Classification: Biological Sciences/Agricultural Sciences

Title: Global wheat production with 1.5 and 2.0°C above pre-industrial warming

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Keywords:

1.5 and 2.0°C HAPPI scenarios, wheat yields, climate impacts, food security, extreme low yields, yield variability.

Abstract

Efforts to limit global warming to below 2°C in relation to the pre-industrial level are under way, in accordance with the 2015 Paris Agreement. However, most impact research on agriculture to date has focused on impacts of warming >2°C on mean crop yields. Here we used a multi-crop and multi-climate model ensemble over a global network of sites developed within the Agricultural Model Intercomparison and Improvement Project (AgMIP) Wheat Team to represent major rainfed and irrigated systems. Results show that projected global wheat production will change by -2.3% to 7.0% under the 1.5 scenario and -2.4% to 10.5% under the 2.0 scenario, compared to a baseline of 1980-2010, when considering changes in local temperature, rainfall and global atmospheric CO_2 concentration, but no changes in management or wheat cultivars. The projected impact on wheat production varies spatially; a larger increase is projected for temperate high rainfall regions than for moderate hot low rainfall and irrigated regions. Grain yields in warmer regions are more likely to be reduced than in cooler regions. Despite mostly positive impacts on global average grain yields, the frequency of extremely low yields (bottom 5 percentile of baseline distribution) will increase under both warming scenarios for the hot growing environments that supply 50% of global wheat. The projected global impact of warming <2°C on wheat production are therefore not evenly distributed and will affect regional food security across the globe as well as food prices and trade.

Significance Statement

Agricultural production is vulnerable to climate change. Limiting global warming to below 2°C in relation to the pre-industrial level, has been set as the main goal for global temperature change with the 2015 Paris Agreement. Understanding impacts of up to 2°C warming on global and regional crop production is critical for policy makers, agriculturalists and crop breeders to ensure regional and global food security. We show that despite a global positive grain yield impact, some regions will have wheat yield declines under 1.5 and 2°C warming scenarios. Moreover, the frequency of extremely low yields will increase for half of the wheat producing regions. The projected unevenly distributed global impact on wheat production will affect regional and global food security.

Global warming of 2.0°C above pre-industrial levels has been declared the upper acceptable limit for global mean surface temperature change in the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change in Paris, December 2015 (1). Agricultural production and food security is one of many sectors already affected by climate change (2, 3). Wheat is one of the most important food crops, providing a substantial portion of calories for about four billion people (4). Wheat production systems' response to warming can be substantial (5-7), but restricted warming levels of < 2.0°C global warming of above pre-industrial are underrepresented in previous assessments (3). Thus, assessing the impact of 1.5 and 2.0°C global warming of above pre-industrial conditions on crop productivity levels, including the potential benefits of associated CO_2 fertilization, and the likelihood of extremely low yielding wheat harvests is critical for understanding the challenges of global warming for global food security.

Previous impact assessments lacked details for < 2°C of warming and did not focus sufficiently on extreme events (3, 8). In particular, studies on impact of 1.5°C global warming on wheat production at a global and regional scale are missing. Process-based crop simulation models, as tools to quantify the complexity of crop growth in its interaction with climate, soil, and management practice, have been widely used in climate change impact assessments at different spatial scales (3, 8-10), including multi-model ensemble approaches (7, 11, 12). Here, we applied a global network of 60 representative wheat production sites (Table S1) and an ensemble of 31 crop models (Table S2) developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP) Wheat Team (7, 13) with climate scenarios from five Global Climate Models (GCMs) from the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) project (14) to evaluate the impacts of the 2015 Paris Agreement range of global warming (1.5°C and 2.0°C warming above the pre-industrial period, referred hereafter as '1.5 scenario' and '2.0 scenario') on global wheat production.

Results and Discussion

Impacts of 2015 Paris Agreement compliant warming. Compared with the present baseline period (1980 to 2010; 0.67 ºC above pre-industrial) used in the wheat model configuration, the HAPPI scenarios gave projected temperature increases of 1.1ºC to 1.4ºC [25% to 75% range of 60 locations] for the 60 wheat-growing locations spread over the globe under the 1.5 scenario, and 1.6ºC to 2.0ºC under the 2.0 scenario (Fig. S1). Atmospheric CO_2 concentration will be 63 and 127 ppm higher under the 1.5 and 2.0 scenario compared to the baseline (360 ppm), respectively. Wheat growing seasons (that is, simulated sowing to maturity periods) typically warm about 0.5°C less than the annual mean under the HAPPI scenarios: 0.7ºC to 1.0ºC [25% to 75% range of 60 locations] under the 1.5 scenario, and 1.0ºC to 1.5ºC under 2.0 scenario (Fig. S2). In the HAPPI scenarios, annual rainfall is projected to increase in most of the 60 locations under both warming scenarios (Fig. S3) (15).

