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Review article

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Climate change impacts on crop yields

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Abstract

Climate change challenges efforts to maintain and improve crop production in many regions. In this Review, we examine yield responses to warmer temperatures, elevated carbon dioxide and changes in water availability for globally important staple cereal crops (wheat, maize, millet, sorghum and rice). Elevated CO_2 can have a compensatory effect on crop yield for C3 crops (wheat and rice), but it can be offset by heat and drought. In contrast, elevated CO_2 only benefits C4 plants (maize, millet and sorghum) under drought stress. Under the most severe climate change scenario and without adaptation, simulated crop yield losses range from 7% to 23%. The adverse effects in higher latitudes could potentially be offset or reversed by CO_2 fertilization and adaptation options, but lower latitudes, where C4 crops are the primary crops, benefit less from CO_2 fertilization. Irrigation and nutrient management are likely to be the most effective adaptation options (up to 40% in wheat yield for higher latitudes compared with baseline) but require substantial investments and might not be universally applicable, for example where there are water resource constraints. Establishing multifactor experiments (including multipurpose cultivar panels), developing biotic stress modelling routines, merging process-based and data-driven models, and using integrated impact assessments, are all essential to better capture and assess yield responses to climate change.

Sections

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Introduction

Barring major shifts in diet towards plant-based diets[1], increased cereal crop production will be required to meet the future food demands of a larger and more affluent world population. Compared with 2010, global total food demand is projected to increase by 30–62% by 2050[2]. Meeting this demand is possible through sustainable intensification, particularly for world regions currently far below potential production[3]. With cropland expansion posing unacceptable threats to biodiversity and the environment[2,4], increased production must primarily come from higher crop yields, with improved cultivars and/or the closing of yield gaps associated with suboptimal crop management[5].

Climate change is expected to affect yields and will challenge efforts to increase yields in many world regions, where higher temperatures will further intensify drought stress and drive faster crop development, as well as increasing crop yield variability and the risk of yield failures[6,7]. Conversely, several regions (such as southern Europe) and crops (winter wheat) could experience yield increases owing to elevated atmospheric CO_2 concentrations and warmer temperatures extending the growing season in temperate and cold regions[8]. Altered growth and development processes in response to warmer temperatures will change water demand and supply, and elevated atmospheric CO_2 concentration is a key contributor to crop yield change under climate change.

The interactions between impacts of elevated temperatures and changes in water availability and CO_2 fertilization on crop yield are specific to the crop, cultivar, production system and region[9–11]. Attribution of yield change to different climate drivers and underlying processes is indispensable to designing, implementing and testing practical and effective regional-specific adaptation strategies[12,13]. As countries work to meet their Paris Agreement commitments, a comprehensive comparison of projected climate impacts across regions and crops can inform targeted policies and interventions to build the resilience of global crop production, explicitly highlighting regional disparities in crop yields[14].

In this Review, we summarize existing evidence on climate change impacts on crop yields for staple food cereals at both regional and global scales, considering observational and process-based crop model projections. Additionally, we explore the response of crops to temperature, elevated CO_2, and water availability, drawing on evidence from experimental results, both individually and in combination with each other. We discuss the knowledge gaps in process understanding, the uncertainties and the limitations in available crop models, and propose potential options for addressing each challenge individually. Finally, we compile evidence about the potential of adaptation options to offset adverse impacts.

Driving mechanisms of yield change

This section provides a brief overview of the primary mechanisms influencing crop yield amid climate change.

Elevated carbon dioxide

Elevated CO_2 enhances photosynthesis while inhibiting photorespiration owing to increased carboxylation activity of the enzyme Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase)[15,16]. Such a response is substantially more pronounced in C3 crops (wheat and rice) than in C4 (maize, millet and sorghum), as CO_2 is concentrated around Rubisco in C4 species owing to anatomical and biochemical modifications[17]. Stomatal conductance decreases under elevated CO_2, thus enhancing transpiration efficiency and minimizing water loss through the stomata for both photosynthesis types[18]. However, this phenomenon is observed at leaf level, whereas at canopy level, crop water use can even increase in C3 crops under elevated CO_2, as leaf area increases with greater biomass accumulation and under improved water status. Some evidence suggests that increasing CO_2 concentrations could adversely affect grain protein concentration by increasing non-structural carbohydrates and lowering protein levels[19–21].

Water availability

In rainfed production systems, water availability is determined by the balance of water supply (precipitation, groundwater use) and water demand (daily evaporative demand over the growing season duration). Water or drought stress can delay seed germination, leading to reduced crop densities and less optimal plant stands[22]. Drought stress reduces leaf area production and photosynthesis[23] through stomatal closure and later damage to the photosynthesis apparatus, reducing Rubisco activity and thylakoid membrane stability[24]. However, feedbacks of reduced biomass assimilation to reduced leaf area expansion can reduce rates of soil water use, potentially slowing down further drought stress. Beyond effects of stomatal conductance on photosynthesis and water use, drought can increase crop temperature as a result of stomatal closure, which accelerates development and intensifies leaf senescence rate, resulting in yield penalties[25]. Finally, drought can increase the partitioning of assimilate to roots[26] or increase stem carbohydrate translocation to grains[27], with the ultimate effect of these stress pathways dependent on drought characteristics[28–30].

Conversely, crop growth and yield can be reduced by too much water, as expected with more intense rainfall events. Restricted oxygen availability under excessive soil water hampers root growth and nutrient uptake, and leads to stomatal closure. This stomatal closure results in chlorophyll degradation, reduced light interception by canopies for photosynthesis, and reduced grain number and single-grain weight[31], consequently decreasing crop yields[32]. Under excessive water, phenology could be substantially delayed as it can slow the leaf appearance rate[33].

High temperatures, heat and frost stress

Temperature affects many growth and yield formation processes in crops. Depending on the process and current ambient temperatures, warmer temperature can lead to increased or decreased yield. One key process strongly influenced by temperature is crop development rate. Higher temperatures generally act to shorten the growing period by accelerating development rates and thereby reducing potential radiation interception by canopies, leading to reductions in potential biomass accumulation and yield[34]. However, warmer temperatures could extend potential growing season length by altering expected frost dates such that longer season cultivars or new crops can be grown in some temperate regions. Increased crop yields have been reported due to extended growing periods and reduced likelihood of frost damage at higher latitudes under climate change[35].

Higher temperatures also raise the daily crop water demand as saturation vapour pressure increases, leading to a relatively drier air and more drought stress if soil water supply does not increase[36]. Higher vapour pressure deficit increases drought stress, but, depending on the crop species, it can also do so in the absence of soil water deficit or under moderate to mild water deficit. Heat stress, or extreme heat episodes around anthesis and grain-filling stages, can cause substantial yield loss because of reduced grain number due to pollen sterility, grain abortion, reduced assimilate transport to grains and accelerated leaf senescence[37].

In addition, high temperature increases photorespiration[38] (mainly in C3s) and also reduces photosynthesis as a result of impaired metabolic functioning and oxidative damage to chloroplasts[39]. Under drought conditions, root growth and function are more susceptible to heat than shoots; hence, higher soil temperatures contribute to yield losses, driven by the restriction of nutrients and water uptake[40–42]. Increased night-time temperatures can cause decreases in cereal yields of 4–7% per degree Celsius rise[43,44] due to an increase in night respiration[45], although there is disagreement[46]. The risk of exposure of actively growing plants to late-spring frosts is increased under climate change, particularly in Asia and Europe[47,48], because anthesis is accelerated and damage to reproductive organs would severely affect crop yield[49]. In addition, diminished snow-cover insulation by warmer temperatures would exacerbate the risk of frost damage on crop yield[50].

