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Similar estimates of temperature impacts on global wheat yield by three independent methods

Bing Liu^{1,2†}, Senthold Asseng², Christoph Müller³, Frank Ewert^{4,5}, Joshua Elliott^{6,7}, David B. Lobell⁸, Pierre Martre⁹, Alex C. Ruane^{6,10}, Daniel Wallach¹¹, James W. Jones², Cynthia Rosenzweig^{6,10}, Pramod K. Aggarwal¹², Phillip D. Alderman¹³, Jakarat Anothai¹⁴, Bruno Basso^{15,16}, Christian Biernath¹⁷, Davide Cammarano¹⁸, Andy Challinor^{19,20}, Delphine Deryng^{6,7}, Giacomo De Sanctis²¹, Jordi Doltra²², Elias Fereres²³, Christian Folberth^{24,25}, Margarita Garcia-Vila²³, Sebastian Gayler²⁶, Gerrit Hoogenboom^{2,27}, Leslie A. Hunt²⁸, Roberto C. Izaurralde^{29,30}, Mohamed Jabloun³¹, Curtis D. Jones²⁹, Kurt C. Kersebaum³², Bruce A. Kimball³³, Ann-Kristin Koehler¹⁹, Soora Naresh Kumar³⁴, Claas Nendel³², Garry J. O’Leary³⁵, Jørgen E. Olesen³¹, Michael J. Ottman³⁶, Taru Palosuo³⁷, P. V. Vara Prasad³⁸, Eckart Priesack¹⁷, Thomas A. M. Pugh^{39,40}, Matthew Reynolds⁴¹, Ehsan E. Rezaei^{4,42}, Reimund P. Rötter^{37,43}, Erwin Schmid⁴⁴, Mikhail A. Semenov⁴⁵, Iurii Shcherbak^{15,16}, Elke Stehfest⁴⁶, Claudio O. Stöckle⁴⁷, Pierre Stratonovitch⁴⁵, Thilo Streck²⁶, Iwan Supit⁴⁸, Fulu Tao^{37,49}, Peter Thorburn⁵⁰, Katharina Waha^{3,50}, Gerard W. Wall³³, Enli Wang⁵¹, Jeffrey W. White³³, Joost Wolf⁴⁸, Zhigan Zhao^{51,52} and Yan Zhu^{1*}

The potential impact of global temperature change on global crop yield has recently been assessed with different methods. Here we show that grid-based and point-based simulations and statistical regressions (from historic records), without deliberate adaptation or CO₂ fertilization effects, produce similar estimates of temperature impact on wheat yields at global and national scales. With a 1 °C global temperature increase, global wheat yield is projected to decline between 4.1% and 6.4%. Projected relative temperature impacts from different methods were similar for major wheat-producing countries China, India, USA and France, but less so for Russia. Point-based and grid-based simulations, and to some extent the statistical regressions, were consistent in projecting that warmer regions are likely to suffer more yield loss with increasing temperature than cooler regions. By forming a multi-method ensemble, it was possible to quantify ‘method uncertainty’ in addition to model uncertainty. This significantly improves confidence in estimates of climate impacts on global food security.

Global demand for food is expected to increase 60% by the middle of the twenty-first century¹. Climate change, and in particular rising temperatures, will impact food production². For global food security, it is important to understand how climate change will impact crop production at the global scale to develop fact-based mitigation and adaptation strategies. Many studies have shown a wide range of temperature impacts on yields of different crops in different seasons at different locations³, including Europe⁴, China⁵, India⁶ and sub-Saharan Africa⁷. A few studies have considered impacts on the entire globe^{8–11}. However, the methods used to make these assessments are based on very different premises and use different methodological steps.

The uncertainty of estimates of global temperature impact on crop yields was analysed for the crop model component (that is, model uncertainty) by using two different multi-model ensemble approaches^{8,9}. While both studies used process-based crop simulation models, the scaling approach and input data differed greatly. The first study divided the globe into geographical grid cells defined by latitude and longitude and used climate and crop management data integrated over each grid as input for seven crop

models⁹. This grid-based system was used to estimate relative yield changes for rice, maize, wheat and soybean. The second study used data from 30 individual field sites deemed to represent two-thirds of wheat-producing areas worldwide⁸. In this point-based approach estimates from sentinel sites were scaled up and extrapolated to cover geographical areas with similar conditions.