Based on baseline climate conditions (1980 to 2010), we categorized the 60 wheat production sites into three environment types (temperate high rainfall, moderately hot low rainfall, and hot irrigated) (Fig. S5). Across these environments, increasing temperatures reduce wheat crop duration due to accelerated phenology. As a consequence, the reference crop duration declines with future climate change scenarios. For temperate high rainfall and moderately hot low rainfall regions, simulated cumulative crop duration (sowing to maturity) evapotranspiration and growing season rainfall decreased slightly under the 1.5 and 2.0 scenario (Fig. S6). In hot irrigated regions, simulated cumulative rainfall decreased (in average by -2.0 and -5.4 mm under the 1.5 and 2.0 scenario) and evapotranspiration decreased (in average by -16 and -25 mm) under both warming scenarios during the crop duration. The decrease in cumulative rainfall and evapotranspiration was mostly due to shorter crop duration (in average by -4.9 and -7.2 days) due to warming (Fig. S6). Heat stress days (daily maximum air temperature > 32ºC) (16) during grain filling already occurs in almost all regions, but their frequency increases under the HAPPI scenarios, particularly in moderately hot low rainfall (in average by 1.0 and 1.6 days) and hot irrigated regions (in average by 1.8 and 2.5 days; Fig. S6). Similar projected increases in heat stress events during wheat grain filling have been found in southern low rainfall European sites (17), but using a different scenario framework and a more severe temperature increase.

Simulated impacts on wheat yields of the 1.5 and 2.0 scenario are negatively correlated with crop season mean temperature (Fig.1A), suggesting that cooler regions will benefit more from moderate warming. For example, most regions with crop growing-season mean temperature (sowing to maturity) < 15°C will have mostly positive yield changes, while for growing-season mean temperature > 15°C, any increase in temperature will reduce grain yields (Fig.1A) despite the growth-stimulation from elevated atmospheric CO_2 concentration (18). Generally, regions which produce a largest proportion of global wheat are projected to have small positive yield changes under the 1.5 and 2.0 scenario, but there are exceptions such as India, the second largest wheat producer (Fig. 1).

Recent studies have shown that local point-based (as in our study), global gridded based, and statistical regression based methods, give similar estimates of impacts of temperature increase on crop yield, both at the regional and global scales (5, 19), suggesting that the local point-based method is robust to upscale from the local point simulations to regional and global responses. When scaling up from the 60 locations, we found that wheat yields in about 80% of wheat production areas will increase under 1.5 scenario, but usually by less than 5% (Fig. 2). Largest positive impacts under 1.5 scenario are projected for USA (6.4%), the third largest wheat producer in the world. Loss in wheat yields under the 1.5 scenario is suggested mostly in central Asia, Africa and southern America (Fig. 2), countries with generally high growing season temperature, shorter crop duration, and more heat-stress days during grain filling (Fig. S7). Further yield declines in these countries are expected with the 2.0 scenario, including in large wheat producing countries like India (-2.9%; Fig. 2).

Analysis for the three environment types projects a larger yield increase for temperate high rainfall regions (3.2% and 5.5% under 1.5 and 2.0 scenario, respectively) than for moderately hot low rainfall (2.1% and 2.4%) but a decline in hot irrigated regions (-0.7% and 0.02%; Fig. S8). These positive values contrast with the negative trend found across a meta-analysis, with a large uncertainty range, with local temperature change of 1.5 to 2.0^{o}C, despite positive effects from elevated atmospheric CO_2 concentration (8).

Aggregated to the globe, wheat production on current wheat-producing areas is projected to increase by 1.9% (-2.3% to 7.0%, 25th percentile to 75th percentile) under the 1.5 and by 3.3% (-2.4% to 10.5%) under 2.0 scenario (Fig. 3A). Under the Representative Concentration Pathway 8.5 (RCP8.5) for the 2050s, with a global mean temperature increase of 2.6^{o}C above pre-industrial, global production grain yields are suggested to increase by 2.7% (20), highlighting the non-linear nature of climate change impact. Using four independent methods (5, 19), global wheat yields had been previously projected to decline by an average of -5.0% for each increase in 1.0^{o}C global warming, but in the absence of concomitant atmospheric CO_2 concentration increase. Similar findings have been reported for various typical wheat cultivation regions in Europe when applying systematic climate sensitivity analysis (21). Here, most of the increases in global wheat production under the 1.5 and 2.0 scenario are attributed to a CO_2 fertilization effect (Fig. 3B), consistent with field observations in a range of growing environments (18, 22), and with a rate of 0.06% yield increase per ppm CO_2 derived from a meta-analysis of simulation results (8). The CO_2 fertilization effect is often found to dominate model-based projections of future global wheat productivity (6, 23, 24), but with substantial uncertainties and regional differences (25-27). The relatively low warming levels of the HAPPI scenarios (0.6 and 1.1°C above 1980-2010 global mean temperature) but high increases in CO_2 mixing ratios suggests that CO_2 fertilization effects also dominate here (18, 22), but could be less, if nitrogen is limiting growth.

