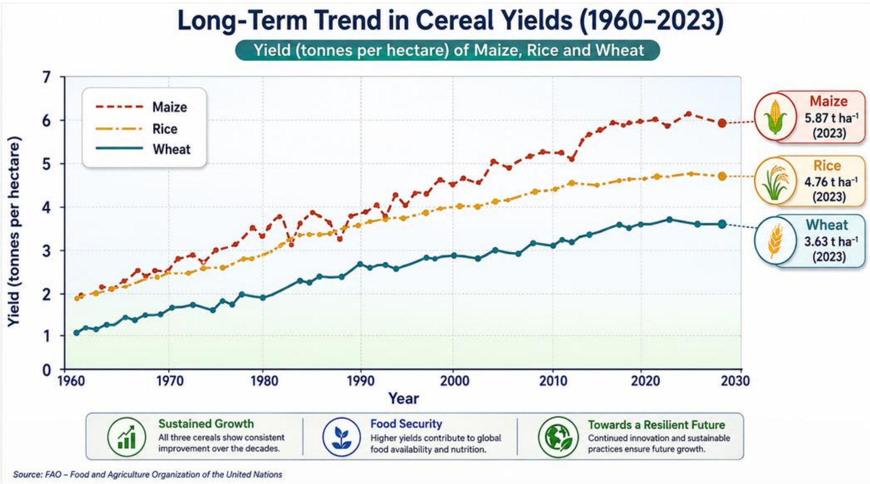

Figure2. Global average yields of wheat, maize and rice, 1961–2023. Line style varies in addition to colour for accessibility. Data: FAOSTAT, processed by Our World in Data (Ritchie et al., 2023)

Aggregate growth conceals climate-attributable losses already embedded in the record. Lobell et al. (2011) estimated that observed 1980–2008 climate trends reduced global maize production by 3.8% and wheat by 5.5% relative to a counterfactual without those trends, with gains and losses roughly cancelling for rice and soybean. Earlier work established that growing-season temperature and precipitation explain about 30% or more of interannual yield variation in the world's major crops, and that warming since 1981 had already cost approximately 40 million tonnes annually across wheat, maize and barley (Lobell & Field, 2007). At sector level, Ortiz-Bobea et al. (2021) found that anthropogenic climate change has reduced global agricultural total factor productivity by about 21% since 1961, equivalent to forfeiting the most recent seven years of growth, with losses of 26–34% in the warmer regions of Africa and Latin America. The IPCC concurs that human-induced warming has slowed agricultural productivity growth in mid- and low-latitude regions over the past 50 years (IPCC, 2022b).

Physiological and Environmental Mechanisms

Temperature and heat stress

Cereal yield responds non-linearly to temperature. Moderate warming shortens the duration of the crop cycle, reducing the interval available for radiation interception and assimilate accumulation. Controlled-environment work shows that warmer regimes accelerate phenology without necessarily reducing leaf area or vegetative biomass, but that the decisive damage occurs during reproduction: maize grain yield fell by as much as 80–90% under extreme heat relative to a normal temperature regime, with losses amplified where heat coincided with water deficit (Hatfield & Prueger, 2015). For wheat, an optimum near 15 °C has been identified, above which each additional degree reduces yield by 2–8% (Asseng et al., 2015). In United States field data, yields rise with temperature up to thresholds of 29 °C for maize and 30 °C for soybean and decline steeply beyond them, a non-linearity that successfully anticipated the approximately 25% maize yield loss during the 2012 Corn Belt heatwave (Schlenker & Roberts, 2009).

Water availability and hydrological extremes

Because cereals are largely rainfed outside Asia, hydrological variability is often the proximate cause of yield failure. Drought events that historically recurred once per decade are now roughly twice as frequent and will occur 2.4 and 3.1 times as often at 1.5 °C and 2 °C of warming, respectively (IPCC, 2021). Synthesis of historical European events indicates mean cereal yield reductions of 9% during droughts and 7.3% during heatwaves, with an interquartile spread extending beyond 20% losses, non-cereal crops proving markedly less sensitive. The heaviest daily precipitation events have simultaneously become more frequent (IPCC, 2021), raising exposure to waterlogging, lodging and harvest losses.