In further contrast, statistical regressions based on global and country-level data have been used to quantify the impact of increasing temperatures on yields of wheat, maize, barley, soybean, sorghum and rice^{10,11}. An important difference from the simulation models is that statistical models do not directly consider processes inherent to crop growth. However, statistical models may include indirect effects of climatic variability, such as those related to pests and diseases, which are not well captured by simulation models¹². When assessing climate effects on crop yields, crop models can take into account autonomous adaptation and an increase in atmospheric CO₂ concentration. Also some statistical regressions include the yield effects associated with autonomous adaptation¹⁰. For the effects of gradual increase in CO₂ concentration in the past, statistical models may inherently include these within yield effects¹³,

† A full list of affiliations appears at the end of the paper.

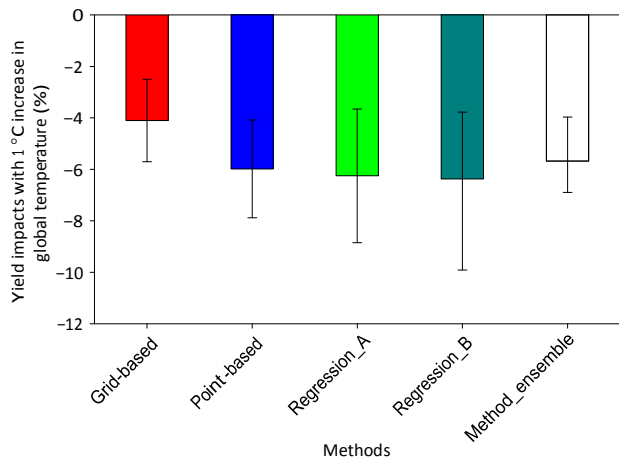


Figure 1 | Impacts of 1 °C global temperature increase on global wheat yield estimated by different assessment methods. The grid-based ($0.5^\circ \times 0.5^\circ$ grid cells) method is an ensemble median from seven global gridded crop models, averaged over 30 years and aggregated over all simulated grid cells (after ref. 9). The point-based method is an ensemble median from 30 models, averaged over 30 years and aggregated over 30 global locations (after ref. 8). Regression_A is based on a country-level statistical regression from ref. 10. Regression_B is based on a global-level statistical regression from ref. 11. The error bars for the four different methods indicate the 95% confidence intervals based on multi-model ensembles in the simulations and bootstrap resampling in the statistical regressions. The mean of the method_ensemble is shown with error bars indicating the 95% confidence intervals based on medians of individual methods.

but for some regression models with a linear time term, effects of steady increase in CO_2 can be removed from yield impacts, just as the effects of technology improvement. In addition, upscaling methods influence the outcomes from regional assessments¹⁴. The statistical approach obtained global or regional impacts by aggregating county districts or countries^{10,11}. The grid-based system obtained global or regional impacts by aggregating $0.5^\circ \times 0.5^\circ$ grid cells⁹, while the point-based approach employed 30 sites to represent global wheat regions⁸. Therefore, differences in upscaling could add uncertainties in the impact estimated in these studies.

In this letter, we compared three largely independent assessment methods used to estimate temperature impacts on wheat yields: grid-based simulations, point-based simulations, and statistical regressions. The details of each method are shown in Supplementary Table 1. The methods used independent different dynamic, statistical, upscaling and source data approaches. The grid-based simulations used here were from the Agricultural Model Intercomparison and Improvement Project (AgMIP)¹⁵ as part of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). Wheat yields were simulated with seven global gridded crop models during 1980–2099 under Representative Concentration Pathway (RCP) 8.5, a greenhouse gas emissions scenario (here without CO_2 fertilization effects), over $0.5^\circ \times 0.5^\circ$ grid cells⁹. The point-based simulations from the AgMIP-Wheat project⁸ consisted of simulations from 30 wheat models (including one statistical model) for 30 representative locations around the world from a baseline of the 1981–2010 period and a linear temperature increase. Temperature impacts determined by statistical regression methods were obtained directly from previously published data or our own statistical analysis (Supplementary Table 1 and Supplementary Methods).

Similar global impact from different methods

The average reductions in global wheat yield with 1 °C global temperature increase estimated from grid-based simulations,

point-based simulations, and statistical regressions at global level were all between 4.1% and 6.4% (Fig. 1). The average estimated temperature impact from all three methods (and four studies) was a 5.7% reduction in global yield per degree of global temperature increase. The estimated temperature effects on global wheat yield from the three different methods were similar.