Other driving factors

Elevation in ground-level ozone concentration near pollution sources negatively affects crop growth under climate change[51,52]. Higher ozone levels reduce photosynthesis and stomatal conductance, and accelerate rates of respiration[53]. Other yield-reducing factors, including pest, disease and weed damage, are also influenced by climate change[54], although such ramifications are rarely taken into account in climate change impact assessments. A substantial increase in pest and disease outbreaks, along with a geographical shift, has been observed at both the regional and global scales, threatening crop yields[55–57]. The complex interactions among crop, climate, nutrients (mainly nitrogen and phosphorus)[58], pests, disease and weeds make it challenging to consider those factors in process-based modelling[59].

Yield response to climate drivers

Changes in temperature, water availability and CO_2 concentration are the principal contributors to changes in yield under climate change. This section summarizes the yield response to these drivers individually, then examines the response to their co-occurrence through experimental evidence.

Individual drivers

The photosynthesis rate of C3 crops is more responsive to CO_2 concentration than that of C4 crops[60]. At the same time, the amount of available experimental evidence for crop yield response to elevated atmospheric CO_2 concentration is much larger for C3 crops than for C4 crops (Fig. 1a). According to free-air CO_2 enrichment experiments (FACE, Box 1), elevated CO_2 (550–590 ppm) increased wheat and rice yield by about 17% relative to ambient concentrations (350 ppm) at the time the experiments were conducted. Maize and sorghum yields were not increased by elevated CO_2 under irrigation, but were increased under combined elevated CO_2 and drought (Fig. 1a). Yield benefits for maize and sorghum can be up to 41% in presence of drought (Fig. 1a) through the influence of elevated CO_2 on stomatal conductance and water conservation. There are no published FACE data available for millet, but in confined open-top chamber experiments, millet had a wide range of yield responses (7–37%) under different magnitudes of CO_2 enrichment. However, comparisons between results from FACE and non-FACE experiments can be biased; non-FACE platforms could typically implement higher CO_2 concentrations because maintaining high levels of CO_2 in such facilities is substantially less challenging and costly[61].

Understanding crop response to drought stress is challenging, as drought stress will vary in duration, intensity, timing and frequency (during a growing season) and in how these factors correspond with crop phenological stage[62]. With these caveats in mind, there are some lessons to be drawn from the wide body of reporting on crop response to drought stress. There are clearly differences in drought response among crop species. Wheat yield is least affected by drought when stress intensity is comparable (Fig. 1b), with maize having a much greater sensitivity to drought stress[63]. The sample size of available experimental results (cumulative sum of the reported treatments across the studies) for millet ($n = 75$) and aerobic rice ($n = 75$) was substantially less than for wheat ($n = 583$), maize ($n = 580$) and sorghum ($n = 170$), constraining fair comparison among those crops (Fig. 1b).

For excess water, there were very few assessments investigating millet (pot experiments), but many field experiments for wheat, maize and rice yield response to waterlogging (Fig. 1c). Sorghum had the greatest sensitivity (−42% compared with control), followed by maize (−35%), then wheat (−28%) (Fig. 1c). The extent of yield penalties is determined by the duration of the waterlogging period and the phenological stage at which it occurs, independent of the study crop[64]. However, excess water can also lead to yield reductions through indirect effects such as nitrogen leaching[65], increased pest and disease pressure[66], and delays in field operations. Hence, these results are conservative.

Yield response to elevated temperature depends on the ambient range and degree of warming, as well as the crop-specific cardinal temperatures[67], particularly for critical development phases such as anthesis[68]. Sorghum and millet tend to tolerate greater ranges of temperature increases compared with C3 crops such as wheat and rice (Fig. 1d), explaining their ability to thrive in warmer climates. Most experiments exploring the effects of heat stress also targeted the anthesis and grain-filling periods[69] as the most vulnerable phenological stages. In these stages, C3 crop yield was reduced by 30%, but such a steep reduction was not apparent for C4 crops (−10% compared with control) (Fig. 1e). Maize and wheat yields respond linearly to increases in seasonal mean temperature (Fig. 1e). However, the type of yield response to warming is regional and cultivar-specific, as the ambient temperature conditions could be either near or far from the crop's particular temperature optimum[70,71].

Co-occurring drivers

The frequency of extreme heat and drought co-occurrence[72,73] is projected to increase under climate change by up to a factor of six[74], but there is relatively limited experimental evidence of the effects of multiple stresses, such as combined heat and drought and interactions with CO_2, on crop yield. The available experimental evidence suggests that the compound effects of heat and drought stress have more adverse impacts on growth and yield of wheat[75], maize[76], rice[77] and sorghum[78] than individual stresses (antagonistic and additive interactions[79]). Similarly, the combination of heat and drought leads to synergistic interactions[80] in other species, such as barley[81] and tobacco[82], resulting in more adverse effects from the combined stressors than the sum of the individual stresses. Cereal grain yield (wheat, maize, rice and barley) can be reduced by 60% under heat and drought stress, whereas drought stress alone led to a reduction of 40% and heat stress alone caused a reduction of 30%[69]. However, the yield of both C3 (mainly soybean, wheat, groundnut, barley, canola and rice) and C4 (mainly maize) crops was affected equally by combined heat and drought stress[69].

Many crops exhibit increased stomatal conductance in response to heat stress, which acts to regulate leaf temperature through transpiration cooling[83]. However, drought stress restricts stomatal conductance as a mechanism for managing water loss[84]. As a result of the prevailing drought signal dominating the heat signal