More variable yields in hot and dry areas. While the 30-year average yield is projected to increase under the 1.5 and 2.0 scenario across many regions, the risk of extremely low yields may increase, especially in hot-dry environments. Extreme low wheat yielding seasons can impact the livelihood of many farmers (28), but also disturb global markets (e.g. Russian Heat Wave in 2010) (29), or even destabilize entire regions of the world (e.g. Arab Spring) (30). The probability of extreme low yields (yields lower than the bottom 5-percentile of the 1981-2010 distribution) will increase in more than half of the moderately hot low rainfall regions under the 1.5 and 2.0 scenario (Fig. 4). For hot irrigated environments, the probability of extreme low yields will increase in 65% of the regions. In some regions, the likelihood of extreme low yields will increase up to 5-times, that is from 5% to 31%, e.g. in Sudan and parts of Canada, Kazakhstan and India. Climate scenarios used for this study included monthly mean changes and shifts in the distribution of daily events within a season but did not include changes in interannual variability; these changes are therefore largely the result of warmer average conditions pushing wheat closer to damaging biophysical thresholds. A recent study based on the HAPPI 1.5 and 2.0 scenario also identified an increased frequency of interannual drought conditions in regions with declining or level precipitation totals (14), although skewness toward drought in the interannual distribution was small and highly geographically variable. Hence, despite mostly positive impacts on average yields, projections suggest that the frequency of extreme low yields will increase under either scenario for hot growing environments (including low rainfall and irrigated regions), that currently supply 50% of global wheat (31). Similarly, an increase in the frequency of crop failures has been shown with 1.5^{o}C global warming above the pre-industrial period for maize, millet and sorghum in West Africa (32).

The probability of extreme low yields for the three environment types is correlated with the inter-annual variability of wheat yields (coefficient of variability; Fig. S9). Even moderate warming of 1.5 to 2.0°C above pre-industrial is projected to increase the inter-annual variability of simulated grain yields in most hot irrigated regions, but to reduce the inter-annual variability of simulated grain yields in most of the temperate high rainfall regions. For example, inter-annual variability of simulated grain yields is projected to increase by 61% to 92% in some parts of India, but to decline by 34% to 44% in parts of Kazakhstan, under 1.5 and 2.0 scenario, respectively. A similar increase in grain yield variability for higher warming scenarios for wheat, rice and maize has been suggested in a previous meta-analysis (8).

Global warming will also affect weeds, pests and diseases, which are not considered in our analysis, but could significantly impact crop production (33-35).

Possible agricultural land use changes were not considered here, which could increase production (36), but also accelerate further greenhouse gas emissions (37), adding to the uncertainty of future impact projections. Wheat yields have been stagnating in many agricultural regions (38-40), and investments in agricultural research and development are desperately needed to keep up with growing food demand (41), including the development of breeding and agronomic adaptation strategies to combat negative impacts from climate change (42, 43). Fertilizer-driven intensification is also projected to increase inter-annual yield variability in many regions of the world (unpublished data), which would amplify the climate-driven increase in yield variability projected here. Shifting agriculture pole-wards has been considered, but might not be always possible or feasible for adapting to increasing temperature due to land use and land suitability constrains. Measures like change in sowing date and irrigation management, improved heat- and drought-resistant cultivars, reduced trade barriers, and increased storage capacity (44) will be necessary to adapt to changes in temperature and precipitation for improving food security. However, since the largest estimated yield losses and increased probability of extreme low yields occur in tropical areas (hot with low temperature seasonality) and under irrigated systems, the above mentioned measures would probably not be sufficient, therefore challenging to find effective incremental solutions, and pushing for a deeper transformation of the agricultural systems (8, 11).

The mean impact of 1.5 and 2.0°C warming above preindustrial on global wheat production is projected to be small but positive. However, the uneven distribution of impacts across regions, including projected yield reductions in regions with rapid population growth (e.g. India), the increased probability of extreme low yields and a higher inter-annual yield variability, will be challenging for food security and markets, particularly in hot growing regions.