A meta-analysis of mostly process-based crop model simulations reported a $3.3 \pm 0.8\%$ decline in wheat yields with a 1 °C increase in local temperature¹⁶. When adjusted to global temperature change (which is usually less than local wheat region temperature changes¹⁷), this impact amounts to 3.9% yield reduction per degree of global temperature increase. Also, a summary of past regression and simulation studies reported an average of 5.9% wheat yield decrease with 1 °C warming¹⁸. These values are very similar to the results obtained here for wheat using three different assessment methods.

The results here are presented for 1 °C of global warming for consistency. However, the estimated impacts do not increase linearly with increasing temperature and the disagreement among method estimates become larger with more temperature change (Supplementary Fig. 9).

Impacts for major wheat-producing countries

To understand how the different methods project such similar temperature impacts on global wheat yields, we disaggregated the temperature impacts to the national scale. Point-based and grid-based simulations were compared for 97 countries (Fig. 2a). Generally, projected temperature impacts on wheat yields for most of the large wheat producers were similar between the two simulation methods (with a R^2 of 0.64 for the top 20 producers, Supplementary Fig. 12), while differences were larger for small wheat-producing countries. Some large differences occurred between point-based and grid-based simulation in irrigated semiarid regions of Africa, which are mostly small wheat producers. The larger differences observed for smaller producers have little weight in the global analysis. However, they are important for regional economies. Method results were compared in more detail for the top five wheat-producing countries (Fig. 2b and Fig. 3). For China, India, USA and France, the different assessment methods resulted in similar values for temperature impacts on country wheat yields. Additional country-level studies relying on other methods and data sources gave similar estimates. For example, for China, point-based simulations, grid-based simulations, and two different regressions all concluded that yield reductions of about 3.0% are expected with 1 °C warming (Fig. 3a). For India, country-level statistical regressions, grid-based and point-based simulations all estimated about 8.0% yield declines per 1 °C of global temperature increase (Fig. 3b). For Russia, the two simulation methods agreed well, but yield reductions estimated from statistical regression were markedly higher (Fig. 3c). Another study using statistical regression methods also showed higher negative temperature impacts on wheat yield than the two modelling methods used here for Rostov, a main wheat-producing region in Russia¹⁹. Since wheat-producing regions in Russia can experience relatively low temperatures (below optimal growth temperature) during early growing stages, a temperature increase during this stage (tillering) may have a positive yield impact, while at a later stage (booting or grain filling) an increase in temperature often reduces wheat yields¹⁹. As an average temperature over a growing season is usually used in statistical regressions, such in-season variability in temperature impacts would remain undetected. A dynamic crop simulation model takes in-season variability and impacts into account. This may explain the estimated larger impacts in Regression_A in comparison with the simulation results. For the USA, a recent study using data from wheat variety trials from 1985 to 2013 in Kansas, USA reported a 7.3% decrease (corrected for global temperature change) in wheat yield with