Elevated carbon dioxide and grain quality

Rising carbon dioxide partially offsets thermal damage in C3 cereals, but far less than early enclosure studies implied. Free-Air CO2 Enrichment (FACE) trials at 550 ppm produced yield gains of only 13% for wheat and 14% for soybean, against 31% and 32% projected from chamber experiments, and essentially no response in C4 crops such as maize (Long et al., 2006). A 30-year FACE synthesis across 186 studies of 18 C3 crops found an average 18% yield increase for a 200 ppm enrichment under non-limiting conditions, falling to 10% under nitrogen deficiency or concurrent warming of about 2 °C, with cereals responding less than legumes and root crops (Ainsworth & Long, 2021).

The gain also carries a nutritional penalty (Figure 3). Grains grown at 546–586 ppm showed significant reductions in zinc and iron concentration in all C3 grasses and legumes tested, and lower protein concentration in non-leguminous C3 crops including wheat and rice, while C4 crops were less affected (Myers et al., 2014). Multi-year, multi-location FACE trials on 18 genetically diverse rice cultivars at anticipated end-of-century carbon dioxide recorded mean declines of 10.3% in protein, 8.0% in iron and 5.1% in zinc, alongside consistent losses of vitamins B1, B2, B5 and B9 (Zhu et al., 2018). For populations deriving most of their calories from rice or wheat, the quality effect may matter as much as the quantity effect.

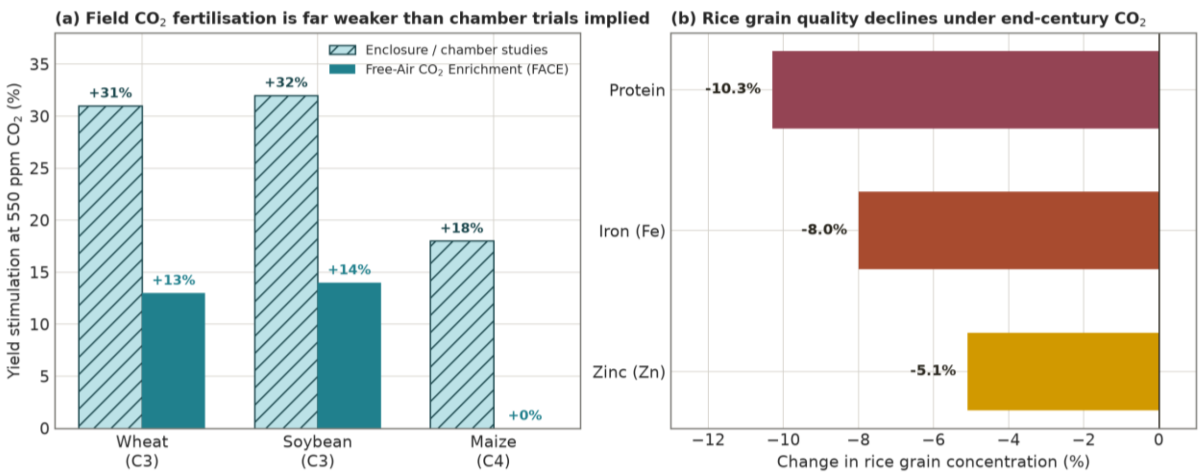

Figure3. The carbon dioxide trade-off. Panel (a) contrasts yield stimulation at 550 ppm measured in FACE field trials with values projected from enclosure studies (Long et al., 2006). Panel (b) shows mean changes in rice grain protein, iron and zinc under end-of-century carbon dioxide across 18 cultivars (Zhu et al., 2018)

Tropospheric ozone

Surface ozone, a co-pollutant of the same combustion processes that drive warming, is an under-recognised yield constraint; the IPCC assigns high confidence to the statement that crop yields are compromised by surface ozone (IPCC, 2022b). Present-day global relative yield losses have been estimated at 7–12% for wheat, 3–4% for rice and 3–5% for maize depending on the exposure metric used, with further deterioration projected for wheat and rice under current-legislation emission scenarios.