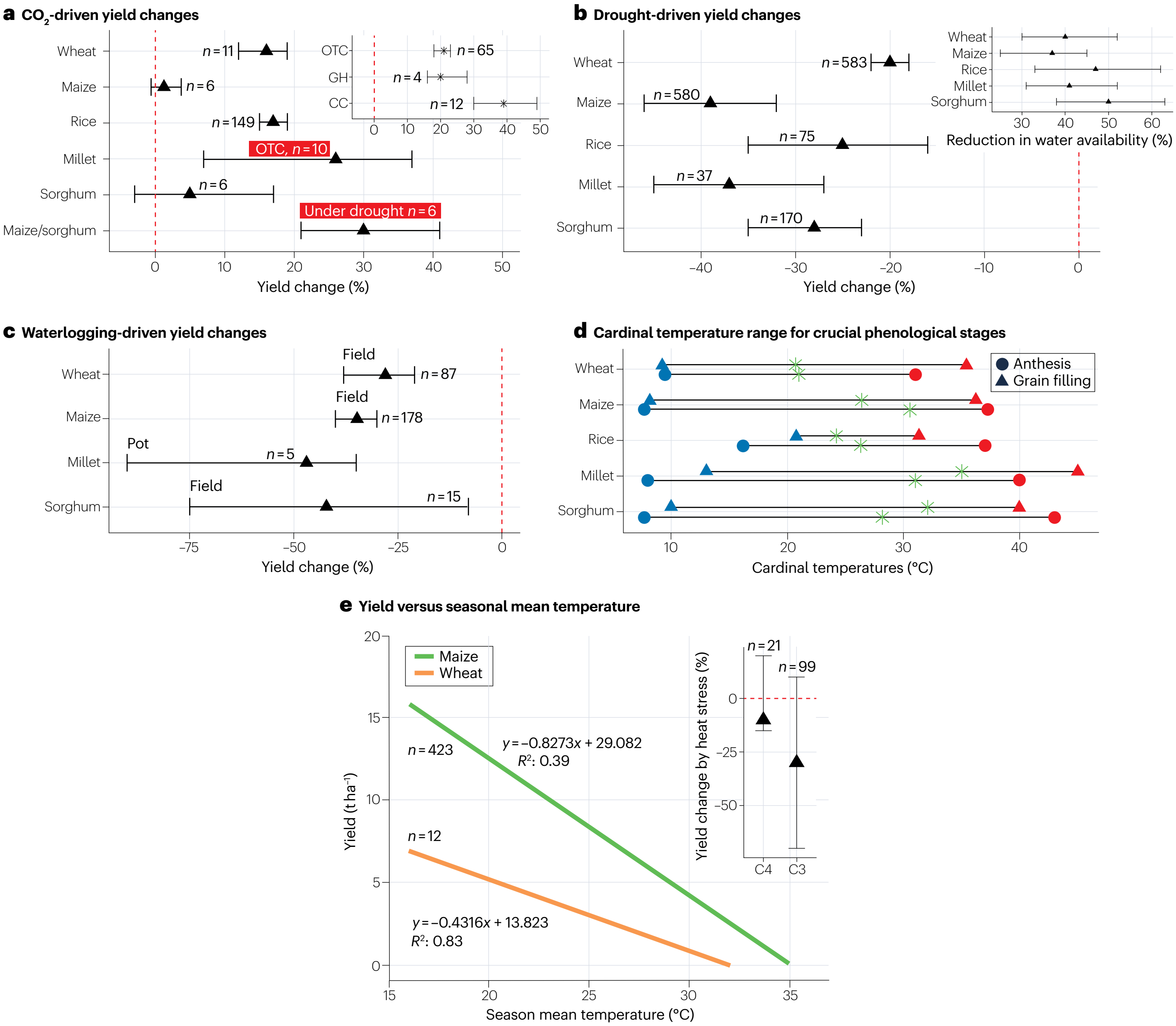


Fig. 1 | Carbon-dioxide-, temperature- and water-availability-driven relative yield changes. a, Yield change under elevated CO_2 (550–590 ppm) in free-air CO_2 enrichment (FACE) platforms. The inset indicates yield response using different non-FACE CO_2-imposing methods for wheat (CC, controlled climate chambers; GH, greenhouse; OTC, open-top chambers)[61,92,211–214]. **b**, Effects of drought on yield of selected crops in field experiments. The inset illustrates the corresponding reduction in water availability for those experiments[63]. **c**, Yield change from waterlogging (or flooding) under field conditions (or pot conditions for millet)[64,215–218]. **d**, The cardinal temperatures of selected crops, including minimum (blue), optimum (star) and maximum (red) temperatures at anthesis (circle) and grain-filling (triangle) phases[67,68,219,220]. **e**, The linear relationship between yield and seasonal mean temperature for maize[221] and wheat[222,223]. The inset presents heat stress effects on yield of crops with C3 and C4 photosynthetic pathways[69]. *n* indicates the number of samples (cumulative sum of the reported treatments). Triangles or circles indicate the mean, and error bars the 95% prediction band using one-way ANOVA (panels **a**, **b** and **c**) or the minimum and maximum data values within 1.5 times the interquartile range (**e**). C3 (wheat and rice) and C4 (maize, sorghum and millet) crops exhibit divergent responses to CO_2, water availability and temperature extremes; C3 crops largely benefit from higher CO_2 levels, whereas C4 crops demonstrate greater resilience to temperature fluctuations and exhibit yield increases in specific conditions of drought coupled with elevated CO_2.

(observed for wheat[85] and maize[86]), stomatal closure in leaves is sustained. The resulting elevated leaf temperatures can lead to potentially irreversible damage to growth processes such as photosynthesis, ultimately resulting in higher yield penalties[80].

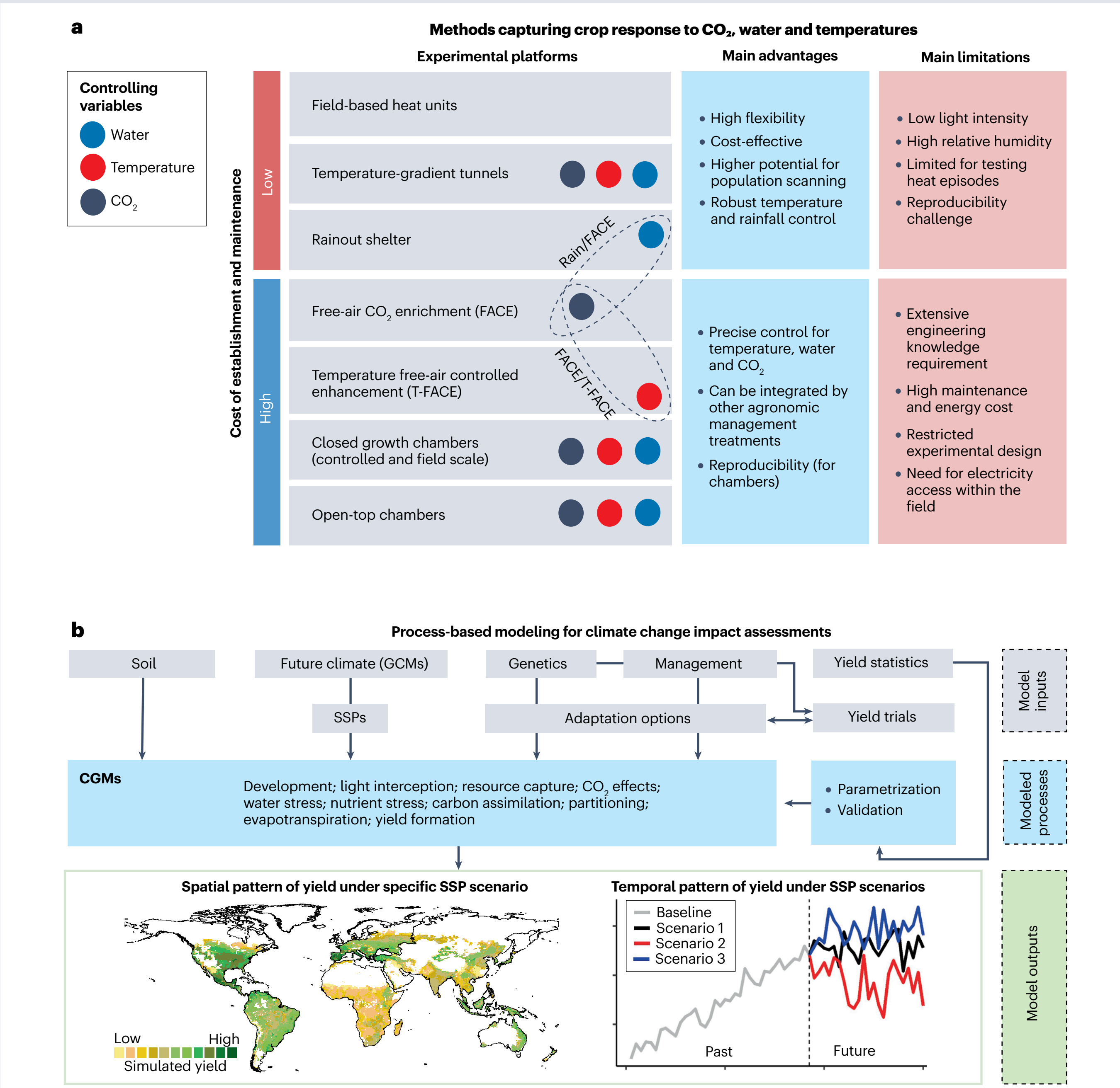
Drought and elevated CO_2 also interact, but because of the complex nature of drought stress[62,87], which includes varying types, intensities, durations and timings, generalizing the interactions between CO_2 and drought[88] on crop yield is challenging. There is evidence that

Box 1

Methods to study climate change impacts on crop yield

Experimental platforms

The selection of a suitable experimental platform depends primarily on the specific research question, crop species, spatiotemporal scale of the investigation, technical proficiency, flexibility to implement various treatments, and budget constraints. There are advantages and disadvantages of commonly used experimental platforms for examining the impact of climate variables on crop growth and development (see figure; GCM, general circulation model; CGM, crop growth model; SSP, Shared Socioeconomic Pathway).