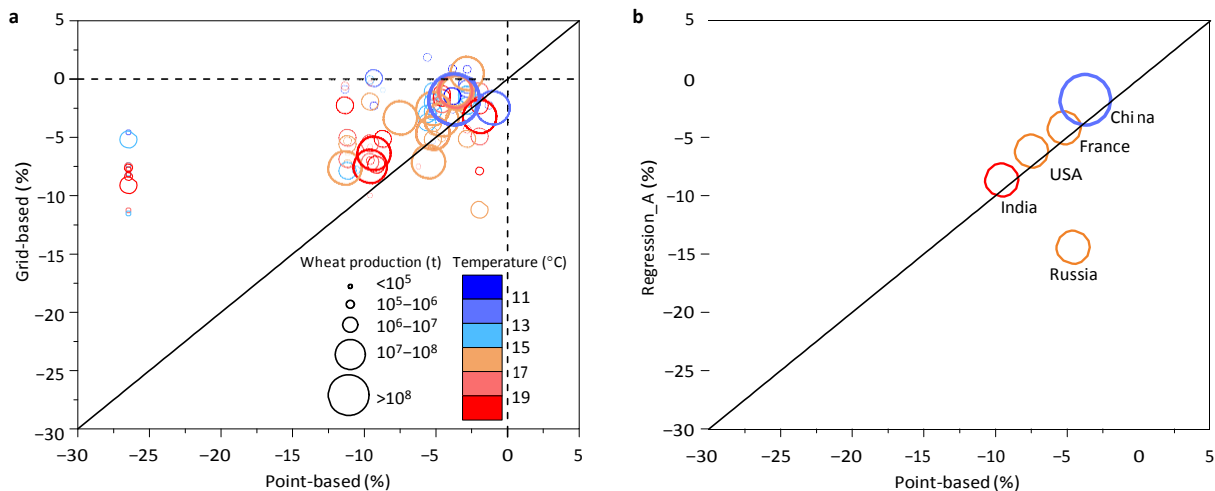


Figure 2 | Comparison of wheat yield changes with 1 °C global temperature increase for 97 wheat-producing countries estimated using three different methods. a, Median simulations of a grid-based (0.5°×0.5°) ensemble of seven models (after ref. 9) versus a point-based (30 locations over 30 years) ensemble of 30 models (after ref. 8). b, Country-level statistical regression for China, India, USA, France and Russia, the top five wheat-producing countries, from ref. 10, versus point-based simulations for these countries (after ref. 8). Note, only data on these five countries were supplied in ref. 10. Circle colour indicates the wheat growing season temperature (from ref. 10). Circle size indicates the amount of wheat production for each country according to FAO statistics²³. The solid line is the 1:1 line and dashed lines represent 0% yield change.

1 °C global temperature increase²⁰. This result is similar to the other estimated temperature impacts on wheat yields for the USA (Fig. 3d). For France, yield reduction estimates from grid-based simulations, point-based simulations, and statistical regressions were 4.6%, 5.2% and 4.2%, respectively (Fig. 3e). In an independent study, a 0.42 t ha⁻¹ reduction in wheat yields, which is a reduction of about 5.5% after correction for global temperature change, was reported in northern France from 1998 to 2008 that included the planting of reference varieties in field experiments²¹. This is also in line with simulated impact response surfaces from a 26-wheat-model ensemble across a European transect²².

With the different temperature impact methods used, despite some variation, there is a general similarity in the magnitude of negative effects of increasing temperature on wheat yields for major wheat-producing countries. As the five largest wheat-producing countries have a combined total >50% of total global wheat production²³, the similarity in method estimates of temperature impacts for these countries also dominates the similar negative temperature impacts computed at the global scale.

Differences in model inputs

At the location scale, the yields from the point-based simulations were highly correlated to the yields from the grid-based simulations for the baseline and baseline +1 °C periods ($P < 0.001$, $R^2 > 0.5$; Supplementary Table 2), but simulated yields were generally higher in point-based than in grid-based simulations (Fig. 4 and Supplementary Fig. 1). The average yields of the 30 locations in the point-based simulations were 3.2 (82%) and 3.0 (82%) t ha⁻¹ higher than in the corresponding grid-based simulations under baseline and baseline +1 °C conditions, respectively. In both studies, mean temperatures were similar across sites for the 90 days period prior to maturity, except for three locations (Supplementary Fig. 2). Seasonal temperature variability in the model input data differed slightly between methods and caused a larger seasonal yield variability in the grid-based simulations compared with the point-based simulations (Supplementary Fig. 7). Solar radiation inputs were 5% to 7% lower in the grid-based than in the point-based simulations (Supplementary Fig. 3), which might have contributed slightly to the simulated yield difference²⁴. Water stress was not considered in either study for the comparison of these 30 locations and any possible differences in precipitation inputs had no impact on the

simulated results (Supplementary Table 3). No nitrogen stress was assumed in the point-based simulations, but four of the seven crop models in the grid-based simulations did consider country-level average N fertilizer application, which could explain why the grid-based model ensemble simulated generally lower yields compared with the point-based simulations (Supplementary Table 3).

Another important factor possibly contributing to yield differences between the grid-based and point-based simulation at the local scale was the models used in the studies. There were 29 crop models and one statistical regression in the point-based simulation ensemble, whereas there were seven crop models in the grid-based simulations. Three models (CERES, EPIC and LPJmL) were common to both studies. These three models tended to simulate lower yields than the 30-model ensemble average from the point-based study for the 30 locations, for example, about 0.9 t ha⁻¹ less in the baseline period (Supplementary Fig. 4). This may have lowered the average simulated yields in grid-based simulations. Differences in the calibration of the crop models would also affect simulations²⁵. Some models in the grid-based simulations were calibrated and some were not, and especially growing periods were not harmonized across grid-based models⁹, while in point-based simulations all models were calibrated for anthesis and maturity dates with local phenology information⁸. Hence, differences in models, solar radiation and inputs such as N fertilizer may explain some of the lower yields found in the grid-based studies. Differences in cultivar calibration, particularly for phenology and growing season, add another source of differences between these two studies.