Quantitative Evidence of Temperature-Driven Yield Loss

Convergent evidence from four methodologically independent approaches now constrains cereal temperature sensitivity (Figure 4). Combining grid-based simulation, point-based simulation, statistical regression and field warming experiments, and excluding carbon dioxide fertilisation, adaptation and genetic improvement, Zhao et al. (2017) estimated that each 1 °C increase in global mean temperature reduces global yields by 6.0% ± 2.9% for wheat, 7.4% ± 4.5% for maize, 3.2% ± 3.7% for rice and 3.1% for soybean. Country-level maize sensitivities were larger still: −10.3% per °C in the United States, −8.0% in China, −5.5% in Brazil and −5.2% in India.

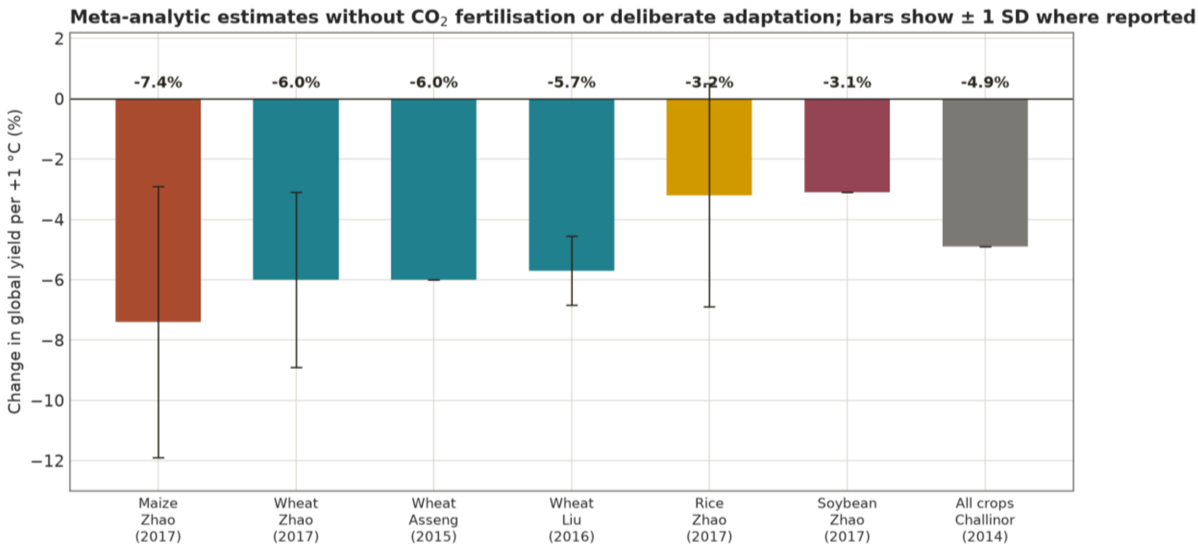

Figure4. Estimated change in global crop yield per 1 °C of warming from independent meta-analyses, excluding carbon dioxide fertilisation and deliberate adaptation. Error bars denote ± 1 standard deviation where reported. Data: Zhao et al. (2017), Asseng et al. (2015), Liu et al. (2016) and Challinor et al. (2014)

These values agree closely with crop-specific ensembles. A 30-model AgMIP wheat ensemble projected an approximately 6% yield decline per 1 °C of global warming, with the largest relative losses in low-yielding, high-temperature environments such as southern India, southern Pakistan and Sudan (Asseng et al., 2015). Liu et al. (2016) reported that grid-based simulations, point-based simulations and statistical regressions independently place global wheat losses between 4.1% and 6.4% per °C, averaging 5.7%, with India (−8.0% per °C) far more exposed than China (−3.0% per °C). Across more than 1,700 published simulations, Challinor et al. (2014) found aggregate production losses for wheat, rice and maize in both temperate and tropical zones once local warming exceeds about 2 °C in the absence of adaptation, with a mean sensitivity of 4.9% per °C and losses larger in the second half of this century than the first. Retrospective attribution is consistent: observed 1981–2010 climate change is estimated to have reduced global mean maize yield by 4.1%, wheat by 1.8% and soybean by 4.5%, with no significant global effect detected for rice (IPCC, 2019). Overall, the IPCC concludes that anthropogenic climate change has decreased major crop production by 4–10% globally over at least the past three decades, particularly in mid- and low latitudes (IPCC, 2022a).