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Process-based models

Process-based crop models are mathematical equations that reflect crop growth and development processes in relation to the environment (climate and soil), agronomic management and genotype[234–236]. These models can play an important role in assessing climate change impacts using two primary approaches. They can be paired with experimental data to examine hypotheses regarding the impact of specific climate variables or their combinations while controlling for the influences of local weather, soil and management practices, thus contributing to process understanding.

In another approach, climate change impact assessments frequently make use of process-based crop models to simulate how crop growth, yield, water use or other variables change in response to a particular climate change scenario. In these assessments, scenario data generated by Earth system or coupled ocean–climate models forced by baseline (representing different levels of warming from different concentrations of greenhouse gas forcing[237]) are used with spatially explicit driving data (such as daily climate variables) in crop models. As attributes of future cultivars and advancements in management practices and agro-technologies are not available, the climate change effects on yield are often presented as relative yield changes. The relative benefits of adaptation strategies (such as irrigation, sowing date, climate-resilient cultivars) on crop yields are quantified using crop models by implementing management decisions interacting with future climate scenarios relative to yield levels in a reference climate[12,238,239].

elevated CO_2 levels mitigate some drought damage, for example leading to a 44% reduction in drought damage to yield[88] in C3 crops, such as wheat, mainly owing to reduced stomatal water loss[89]. Nonetheless, other experimental findings suggest that the mitigation of drought damage by elevated CO_2 levels is considerably smaller (0–18%) for the yield of C3 crops such as wheat[90] and soybean[91]. Elevated CO_2 also partially mitigates drought penalties on maize yield (by 41%)[92] and sorghum yield (15%)[93]. Rice plants maintain photosynthesis for a longer period under drought stress and elevated CO_2 levels, and their photosynthesis rate recovers more quickly after experiencing drought compared with ambient CO_2 conditions[94]. The interaction between elevated CO_2 levels and mild-to-moderate drought intensity results in improved water-use efficiency by modulating stomatal conductance without disrupting photosynthesis[95]. In contrast, sustained drought had a more substantial influence on stomatal behaviour than CO_2 levels[96]. Overall, CO_2 has compensatory effects, but they cannot fully offset the negative impacts of drought on yield[92,97].

Three-way interactions of heat, drought and elevated CO_2 have primarily been investigated in experiments with wheat[98]. Elevated CO_2 levels combined with a 2 °C temperature rise in the warm temperate climate of Western Australia increased wheat grain yield and biomass independent of soil water status. However, when temperatures exceed 2 °C above the baseline, the cumulative CO_2 benefits diminish in combination with drought[99]. The combination of heat and drought intensified the negative impact on yield as well as compromising the mitigating effect of elevated CO_2 (ref. 100). Despite the limited evidence available, it seems that crop yield response to multiple stress interactions could be cultivar-specific[85]. The interactions between the drivers (CO_2, heat and drought) and crop growth processes are not uniform; instead, they are interdependent. For instance, drought can amplify heat damage through stomatal closure[101]. Alternatively, elevated CO_2 can decrease a crop's water requirements[102]. The importance of each driver is influenced by a range of factors such as the environment, crop species, genotype and agronomic management practices. As such, it poses a challenge to universally determine which driver and process have the most significant influence on yield. Experimental efforts need to be individually adapted and integrated with modelling to quantify the contribution of each driver under a simultaneous change in water status, temperature and CO_2 to yield across genotypes, environments and management practices.

Several critical processes that must be considered in impact assessment studies are currently poorly understood. Experimental research focusing on the effects of sequential stresses[103], which can substantially influence crop yield through stress acclimation[104] and stress memory[105], has been largely absent in context of climate change impact assessment. Crop experiments typically test a limited number of cultivars, which probably do not encompass the full range of potential responses to multiple climatic stresses. Similarly, phenotypic plasticity in response to climate change and crop yield responses to changes in plant–microbe interactions[106] resulting from combined climatic stressors are underexplored. Despite their inherent uncertainties and limitations, crop models remain indispensable tools for assessing the impacts of climate change and devising effective adaptation strategies.

Relative yield impacts and adaptation

Process-based crop models have been frequently used to simulate the potential impacts of climate change on crop growth and productivity. They also quantify the ability of adaptation strategies to offset the adverse effects of climate change on crop yields. This section outlines the regional disparities in simulated relative yield impacts and the adaptation potential of different management options, not only focusing on wheat, maize and rice, but also extending the analysis to include millet and sorghum, key food security crops in Sub-Saharan Africa.

Yield impacts

Under mild-to-extreme warming climate scenarios without adaptation options, temperature increases are expected to decrease the relative yield of all study crops by −6.2% to −18.3% in tropical and temperate regions (Fig. 2). These impacts are stronger in the tropics (+2% to −37%) than in temperate regions (+4% to −20%) (Fig. 2). For maize, the mean and probability density of yield change is nearly equal between tropical and temperate regions for various levels of warming, but the same does not hold for other crops (Fig. 2). In the tropics, impact projections for rice and sorghum are more variable than in temperate regions, but the average change was similar. However, the projected impacts for millet show a reverse pattern (Fig. 2).

In general, climate change is expected to affect crop yield more adversely in the tropics than in temperate regions, although the difference is not statistically significant[107]. Temperature sensitivity is the primary driver of increased crop yield penalties in tropical regions. Crops grown in these areas are already near their optimal temperature thresholds, and so any additional temperature increase exacerbates the