More yield reduction at warmer regions

Interestingly, when comparing the grid-based and point-based simulations, no obvious bias was observed in the simulated relative yield impacts between point-based and grid-based simulations (Fig. 4c and Supplementary Fig. 1c), even though simulated absolute yields with point-based simulations were much higher than grid-based simulations. This was still true when the outlier location in Fig. 4c was removed from calculations. Temperature impacts at the local scale in grid-based and point-based simulations were highly correlated. With 1 °C global temperature increase, higher yield reductions were observed at locations with higher baseline temperatures than locations with lower baseline temperatures in both point-based and grid-based simulations (Fig. 4c). For example,

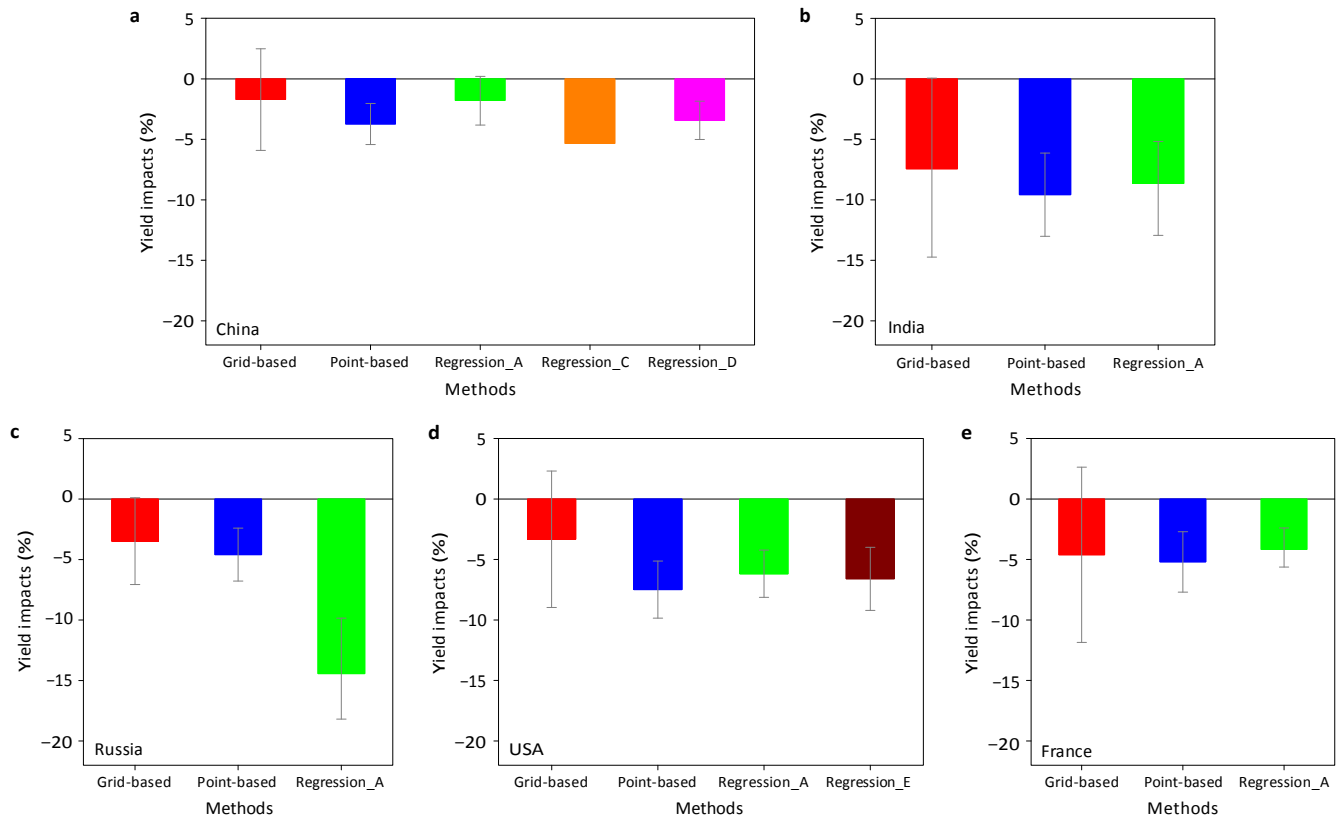


Figure 3 | Estimated impacts of 1 °C global temperature increase on wheat yield. a–e, China (a), India (b), Russia (c), USA (d) and France (e) using different assessment methods. The grid-based ($0.5^{\circ} \times 0.5^{\circ}$) method produced an ensemble median from seven global gridded crop models (after ref. 9). The point-based method produced an ensemble median from 30 models from 1 to 3 country locations (after ref. 8). Regression_A is a statistical regression based on country statistics after ref. 10. Regression_C is a statistical regression based on $0.5^{\circ} \times 0.5^{\circ}$ grid statistics after ref. 45. Regression_D is county-level statistical regressions produced by two different regression methods from ref. 49. Regression_E is a county-level regression produced for this study. The error bars indicate the 95% confidence interval based on multi-models for the simulations and bootstrap resampling (Regression_A, Regression_B, and Regression_D) or *t*-tests (Regression_E) for the statistical regressions. No error bar was provided for Regression_C in ref. 45.