Materials and Methods

Climate change impact assessments were conducted using an ensemble of 31 wheat crop models, each calibrated with local cultivars and considering region-specific soils and crop management for 60 representative wheat growing locations developed by the AgMIP-Wheat team (7). Climate scenarios here are consistent with the AgMIP Coordinated Global and Regional Assessments (CGRA) 1.5 and 2.0 ºC World study (15, 45, 46). Climate changes from 100-member climate model ensemble mean projections of the +1.5 and +2.0ºC Worlds from the Half a Degree Additional Warming, Prognosis and Projected Impacts project (HAPPI) (14) are combined with local weather information (provided by AgMERRA) (47) to generate driving climate scenarios from five GCMs for each location (48). This large climate × crop model setup enabled a robust multi-model ensemble estimate (49) as well as analysis of spatial heterogeneity (5) and inter-model uncertainty. HAPPI anticipates atmospheric CO_2 mixing ratios for 1.5 scenario (1.5°C above the 1860-1880 pre-industrial period = ~0.6°C above current global mean temperature) (50) and 2.0 scenario (2.0°C above pre-industrial = ~1.1°C above current global mean temperature) at 423 ppm and 487 ppm (CO_2 in the center of the 1980-2010 current period is 360 ppm). Uncertainty around these CO_2 levels from climate models' transient and equilibrium climate sensitivity is not explored here, although the CO_2 concentration for 2.0°C warming may be slightly overestimated (15).

As in previous AgMIP Wheat assessments, changes in mean solar radiation were not considered here other than small effects as the number of precipitation days changes (48). Model simulations were carried out by individual modelling groups. Hierarchical clustering on principal components based on climate variables for 1981 to 2010 was applied to classify the 60 representative global wheat growing locations, into environment types (Fig. S5).

Acknowledgements

We thank the Agricultural Model Intercomparison and Improvement Project (AgMIP) for support. B.L., L.X. and Y.Z. were supported by the National High-Tech Research and Development Program of China (2013AA102404), the NSFC-RS International Cooperation and Exchanges Project (31611130182), the National Research

Foundation for the Doctoral Program of Higher Education of China (20120097110042), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD). S.A. and B.K. received support from the International Food Policy Research Institute (IFPRI) through the Global Futures and Strategic Foresight project, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the CGIAR Research Program on Wheat. PM, D.R., and D.W. acknowledge support from the FACCE JPI MACSUR project (031A103B) through the metaprogram Adaptation of Agriculture and Forests to Climate Change (AAFCC) of the French National Institute for Agricultural Research (INRA). F.T. and Z.Z. were supported by the National Natural Science Foundation of China (41571088, 41571493 and 31561143003). R.R. acknowledges support from the German Federal Ministry for Research and Education (BMBF) through project ‘Limpopo Living Landscapes’ project (SPACES program; grant number 01LL1304A) . Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) Designing Future Wheat project [BB/P016855/1]. L.X. and Y.G. acknowledge support from the China Scholarship Council. M.B and R.F. were funded by JPI FACCE MACSUR2 through the Italian Ministry for Agricultural, Food and Forestry Policies and thank A. Soltani from Gorgan Univ. of Agric. Sci. & Natur. Resour. for his support. T.P. and F.T. received financial support from the FACCE MACSUR project funded through the Finnish Ministry of Agriculture and Forestry (MMM) and from the Academy of Finland throughthe projects NORFASYS (decision nos. 268277 and 292944) and PLUMES (decision nos. 277403 and 292836). K.C.K. and C.N. received support from the German Ministry for Research and Education (BMBF) within the FACCE JPI MACSUR project. S.M. and C.M. acknowledge financial support from the MACMIT project (01LN1317A) funded through BMBF. G.J.O. acknowledge support from the Victorian Department of Economic Development, Jobs, Transport and Resources, the Australian Department of Agriculture and Water Resources. P.K.A. was supported by the multiple donors contributing to the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). B.B. received financial support from USDA

NIFA-Water Cap Award 2015-68007-23133. F.E. acknowledges support from the FACCE JPI MACSUR project through the German Federal Ministry of Food and Agriculture (2815ERA01J) and from the German Science Foundation (project EW 119/5-1). J.R.P. acknowledges the supportof the Labex Agro (Agropolis no. 1501-003). La. T.P. and F.T. received financial support from from the Academy of Finland through the project PLUMES (decision nos. 277403 and 292836) and from Natural Resources Institute Finland through the project ClimSmartAgri.