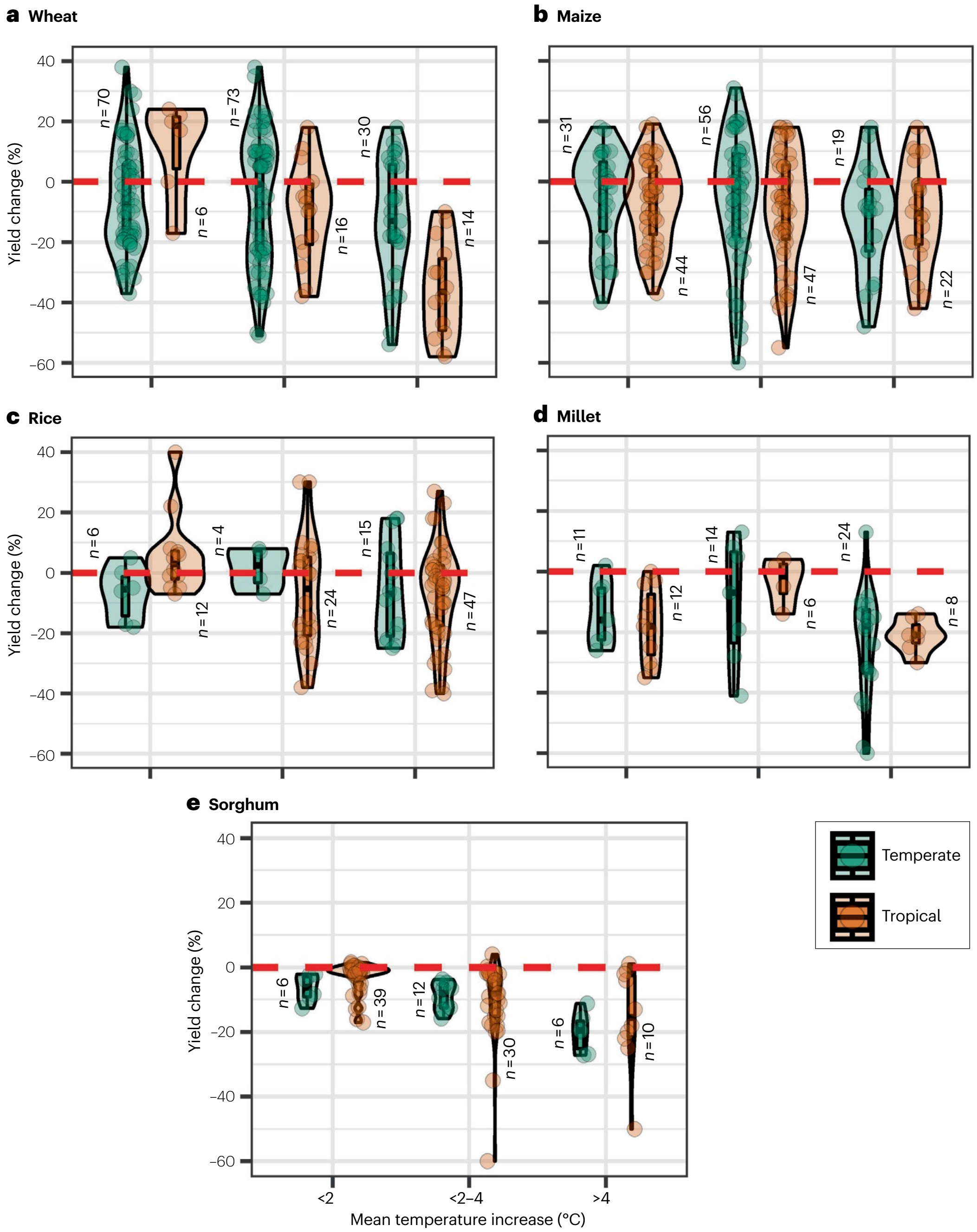

Fig. 2 | Projected yield changes under temperature increase scenarios. **a**, The probability density (violin and boxplot) of yield change relative to baseline without implementing adaptation practices for wheat in temperate (Europe, United States, Andean region and Southern Africa; green) and tropical (Brazil, Central Africa, Central America, East Africa, Sahel, South Asia, Southeast Asia, West Africa and West Asia; brown) regions under three temperature rise scenarios (increase of <2 °C, 2–4 °C and >4 °C)[224]. The violin plot, using kernel density estimation, illustrates the full data distribution including peaks and potential multimodalities. Incorporated boxplots show the interquartile range and median value, summarizing the central tendency and spread of the data. *n* indicates the number of samples. **b**, As in **a**, but for maize[224]. **c**, As in **a**, but for rice[224]. **d**, As in **a**, but for millet[118,139,143,144,224–230]. **e**, As in **a**, but for sorghum[118,139,225,226,229,230]. Under scenarios of mild-to-extreme warming without adaptation measures, all studied crops experience reduced yields, but with pronounced differences between tropical and temperate zones.

negative impact on yields[108]. An additional factor that has a large role is the dominance of C4 crops in the tropics[109], which receive minimal benefits from CO_2 fertilization compared with C3 crops.

There is a notable imbalance in the crops considered in climate change impact assessments: wheat dominates (77%; fractions result from weighting when more than one crop was assessed in a single

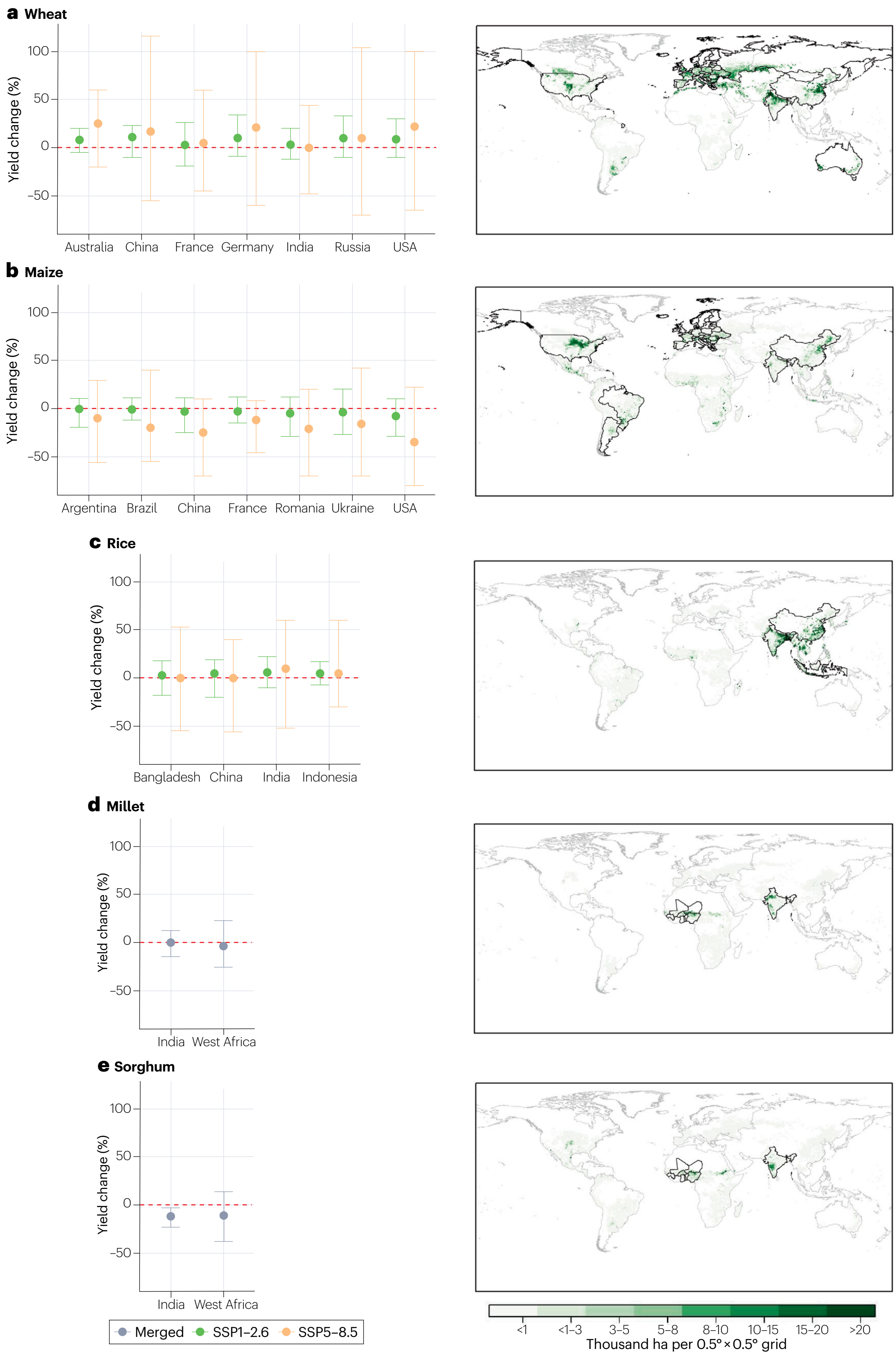
a Wheat
Yield change (%)
100
50
0
–50
Australia
China
France
Germany
India
Russia
USA
b Maize
Yield change (%)
100
50
0
–50
Argentina
Brazil
China
France
Romania
Ukraine
USA
c Rice
Yield change (%)
100
50
0
–50
Bangladesh
China
India
Indonesia
d Millet
Yield change (%)
100
50
0
–50
India
West Africa
e Sorghum
Yield change (%)
100
50
0
–50
India
West Africa
Merged
SSP1–2.6
SSP5–8.5
<1
<1–3
3–5
5–8
8–10
10–15
15–20
>20
Thousand ha per 0.5° × 0.5° grid