at Aswan in Egypt, point-based and grid-based simulations showed about 11% and 20% decline in yield with 1 °C temperature increase, while for Krasnodar in Russia, point-based and grid-based simulations estimated about 4% and 7% yield decline with 1 °C global increase. The spatial pattern of temperature impacts at the location scale was also consistent with that at the country scale (Fig. 2a,b, and Supplementary Fig. 11), which indicated that warmer regions (for example, India) are likely to suffer more wheat yield reductions than cooler regions (for example, China). The exception is for statistical regression estimates for Russia, a generally cooler region (Fig. 2b). The effects of temperature on wheat yields are consistent with reports of impacts on other crops, such as maize, soybean and cotton^{26–28}. An increase in extreme temperature events with increasing mean temperatures²⁹ is likely to further contribute to yield decline in wheat^{30,31}. Several crop models used in point-based simulations (tested against warming experiments) and Regression_A (using a nonlinear regression method) also considered the impacts of extreme temperature^{8,10}.

Effects of upscaling methods

To assess climate impacts on global or country-level crop production, both process-based crop modelling approaches and statistical regressions need to be upscaled from locations to regions and then to the entire globe³². In the point-based simulations, a range of local information (for example, local sowing dates, cultivar, anthesis and maturity date) was used for the 30 locations selected to represent about 70% of current global wheat production, which was then upscaled via FAO (Food and Agriculture Organization

of the United Nations) statistics⁸. Much less local information was available for each of the $0.5^{\circ} \times 0.5^{\circ}$ grid cells which were aggregated to country and global scales in the grid-based simulations⁹. However, very similar estimated temperature impacts on relative global yield changes were simulated with both approaches. This was surprising as it was shown that scaling methods can add significant uncertainties to simulated outcomes¹⁴. Although uncertainties are known to be reduced with multi-model ensembles, these results might also indicate that the selected 30 locations in the point-based study⁸ were indeed representative of agro-climatic variability of wheat-growing conditions throughout the world. The results also suggest that global grid-based models, despite having limited local information, are on a par with point-based approaches, while providing greater coverage of regional heterogeneity.

In the statistical regression methods, yield and weather data from different scales were used to obtain global and country-level temperature impacts. For example, both global¹¹ and country-level¹⁰ regressions, observed yield records were used to conduct global assessments, and both country-level yields and county (or similar)-level yields were used for country assessments (for example, for China, India and USA). Generally, regressions with different spatial scales resulted in similar temperature impacts on yields.

Advantage of different assessment methods

Compared with process-based crop models, statistical regressions are simpler and require less input information. However, other important growth factors that change with climate change, such as radiation or the combined effects of heat, water and nutrient

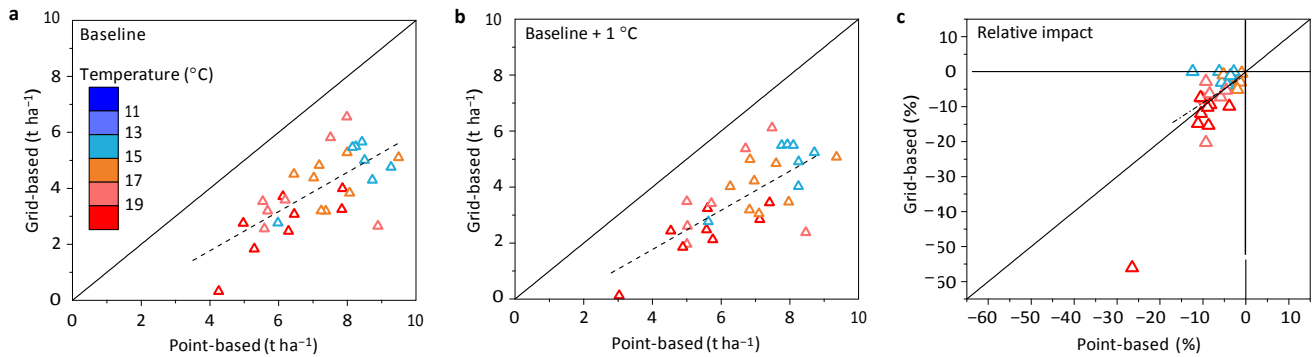


Figure 4 | Comparison of simulated multi-model median wheat yield and yield changes. a–c, Absolute wheat yields for baseline (a) and baseline +1 °C (b) periods, and relative yield change with 1 °C global temperature increase from grid-based simulations ($0.5^\circ \times 0.5^\circ$) (from ref. 9) of cells centred around the 30 locations from the point-based study versus that from the point-based simulations (from ref. 8) (c). Note in c, the regression line is drawn without the outlier (location in Sudan). Dashed lines represent regression lines.