Regional Evidence

South Asia illustrates the vulnerability of wheat to terminal heat. The record March 2022 heatwave in India reduced national wheat production by an estimated 4.5% (95% confidence interval 3.4–5.6%) relative to a normal-weather year, with district-level losses of 10–15% in parts of Uttar Pradesh and Madhya Pradesh; the official national estimate was revised from 111.32 to 106.84 million tonnes, a 4.0% reduction (Kumar et al., 2023). The frequency of Indian heatwaves is projected to increase by up to thirtyfold at 2 °C of global warming, a factor roughly halved at 1.5 °C (IPCC, 2021).

In Sub-Saharan Africa, where maize is the dominant staple and irrigation is scarce, an increase of 1 °C at mean precipitation is estimated to reduce maize yield by 8.3%, and flood events reduce yield by 7.1% relative to normal conditions. Tesfaye et al. (2015) projected that 51–59% of current maize-growing area could experience yield reductions of 5–25% by 2050 depending on nitrogen input, with western and southern Africa more affected than eastern and central Africa; regional ensembles nevertheless disagree in sign for eastern and southern Africa, underscoring genuine sub-continental uncertainty.

Europe demonstrates how a single compound event can propagate through a highly capitalised farming system. During the 2003 heatwave and drought, Italy's Po Valley maize crop fell by a record 36% and French maize by 30% relative to 2002, with French wheat down 21% (IPCC, 2007). European Union arable output fell by more than 23 million tonnes, over 10%, with common wheat down 11% and maize down 21%, and average EU cereal yield falling from 5.60 to 5.12 tonnes per hectare, a decline of 8.6% (COPA-COGECA, 2004). Total agricultural and forestry losses exceeded €13 billion. The 2018–2020 multi-year drought covered about 36% of Europe on average and produced detrended yield anomalies of up to −17.5% for German wheat, −20% to −40% for grain maize across Benelux, Germany and France, and about −10% for barley.

East Asian evidence shows that warming is not uniformly negative in the near term. In north-eastern China, warming between 1980 and 2015 raised rice yield by roughly 10% through reduced chilling injury and additional growing degree-days, with heat extremes so far subtracting only 0.054%; this balance is expected to reverse as warming continues. Chinese cropping systems respond divergently: single-rice yields rise 12.1% per °C while middle-rice yields fall 6.9% per °C, and the area under the most heat-sensitive system is expanding. Chinese maize shows a national mean loss of 2.6% per °C, with 62% of planted area classified as vulnerable, and a systematic review of 667 simulations places China's mean wheat, rice and maize loss at 2.58% per °C, with subregional values reaching −12.70% per °C and carbon dioxide fertilisation adding back about 9.23% (Liu et al., 2020).

Biotic and Edaphic Constraints

Climate change also acts indirectly by rearranging the biotic environment of cereal cropping. Observations of 612 crop pests and pathogens since 1960 reveal a mean poleward shift of 2.7 ± 0.8 km per year, broadly tracking the movement of climatic isotherms, with fungi and oomycetes advancing fastest at approximately 7 and 6 km per year respectively (Bebber et al., 2013). Because insect metabolic and population growth rates rise with temperature, Deutsch et al. (2018) projected that yield losses of wheat, rice and maize to insects will increase by 10–25% per degree of warming, concentrated in temperate regions; at 2 °C, pest-driven losses rise by about 46% for wheat, 31% for maize and 19% for rice, implying roughly 213 million tonnes of additional combined losses. Since insects already consume 5–20% of major grain crops, this represents an added 4–8% penalty on top of the approximately 10% direct heat effect at 2 °C.

Soil degradation compounds these pressures. Roughly 20% of cultivated land and 33% of irrigated agricultural land is already affected by elevated salinity, a share increasing where low rainfall, high evaporative demand and saline irrigation coincide; irrigation with saline water reduces yield by about 17.3% relative to freshwater irrigation. Salinisation, nutrient depletion and reduced organic carbon interact with heat and drought, so that the same warming increment produces larger losses on degraded soils than on well-managed ones.