Footnotes

‡The views expressed in this paper are the views of the author and do not necessarily represent the views of the organization or institution, with which he is currently affiliated.

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Figure legends

Fig. 1. Projected Impact of the 1.5 and 2.0 scenario on wheat grain yield and crop duration. Simulated change in grain yield versus (A) growing season mean temperature and (B) mean growing season duration (sowing to maturity) for the 1.5 (orange) and 2.0 (dark cyan) scenario (HAPPI). (C) Differences in relative change in grain yield between the 1.5 and 2.0 scenario versus growing season mean temperature for 60 representative wheat producing global locations. Relative changes of grain yield were the median across 31 crop models and five GCMs, calculated with simulated 30-year (1981-2010) mean grain yields for baseline, the 1.5 and 2.0 scenario (including changes in temperature, rainfall and atmospheric CO_2 concentration) using region-specific soils, cultivars and crop management. The size of symbols indicates the production represented by each location (using 2014 FAO country wheat production statistics). The vertical and horizontal range crosses indicate the median 25-75% uncertainty range of relative change in grain yields, growing season mean temperature, crop duration across the 31 crop models and five GCMs, respectively. In (A), r^2 of linear regressions were 0.32 and 0.33 under 1.5 and 2.0 scenario, respectively ($P < 0.001$).

Fig. 2. Simulated multi-model ensemble projection of global wheat grain production by country under the 1.5 and 2.0 scenario (HAPPI). Relative climate change impacts on grain production under **(A)** the 1.5 and **(B)** 2.0 scenario (including changes in temperature, rainfall and atmospheric CO_2 concentration) compared with the 1981-2010 baseline. Impacts were calculated using the average over 30 years of yields and the medians across 31 models and five GCMs, using region-specific soils, current cultivars and crop management. Impacts from 60 global locations were aggregated to impacts on country production by weighting the irrigated, high rainfall, and low rainfall production, based on FAO wheat production statistics.

Fig. 3. Simulated global impacts of climate change scenarios on wheat production. Relative impact on global wheat grain production for (**A**) 1.5 and 2.0 warming scenarios (HAPPI) with changes in temperature, rainfall and atmospheric CO_2 concentration. Atmospheric CO_2 concentration for the 1.5 and 2.0 scenario were 423 and 487 ppm, respectively. (**B**) +2°C (360 ppm CO_2 +2^{o}C) and +4°C (360 ppm CO_2 +4^{o}C) temperature increase for the baseline period with historical atmospheric CO_2 concentration (360 ppm CO_2) and elevated CO_2 (550 ppm CO_2) for no temperature change (Baseline), +2°C (550 ppm CO_2 +2^{o}C) and +4°C (550 ppm CO_2 +4^{o}C). Impacts were weighted by production area (based on FAO statistics). Relative change in grain yields were calculated from the mean of 30 years projected yields and the ensemble medians of 31 crop models (plus five GCMs for HAPPI scenarios) using region-specific soils, cultivars, and crop management. Error bars are the 25th and 75th percentiles across 31 crop models (plus five GCMs for HAPPI scenarios).

Fig. 4. Projected impacts of the 1.5 and 2.0 scenario on the probability of extreme low wheat yields. **(A)** Grain yield distribution at three locations representative of the three main types of environments (see below) for the 1981-2010 baseline and for the 1.5 and 2.0 scenario (HAPPI; including changes in temperature, rainfall and atmospheric CO_2 concentration). The yield distribution at the 60 global sites is given in Fig. S10, Fig. S11, and Fig. S12. The vertical dashed lines indicate the value of extreme low yields (defined as the lower 5% of the distribution) for the baseline. **(B)** Probability of extreme low yield (≤ 5% of the baseline distribution) for the 1.5 (circles) and 2.0 (triangles) scenario at 60 representative global wheat growing locations for clusters of temperate high rainfall or irrigated locations (green; 26 locations), moderately hot low rainfall locations (yellow; 20 locations), and hot irrigated locations (red; 14 locations). **(C)** and **(D)** Probability of extreme low yields for each type of environment for the 1.5 and 2.0 scenario, respectively. Horizontal dashed lines are the probability of extreme low yield for the baseline (defined as the bottom 5% of the baseline distribution). Horizontal thick solid lines are the median probability of extreme low yield. The circles are the 60 global locations shown in (B), their size indicates the production

represented at each location (using FAO country wheat production statistics) and their color the growing season mean temperature at each location for the 1.5 and 2.0 scenario. Within each environment type, the circles have been jiggled along the horizontal axis to make it easier to see locations with similar probability values. The shaded areas show the distribution of the data. Numbers above each box are the mean yields for the baseline period and in parenthesis the average yield impacts of the 1.5 and 2.0 scenario compared with the 1981-2010 baseline yield. See Supplementary Material and Methods for more details on clustering of wheat growing environments.