stresses, vary over the period of a crop growing cycle, but are often not directly considered in statistical regressions. Some of these factors might also be confounded in a statistical regression analysis. While there have been attempts to include more factors in statistical impact methods³³, detailed process-based, dynamic crop simulation models may be more suitable to simulate the more complex climate change scenarios, beyond the single impact of temperature change. However, process-based models, like statistical methods, often do not account for many other important factors required for holistic climate change impact assessment. Such factors include impacts from frost, pests, weeds, diseases and floods, and also dissimilar impacts between day and night temperatures³⁴, or extreme temperature events at different growth stages, which are all likely to change with future climates. However, process-based models are capable of accounting for the effects of elevated CO₂ (ref. 35), even though this effect is not considered here, but large uncertainties exist not only with respect to the general effects on crop yields^{36,37} but also with respect to model implementation^{9,38}.

Field or environment-controlled experiments are independent ways to estimate temperature impacts on wheat yields^{8,16}. For example, 2% to 8% reductions in wheat yield for every 1 °C increase of post-anthesis temperature above an optimum season-average temperature of 15 °C (that is, local temperature) have been measured for a range of cultivars under controlled³⁹ and field experiments⁴⁰. Considerable variations of wheat yield impacts with increasing temperature have been found in a four-growing-season warming experiment⁴¹. However, while measured temperature impacts on yields can guide other impact estimation methods, they are often specific to a particular location, cultivar, crop management or experimental treatment and are not representative of a larger region, which makes it difficult to extrapolate such measurements to regional or global impacts.

Applying multi-method ensembles

Understanding and quantifying uncertainty of impact assessments has been a key aspect in assessing climate impacts on crop production in recent studies^{25,42,43}. Most previous studies have focused on uncertainties arising from crop models or climate models²⁵. Here the uncertainties in both point-based and grid-based simulations were quantified by multi-model ensembles. Uncertainties due to crop models, expressed as error bars in the grid-based simulations, were relatively large at both global and country scales (Figs 1 and 3), which was due to the limited number of models and relatively wide spread of model results in this study. The differences in model inputs (for example, nitrogen application, sowing dates, cultivars), calibration methods and model⁹ explain some of the variability between

the point- and grid-based simulations. Many crop models do

not simulate temperature interactions with canopy temperature variation under different soil water conditions, which could result in simulated differences of temperature impacts⁸. However, multi-model ensemble medians have been shown to be more consistently accurate than individual models when comparing measurements across locations and growing environments, adding confidence to the estimates here⁴⁴. Bootstrap resampling methods were employed to estimate the uncertainty of temperature impacts calculated in the two global-scale statistical regressions. Thus, different assessment approaches have independent methods of quantifying uncertainty. Multi-method ensembles can enable the quantification of method uncertainty, similar to how multi-model ensembles enable estimation of model uncertainty. The uncertainty range of wheat yield reduction with 1 °C global temperature increase from the multi-method ensemble calculated from the median of the four methods analysed here was between 4.0% and 6.9% at the global scale (95% confidence interval). While this absolute difference is still substantial, this is narrower than the uncertainty due to the models in the multi-model ensembles from the simulations or the bootstrapping method in the statistical regressions. Therefore, applying multi-method ensembles can improve reliability of the assessment of climate impacts on global food security.

However, the consistency of negative global yield impacts of increasing temperature quantified here at the global level should not be applied to the local or regional scale. As previous studies have found, there were considerable large variations of increasing temperature impacts on wheat yields at the local and regional scale^{8,45}, and the spatial variation of temperature impacts has also been observed in the two modelling approaches here among different locations.