Fig. 3 | Projected yield change compared with baseline across main crop-specific growing areas. **a**, Projected changes in country-level wheat yields under low (SSP1-2.6; green) and high (SSP5-8.5; orange) emission scenarios for 2069–2099 relative to 1983–2013, with results derived from a grid-based model ensemble[231]. Circles indicate the mean, and error bars indicate minimum and maximum data values within 1.5 times the interquartile range. The map depicts the extent of growing areas (rainfed + irrigated) at 0.5° × 0.5° resolution for selected regions[232]. **b**, As in **a**, but for maize. **c**, As in **a**, but for rice. **d**, As in **a**, but for millet, with changes relative to various baselines, and results derived from merging of region-specific modelling assessments[117,144,233]. **e**, As in **d**, but for sorghum. Although yield projections for major crop-growing regions vary, potentially substantial positive impacts are expected for wheat in Australia and China, contrasting with generally negative projections for maize, especially in the United States, and mixed outcomes for rice, sorghum and millet.

publication), followed by maize (54%), rice (25%) and a minor contribution from sorghum (4%) and millet (0.8%)[110]. An insufficient number of millet impact projections and the absence of model ensembles hinder a robust conclusion for this crop. Most climate change impact assessments were carried out in Asia (41%) and Europe (22%)[111]; only 9% and 15% were conducted in South America and Africa, respectively[111].

Yield impact projections under sustainable development (Shared Socioeconomic Pathway SSP1-2.6) and high-end (SSP5-8.5) emissions pathways[112] are highly variable in the major crop-growing regions (Fig. 3). Australia (+25% compared with baseline) and China (+25% compared with baseline) are projected to experience the largest positive wheat yield impacts in SSP5-8.5 and SSP1-2.6, respectively. The impacts on wheat yield in other regions vary from +8.5% (SSP1-2.6) to +13.5% (SSP5-8.5) relative to baseline (Fig. 3). As opposed to wheat, mean projected yield impacts for maize are negative (SSP1-2.6, −0.3% to −8%; SSP5-8.5, −10% to −35%) for the main growing areas under climate change, particularly in the United States. Merging the results of different emission scenarios, crop models and time windows in a meta-analysis focusing on the European Union indicated a relatively similar difference between wheat (+14%) and maize (−6%)[113]. The distinct yield response of wheat and maize on shifting from a low-emission to high-emission scenario can be attributed to the minor impacts of elevated CO_2 on photosynthesis efficiency in maize, a C4 crop, compared with substantial positive effects for photosynthesis in wheat, a C3 crop[114].

Projected impacts on rice yield in China, India, Bangladesh and Indonesia range between 0% and 10% for both emission scenarios (Fig. 3). The variability in maize, wheat and rice impacts is substantially greater in the high-end emission scenario owing to the rise in extreme weather occurrences, especially temperature effects[115,116]. Millet (−3%) and sorghum (−11%) yield reduces under climate change relative to baseline in West Africa, whereas sorghum yield improves by 22% in India (Fig. 3). The marginal projected yield decline could be overcompensated by up to 13% by the implementation of common adaptation practices (changes from the business-as-usual scenario) in West Africa[117]. Other projections suggest that intensifying millet and sorghum in West Africa would increase yields under climate change, but also increase yield sensitivity to further temperature rise[118]. Analysing the cumulative change in wheat, maize and rice yield under climate change indicates that Sub-Saharan Africa, Middle East and North Africa are significantly different (greater yield decline) from other regions[107].

Model uncertainties

There is great uncertainty in these process-based crop model projections, related to model structure[119], the consideration of CO_2 fertilization[110], input datasets including general circulation models[120] and data aggregation across spatial scales[121], cultivar differences[122] and methodologies used to develop modelling routines capturing climate signals on crop growth[123]. Variation in model structure accounted for the majority of yield uncertainty (as opposed to climate downscaling and model parametrization) in a crop model ensemble for barley in boreal and Mediterranean climate zones[124]. However, a systematic review across the crops and environments indicates that the input uncertainty is the most frequently considered source of uncertainty[125].

The potential of process-based models is also limited by the lack of implementation of several crucial processes. For instance, it is common for models to use air temperature rather than canopy temperature, which can lead to an over- or underestimation of heat impact on yield[126]. An additional limitation in crop models arises from the absence of specific processes in crop models such as stress acclimation[127] and stress memory. Furthermore, pest and disease effects[128] are generally not considered, which is particularly relevant for low-input systems. Finally, there is a reliance on air temperature rather than canopy temperature for simulating crop development, and root–soil interactions are often oversimplified as a 1D structure, ignoring their 3D nature[129].

Most crop models are calibrated based on baseline climate and are used to evaluate yield responses to substantially warmer, drier or wetter conditions. If the model is not sensitive to dependencies on temperature, CO_2 and soil water conditions, projected responses could be inaccurate. Moreover, several crop growth and development traits, including yield components, are highly susceptible to interactions between genotype and environment[108]. Crop model limitations in accurately reflecting yield component variations could be related to the models' lack of ability to capture the differences in expression of those traits across diverse environments[129]. This inability could introduce a high degree of uncertainty in the results of these models when they are used to analyse the impact of climate change on yield.

Adaptation

Adaptation (changes from the practices in the baseline) is defined as an activity that alleviates the negative or accentuates the positive impacts of climate change on crop yield and production[111]. The effectiveness of adaptation strategies varies with latitude and the type of adaptation option and emission scenario for wheat, maize and rice, explored here in 2080 (Fig. 4). Among published studies considering adaptation strategies, nutrient management (the change in the dosage, type and timing of fertilizer) represents 32% of studies, followed by irrigation (29%), change in cultivar (17%) and sowing dates (17%)[111].

Irrigation and nutrient management as individual adaptation options and in combination (−5% to +40% compared with baseline yield) with other strategies (sowing date, and adapted cultivars) (−18% to +15%) can offset negative impacts of climate change on a global scale (Fig. 4). In practice, however, the growing demand for irrigation water has become more challenging to address owing to climate change, placing a substantial burden on available water resources[130]. Irrigation presents additional challenges as it is also linked to soil salinization[131], nutrient leaching and the need for substantial infrastructure investments[132]. The sustainability and feasibility of promising adaptations, such as irrigation, depend on various factors like the environment[133,134].