Fig. 1

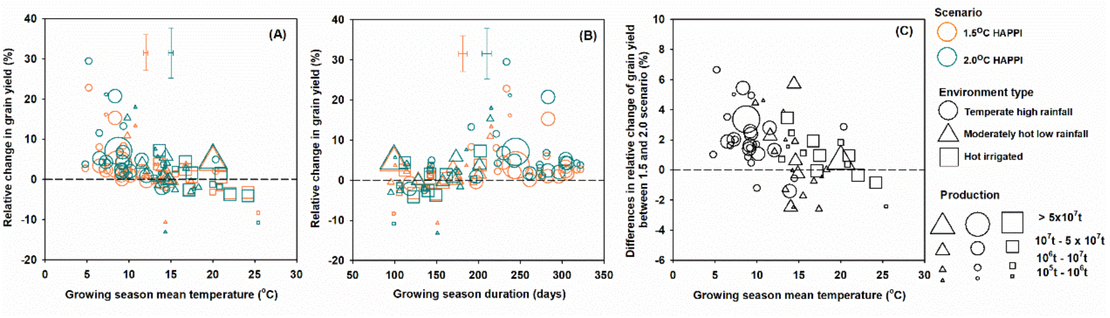

(A)
Relative change in grain yield (%)
Growing season mean temperature (^{o}C)
40
30
20
10
0
-10
-20
0
5
10
15
20
25
30
(B)
Relative change in grain yield (%)
Growing season duration (days)
50
100
150
200
250
300
350
(C)
Differences in relative change of grain yield between 1.5 and 2.0 scenario (%)
10
8
6
4
2
0
-2
-4
-6
Growing season mean temperature (^{o}C)
Scenario
1.5^{O}C HAPPI
2.0^{O}C HAPPI
Environment type
Temperate high rainfall
Moderately hot low rainfall
Hot irrigated
Production
> 5x10^{7}t
10^{7}t - 5 x 10^{7}t
10^{6}t - 10^{7}t
10^{5}t - 10^{6}t