Future Challenges and Projections

The most consequential recent development is that new-generation models have made the maize outlook markedly worse while improving the wheat outlook (Figure 5). Using 12 global gridded crop models driven by five CMIP6 Earth system models, Jägermeyr et al. (2021) found that mean end-of-century global maize productivity shifts from +5% to −6% under SSP1-2.6 and from +1% to −24% under SSP5-8.5 relative to the earlier CMIP5-based ensemble, reflecting warmer climate projections and better-represented crop temperature sensitivity. Wheat, by contrast, strengthens from +9% to +18% under SSP5-8.5, driven by carbon dioxide response and expanding high-latitude suitability. Critically, climate impacts emerge from the noise of natural variability earlier than previously thought, before 2040 in several major breadbasket regions.

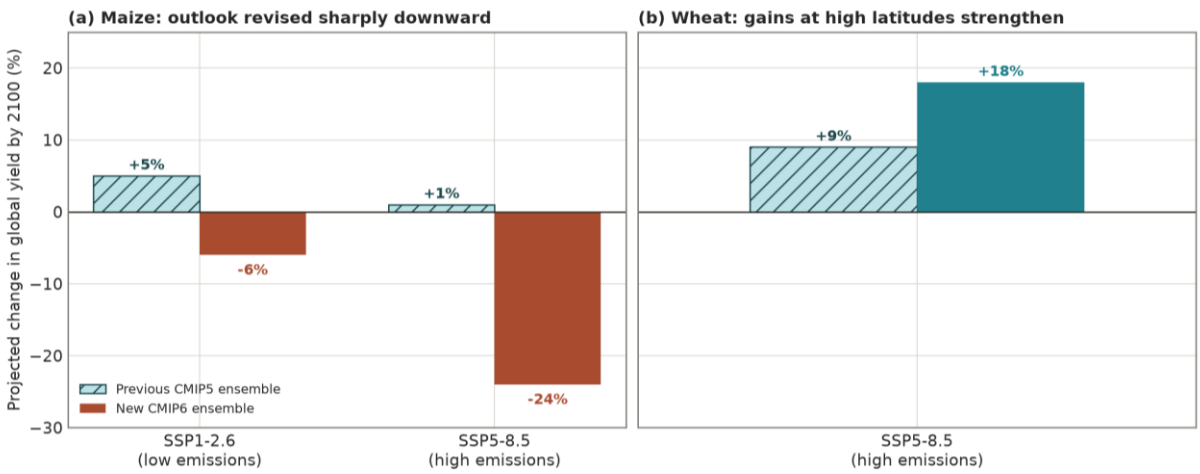

Figure5. End-of-century global yield projections for maize and wheat under low- and high-emission pathways, comparing the new CMIP6-driven crop model ensemble with the previous CMIP5-based ensemble. Data: Jägermeyr et al. (2021)

Assessment-level projections point the same way. Median maize yield changes for 2080–2099 relative to 1986–2005 show decreases across low- and mid-latitude growing regions with localised high-latitude gains at a warming level near 2 °C, worsening progressively at 4.1 °C and 4.9 °C; global maize productivity decreases under all scenarios while wheat increases in some regions under moderate warming (IPCC, 2023). Production of all three major cereals is expected to decline once warming exceeds 2 °C, maize yields could fall by up to 17% in some countries by mid-century under RCP8.5 with current practices, and wheat losses of 5–22% are projected for 2021–2050 as resilience declines and interannual variability rises (IPCC, 2022a). Approximately 10% of current global crop and livestock area could become climatically unsuitable by 2050, rising to more than 30% by 2100 under SSP5-8.5 against under 8% under SSP1-2.6 (IPCC, 2022b).

The food-security implications are direct. Climate change is projected to place an additional 8 to 80 million people at risk of hunger by 2050, depending on warming level and development pathway (IPCC, 2022a), and multi-model ensembles indicate cereal price increases of 1–29% by 2050 across socioeconomic pathways under RCP6.0

(IPCC, 2019). These pressures compound an already deteriorating baseline: an estimated 735 million people faced hunger in 2022, about 122 million more than in 2019, while 2.4 billion people, or 29.6% of the world population, were moderately or severely food insecure and more than 3.1 billion could not afford a healthy diet (FAO et al., 2023).