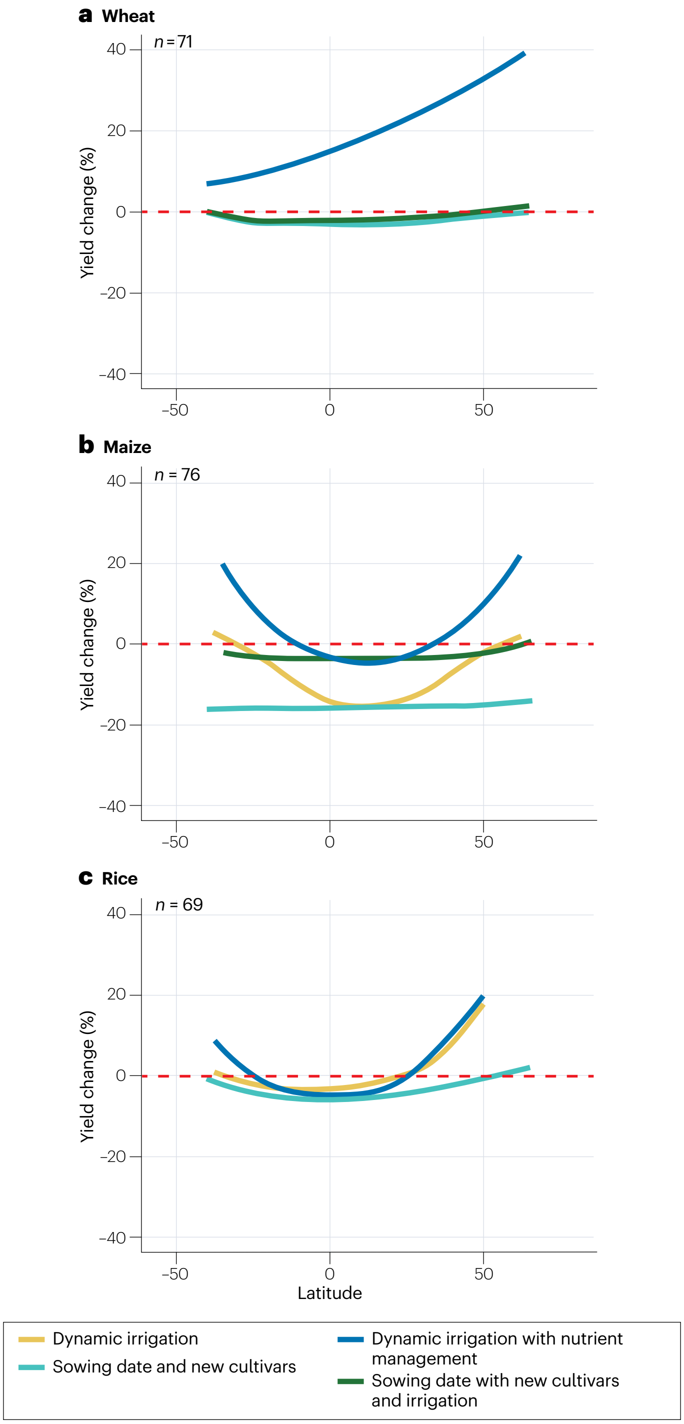

Fig. 4 | Mean relative yield change in response to climate change under various adaptation practices. a, Change in wheat yields by latitude under various adaptation practices in 2080 relative to 1960–1990. Yields are derived from multiple simulations by crop models across varied projected future windows and emission scenarios relative to the baselines[107]. The lines in each panel indicate the best regression fit of data extracted from individual assessments, aggregated to the country level as the centroid of each country[107]. *n* indicates number of countries. **b**, As in **a**, but for maize. **c**, As in **a**, but for rice. Irrigation and nutrient management are particularly effective adaptation strategies, potentially more so than altering sowing dates and using adapted cultivars, in mitigating the negative impacts of climate change on wheat, maize and rice yields by 2080, albeit with latitudinal and crop variations.

Other adaptation practices, such as earlier sowing dates, have also shown notable potential to cope with heat in the case of Australian wheat[135]. Additionally, new cultivars have demonstrated robust potential to alleviate the adverse effects of climate change on crop yields in China[136]. Similarly, the long-term breeding advancements in Western Europe under optimal management have enhanced the adaptability of modern wheat cultivars to low-rainfall conditions under low-input management regimes[137]. The effect of changing cultivars on climate change adaptation has not been extensively examined in impact assessments, as relevant cultivar panel data for crop model calibration is often unavailable. Other robust yet less-examined adaptation practices, such as the diversification[138] of cropping systems, can also considerably enhance yield resilience to climate change.

Wheat yield exhibits the best potential for adaptation options as a temperate C3 cereal across latitudes. Maize and rice yield would not be fully compensated for by adaptation strategies in the tropics (Fig. 4). In light of the limited number of large-scale adaptation studies available for sorghum (five countries[139–142]) and millet (four countries[143,144]) and difference in projected future windows, a fair comparison with other crops (>60 countries) is not possible. Additional research is greatly needed to perform a comprehensive comparison of the efficacy of adaptation strategies among different crops. The few available results indicate that irrigation, change in sowing dates and changes of cultivars might reverse the climate change impacts on yield and could also assist pest management[145]. Yet adaptation practices suffer from implementation difficulties[146] and serious concerns related to available water resources[147], sociocultural barriers[148], environmental consequences[149] and sustainability[150]. It is therefore challenging to generalize which adaptation strategy can provide the most promising outcome globally. Instead, implementation of regional and crop-specific strategies would be likely to be more effective. Targeted implementation can be done by integrating crop with socioeconomic models that incorporate multiscale trade-offs among a variety of socioeconomic and environmental variables.

Implications for global production

In high-latitude regions, expected warmer temperatures and CO_2 fertilization could have positive impacts on yield, which could, in turn, have a positive impact on production[151]. However, intensifying of weather extremes in those areas would lead to increased yield variability and fluctuating global market conditions, causing uncertainty for main producers, inflating prices and restricting exports to food-insecure regions, particularly in the case of synchronous shocks[152]. Climate extremes affected many crop exporters in 2007–2008, exacerbating the structural causes of world food prices[153] and even triggering price explosions[154] and political instability[155] in some regions.

Crop production in lower latitudes might suffer severely from climate change[156], particularly for C4 crops such as maize, which are less positively affected by CO_2 increase. The projected increase in cropping frequency (number of production seasons per year) at higher latitudes would only partially offset greater decline in lower latitudes (such as Brazil and Sub-Saharan African countries), leading to a global production decline (−4.2 ± 2.5% in a high-emissions scenario, SSP5-8.5) by 2050[157]. In a high-emissions scenario (RCP8.5), without implementation of adaptation strategies, production of four major crops (wheat, maize, rice and soybean) at the global scale was projected to reduce by approximately 2%[158]. This production is far below the production increment required to meet food demand for the growing population with changing diets[159], affirming the necessity of swift and effective adaptations[160].