Fig. 2

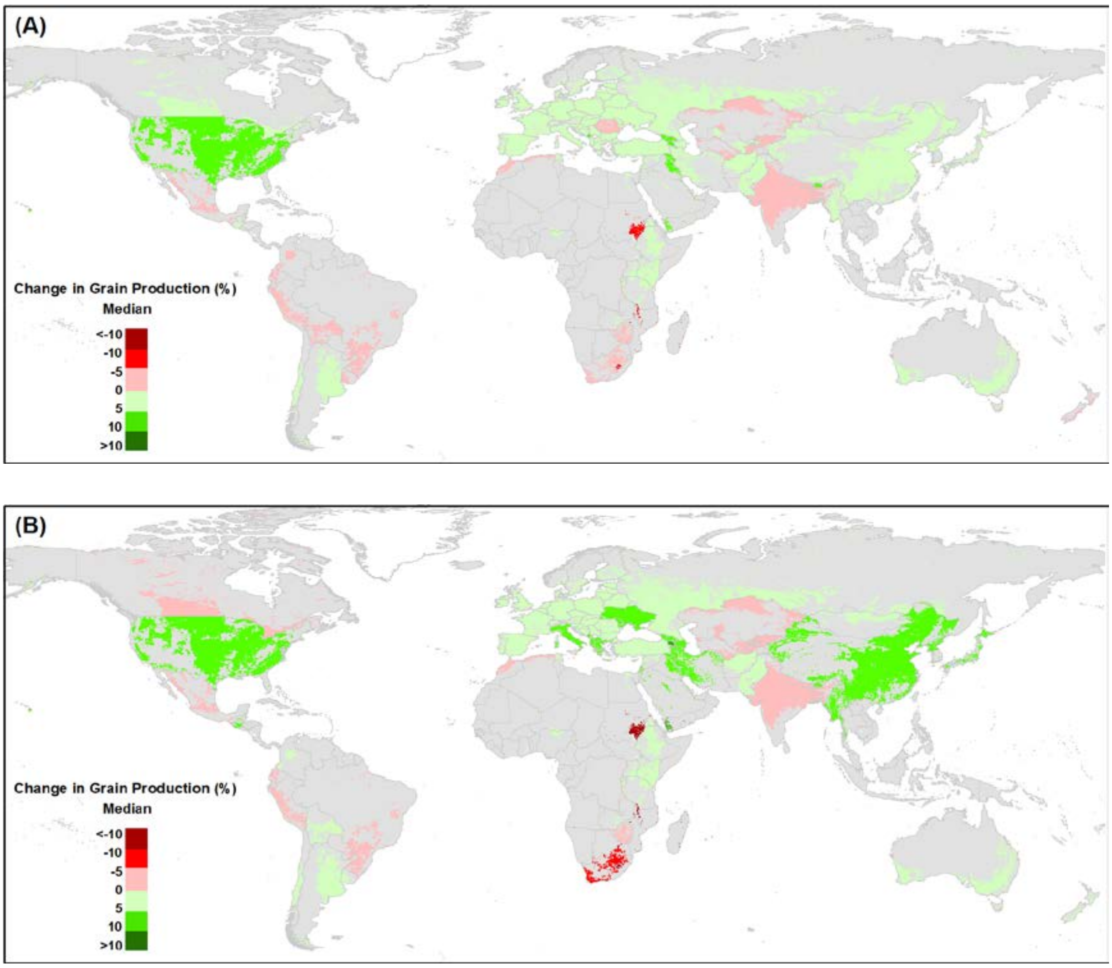

(A)
Change in Grain Production (%)
Median
<-10
-10
-5
0
5
10
>10
(B)
Change in Grain Production (%)
Median
<-10
-10
-5
0
5
10
>10

Fig. 3

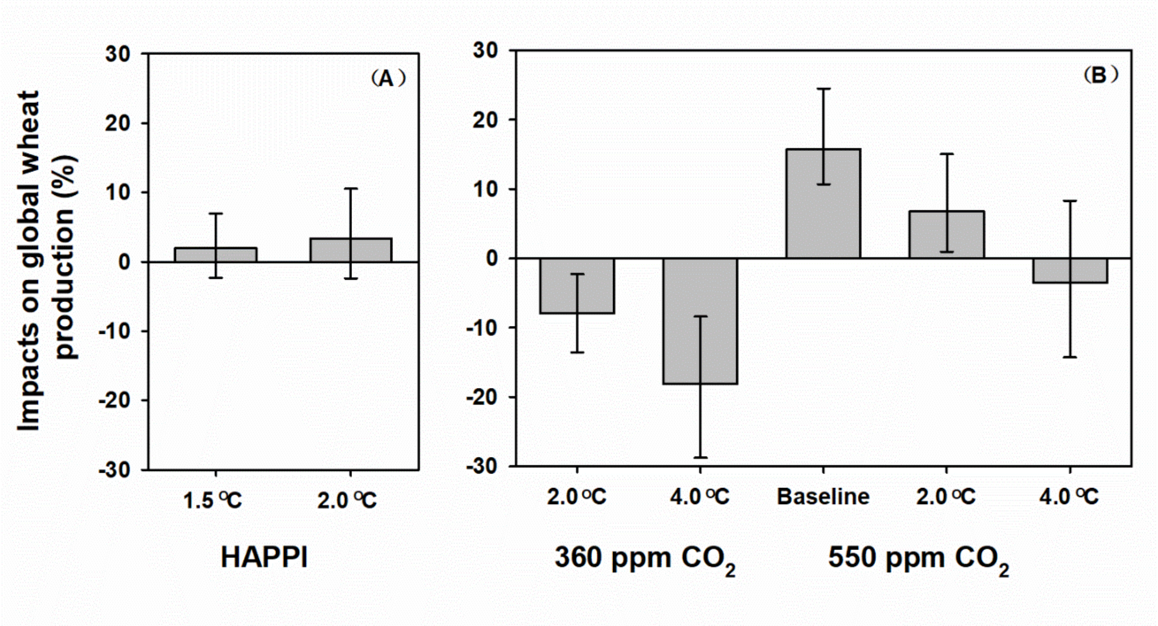
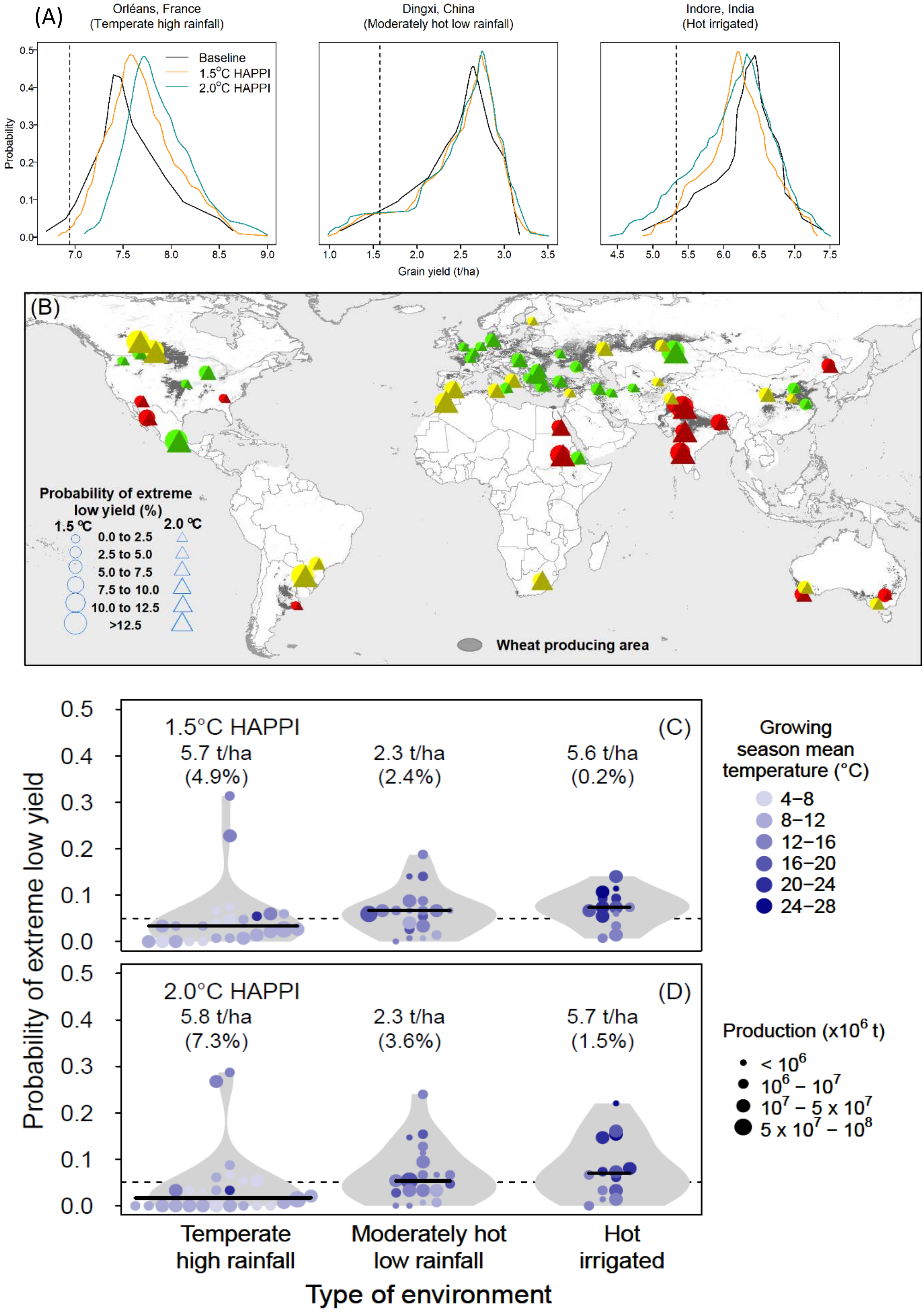