Adaptation and Mitigation Pathways

Adaptation demonstrably narrows the projected losses. Crop-level adaptations raise simulated yields by an average of 7–15%, with greater efficacy for wheat and rice than for maize (Challinor et al., 2014), and IPCC assessment finds that including adaptation reduces median yield losses from −33% to −10% of 2005 levels at 2 °C of warming and from −46% to −23% at 4 °C (IPCC, 2022b). Realising this potential requires several complementary lines of action.

Adjusting crop calendars is among the cheapest and most immediately available options. A global study coupling farmer decision models with biophysical simulation for maize, rice, sorghum, soybean and wheat found that timely adaptation of sowing dates and cultivar maturity could raise actual yields by about 12% worldwide, simultaneously reducing negative climate impacts and better exploiting carbon dioxide gains; larger shifts are required poleward of 30° latitude, and later-maturing cultivars will be needed at higher latitudes (Minoli et al., 2022).

Genetic improvement remains the central long-term instrument. Priorities include heat tolerance during anthesis and grain filling, drought tolerance, and greater responsiveness to elevated carbon dioxide, alongside biofortification to counter carbon-dioxide-induced quality decline. Genome editing has been applied to drought-associated regulatory genes in rice and wheat, though field-scale validation and regulatory pathways remain incomplete.

Agronomic and system-level measures provide near-term resilience. A meta-analysis of 60 African studies found that climate-smart practices, comprising green manuring, crop residue retention and conservation tillage, raised yield by a mean of 9.2% and soil organic carbon by 14.7%, with green manure alone increasing yield by 63.5%. Conservation agriculture has been reported to improve water-use efficiency by 15–30%. Benefits are, however, strongly context-dependent: an analysis of 5,463 paired observations from 610 studies found that no-till practised in isolation typically imposes a yield penalty of about 10%, largest for cereals (Pittelkow et al., 2015). Effective adaptation therefore means integrated packages supported by irrigation efficiency, soil health investment, insurance, seed systems and early warning.

Because every adaptation option has finite reach, mitigation remains the decisive variable. The gap between the SSP1-2.6 and SSP5-8.5 maize projections, −6% against −24% (Jägermeyr et al., 2021), is a measure of what emission reduction alone protects.

Research Gaps

Four gaps limit current confidence. Crop models still represent compound heat–drought events, waterlogging, ozone and pest damage incompletely, so aggregate projections may understate risk. Projections for Sub-Saharan Africa and other data-scarce regions diverge in sign, reflecting sparse observational networks. Barley, sorghum and the millets are far less studied than the three major cereals despite their prominence in dryland systems. Finally, the economics of adaptation, including adoption constraints facing smallholders, remain thinly evidenced relative to the biophysical literature.

CONCLUSION

Global cereal production reached a record 3,126 million tonnes in 2023, and average cereal yield has more than tripled since 1961, yet this trend is the net result of vigorous technological progress working against an intensifying climatic drag. Independent lines of evidence converge on mean global yield losses of approximately 6.0% for wheat, 7.4% for maize and 3.2% for rice per degree Celsius of warming in the absence of adaptation, and anthropogenic climate change has already reduced global agricultural productivity growth by about 21% since 1961. Carbon dioxide fertilisation compensates only partially, benefits C3 cereals but not maize, sorghum or millets, and erodes grain protein and micronutrient content. Latest-generation model ensembles indicate that maize productivity declines under every emission pathway, that impacts emerge in major breadbaskets before 2040, and that pest pressure, ozone and soil salinisation will add substantially to direct thermal damage. Adaptation is genuinely effective, capable of halving projected losses through adjusted crop calendars, stress-tolerant germplasm and integrated climate-smart management, but its reach is bounded, with tropical and low-input systems in South Asia and Sub-Saharan Africa carrying the greatest residual risk. Sustaining cereal supply therefore demands the simultaneous pursuit of aggressive mitigation, regionally targeted breeding and agronomy, restored soil and water resources, and investment in the under-researched coarse grains that will matter most where the climate becomes least forgiving.

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Author Contributions:
All authors contributed to manuscript preparation, critical revision, and final approval.

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