Crop production is not solely driven by yield, but also by the extent of harvested area, changes in consumption pattern[161] and food waste[162]. Therefore, quantifying the effects of climate change on production is more complex than merely analysing yield responses[157], as both crop production and yield would be affected by climate change through distinct mechanisms[163]. Shifts in harvested area in response to climate change are generally gradual owing to socioeconomic constraints[164], rapid changes in policies[165] (such as the use of chemicals in Europe) and subsidies[166] (such as durum wheat insurance in Italy). A 5.6-million-km^2 expansion in suitable growing areas is projected under climate change by 2100, in high latitudes (primarily in Canada, China and Russia)[167]. However, the intensification opportunities for most of the current croplands will be severely restricted by 2050[156].

Most impact assessments have assumed no change in the geographical distribution of cropping areas, which seems to be a strong oversimplification of reality[168]. A historical global-scale analysis (1973–2012) showed that crop immigration to more temperature-favourable areas (including crop substitution) and irrigation expansion alleviated the damaging impacts of rising temperatures (both for mean and heat episodes) on wheat, maize and rice, aiding yield and crop production[164]. Such a strategy might not be feasible or sustainable in the future[169]. More than a 5% expansion in irrigated areas would be needed at lower latitudes by 2050 to counterbalance climate-driven crop production loss at global scale[157]. This expansion would be challenging, as those areas are already suffering from droughts[170] and from lack of resources to invest in irrigation infrastructure[171]. In regions with sufficient irrigation water resources in the current climate, there is still a risk of progressive soil salinization, as increased water demand due to climate change could mandate the use of more brackish water to meet the growing need[172]. In addition, the availability of land for a further shift is limited, and the negative consequences of such a shift, such as losing biodiversity, water quality and soil carbon storage, would be severe and inevitable[7,173,174].

Summary and future perspectives

Climate change impacts on yield vary between the crop, region and adaptation strategies. Compared with other crops, wheat demonstrates the best prospects for positive responses to climate change, largely through CO_2 fertilization and adaptation strategies. Maize, sorghum and millet are only positively affected by elevated CO_2 when crops are exposed to mild-to-moderate drought and tend to be less negatively affected by heat stress than wheat and rice. Unfortunately, there is no single universally feasible solution to fully mitigate the negative impacts of climate change on yield. However, a combination of region-specific adaptation practices could offset yield loss, or even reverse it, particularly for crops grown in temperate regions. Irrigation and nutrient management are the most promising adaptation options, but negative climate impacts in tropical regions would not be fully offset by any adaptation option. Moreover, extreme weather events represent considerable threats to future food security at the global scale. To better predict and mitigate climate change impacts on crops, the shortcomings in climate change impact assessments must be overcome, including data deficiencies, limited process understanding and implementation into crop models, and the need for improved integrated assessment tools.

Availability and quality of large-scale and high-resolution climate, crop, soil and management data are regionally variable. Data limitation in Africa contributes to a large degree of uncertainty for climate impact studies[175,176] — Asia and Africa are covered by only 12% of available climate stations, despite consisting of close to half the land mass of the Earth[177] and having substantial diversity in management practices[178]. Moreover, uncertainty in soil data is larger than the climate signal in yield projections under low-input cropping systems[179]. The lack of high-resolution cultivar-specific and agronomic management data is a challenge in large-scale yield projections that are forced using aggregated inputs[180]. Aggregation eliminates spatiotemporal heterogeneity of simulations within the simulation units and creates bias[121]. Uncertainties in simulated impact stem from data quality and other uncertainties propagating through integrated climate assessment into economic models[181]. High spatiotemporal resolution of crop phenology[182], leaf area expansion[183], crop water status[184] and nutrient status[185] is needed, and should be widely accessible through large-scale sensing technologies and integrated into crop models through data assimilation[186].

New experiments that span from the organ to the canopy scales in both controlled environments and field settings are needed to understand yield responses to multiple stressors. Newly established high-throughput phenotyping platforms, such as PhenoSphere[187], have been constructed to manipulate temperature, water and CO_2 levels for a broad array of cultivars, providing sub-daily monitoring measures for the growth and development of both aboveground and belowground organs, and can deliver a means for tackling these gaps in understanding. Furthermore, increased investment in fusing modelling approaches and experimentation[188–191] can provide a way to disentangle and quantify yield responses to individual yield-driven variables. Integrating crop models with data-driven algorithms, including machine learning, can offer hybrid modelling solutions that effectively capture interactions between multiple stress factors that affect crop growth processes[189].

Given a rising potential for pest and disease damage under climate change and the limited ability of crop models to account for biotic stresses, the call to integrate these effects into crop models is increasing[192]. Advances in integration have focused on modelling the life cycle of biotic stressors in conjunction with crop phenology, rather than general routines that use empirical functions that reduce yield (through decreased photosynthesis or leaf area) at a fixed rate adjusted by temperature or soil moisture[193]. This approach enables more accurate representation of the coincidence between pest activity and sensitive growth stages of crops as well as improved modelling of resource competition. It can be conceptualized in a two-way feedback system that interconnects insect pests and crops driven by temperature, water status and atmospheric CO_2 concentration[194].

Models often overlook the interactions of multiple stressors (simultaneously or in a row) on crop growth, thereby providing an implausible yield response to climate change[189]. Indeed, model structure contributes significantly more to projected yield uncertainty than climate projections and model parameterization[124]. Yield projection uncertainties could be better addressed by design and implementation of combined model and experimental studies for crops and cultivars grown in low-input systems[195] and under multiple stresses[189] that reflect the yield response to a simultaneous change in climate variables[196]. The CO_2 compensatory potential in impact assessments warrants further investigation, as FACE experiments (Box 1) used for model calibration can underestimate the yield enhancement by about 30% owing to rapid fluctuation of CO_2 concentration (10-fold greater than in nature) during the growing season[197]. Previous studies based on FACE have suggested that crop models overestimate CO_2 impacts on yield, but this has been challenged[198]. Further encouraging the use of targeted model ensembles also deserve attention to minimize structural model uncertainty[199].

Model ensembles outperform individual models in projected yield response to climate change[122,200,201]. The organization of model ensembles is complex and time-consuming, making the selection of an appropriate combination crucial. The outcomes of the AgMIP-wheat activity, a leading crop modelling intercomparison, showed that increasing the number of models in an ensemble significantly improved the model ensemble's accuracy up to 10 models, but showed only marginal improvement beyond that[199]. Lessons learned from the climate modelling community indicated the need for a systematic model selection protocol along with calibration protocols[202] to ensure equal weighting of models with different structures, rather than merely pooling as many models as possible in a random manner. Using probabilistic data-driven approaches such as machine learning may significantly improve the parametrization performance by addressing spatiotemporal heterogeneity in cultivars and management inputs for large-scale assessments[203–205].

There is also a critical need to integrate biophysical yield assessments with economics and environmental models in order to consider multiscale trade-offs with a range of socioeconomic and environmental variables, such as nitrogen losses, soil organic matter change, nutritional quality and yield suitability[181,206–208]. Integrated assessments would also assist in quantifying the socioeconomic consequences and feasibility of adaptation options across various regions. Results highlight the importance of enhancing interdisciplinary research to address uncertainties in econometric damage forecasts, pinpoint key socioeconomic impacts and emphasize the necessity of a structured model intercomparison concerning economic consequences of climate change on cropping systems for future research[209]. On-farm management data collection, complemented by large-scale observation networks, can support our understanding of yield response to extreme events, particularly under suboptimal management[210]. This is vital to project how climate risk, not only average climate, will affect future crop yield[210].

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Author contributions

H.W. conceived the idea and outlined the structure. E.E.R. researched data for the article, prepared the visualizations and wrote the article. All authors contributed substantially to the discussion of the content, and reviewed and/or edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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