Impacts on global wheat production (%)
(A)
30
20
10
0
-10
-20
-30
1.5 ℃
2.0 ℃
HAPPI
(B)
2.0 ℃
4.0 ℃
Baseline
2.0 ℃
4.0 ℃
360 ppm CO_2
550 ppm CO_2

Fig. 4



(A)
Orléans, France
(Temperate high rainfall)
Dingxi, China
(Moderately hot low rainfall)
Indore, India
(Hot irrigated)
Probability
Baseline
1.5°C HAPPI
2.0°C HAPPI
Grain yield (t/ha)
(B)
Probability of extreme low yield (%)
1.5 °C
2.0 °C
0.0 to 2.5
2.5 to 5.0
5.0 to 7.5
7.5 to 10.0
10.0 to 12.5
>12.5
Wheat producing area
(C)
1.5°C HAPPI
5.7 t/ha (4.9%)
2.3 t/ha (2.4%)
5.6 t/ha (0.2%)
(D)
2.0°C HAPPI
5.8 t/ha (7.3%)
2.3 t/ha (3.6%)
5.7 t/ha (1.5%)
Probability of extreme low yield
Growing season mean temperature (°C)
4–8
8–12
12–16
16–20
20–24
24–28
Production (x10^6 t)
< 10^6
10^6 – 10^7
10^7 – 5 x 10^7
5 x 10^7 – 10^8
Temperate high rainfall
Moderately hot low rainfall
Hot irrigated
Type of environment