Adaptation to global warming, for example, farmer's autonomous adaptation through changing sowing dates or cultivars, has been suggested in several studies to compensate negative impacts of increasing temperature⁴⁶. At the global scale, point-based simulations did not consider adaptation. Also a panel regression approach attempted to exclude adaptations¹⁰. In the grid-based simulations, four of the seven models did allow cultivar and sowing date adaptation with a changing climate (Supplementary Table 3), and the simulated impacts tended to be lower with simulated adaptation (Supplementary Fig. 10). However, temperature impacts from models with adaptation varied largely. Temperature impacts with and without adaptation were estimated from different models in grid-based simulations, which added considerable uncertainty in the results. The adaptation effects on temperature impacts should be further studied with more consistent protocols for multi-model assessments. Other future adaptation, for example, wheat cultivation shifting to marginal regions in higher latitudes, could offset some of the negative impacts.

Assessing climate change impacts on crop production is a key aspect in determining appropriate global food security strategies⁴². Reliable estimates of climate change impacts on food security require an integrated use of climate, crop and economic models¹⁵. Applying multi-method ensembles further improves the estimated impact precision and confidence in assessments of climate impacts on global food security. The consistent negative impact from increasing temperatures confirmed by three independent methods warrants critical needed investment in climate change adaptation strategies to counteract the adverse effects of rising temperatures on global wheat production, including genetic improvement and management adjustments^{47,48}. However, some or all of the negative global warming impacts on wheat yield might be compensated by increasing atmospheric CO₂ concentrations under full irrigation and fertilization²⁵.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

B.L., S.A., C.M., F.E., J.E., D.B.L., P.M., A.C.R., D.W., J.W.J., C.R. and Y.Z. motivated the study, S.A. coordinated the study, B.L., S.A., C.M., F.E., J.E., D.B.L., P.M., A.C.R. and D.W. analysed data, P.K.A., P.D.A., J.A., B.B., C.B., D.C., A.C., D.D., G.D.S., J.D., E.F., C.F.,

M.G.-V., S.G., G.H., L.A.H., R.C.I., M.J., C.D.J., K.C.K., A.-K.K., C.M., S.N.K., C.N., G.O'L., J.E.O., T.P., E.P., T.A.M.P., E.E.R., R.P.R., E.Schmid, M.A.S., I.Sherbak, E.Stehfest, C.O.S., P.S., T.S., I.Supit, F.T., P.T., K.W., E.W., J.W., Z.Z. and Y.Z. carried out crop model simulations and discussed the results, C.M., J.E., B.A.K., M.J.O., G.W.W., J.W.W., M.R., P.D.A., P.V.V.P. and A.C.R. provided experimental data, B.L., S.A., C.M., F.E., J.E., D.B.L., P.M., A.C.R., D.W., J.W.J., C.R. and Y.Z. wrote the paper. All other authors gave comments on the earlier version of this manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y.Z.

Competing financial interests

The authors declare no competing financial interests.

¹National Engineering and Technology Center for Information Agriculture, Jiangsu Key Laboratory for Information Agriculture, Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing, Jiangsu 210095, China. ²Agricultural & Biological Engineering Department, University of Florida, Gainesville, Florida 32611, USA. ³Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany. ⁴Institute of Crop Science and Resource Conservation INRES, University of Bonn, Bonn 53115, Germany. ⁵Leibniz Centre for Agricultural Landscape Research (ZALF), 15374 Müncheberg, Germany. ⁶Columbia University Center for Climate Systems Research, New York, New York 10025, USA. ⁷University of Chicago Computation Institute, Chicago, Illinois 60637, USA. ⁸Department of Environmental Earth System Science and Center on Food Security and the Environment, Stanford University, Stanford, California 94305, USA. ⁹UMR LEPSE, INRA, Montpellier SupAgro, 34060 Montpellier, France. ¹⁰National Aeronautics and Space Administration Goddard Institute for Space Studies, New York, New York 10025, USA. ¹¹INRA, UMR1248 Agrosystèmes et développement territorial (AGIR), 31326 Castanet-Tolosan Cedex, France. ¹²CGIAR Research Program on Climate Change, Agriculture and Food Security, Borlaug Institute for South Asia, CIMMYT, New Delhi-110012, India. ¹³Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma 74078, USA. ¹⁴Department of Plant Science, Faculty of Natural Resources, Prince of Songkla University, Songkhla 90112, Thailand. ¹⁵Department of Geological Sciences, Michigan State University East Lansing, Michigan 48823, USA. ¹⁶W. K. Kellogg Biological Station, Michigan State University East Lansing, Michigan 48823, USA. ¹⁷Institute of Ecology, Helmholtz Zentrum München – German Research Center for Environmental Health, Neuherberg D-85764, Germany. ¹⁸The James Hutton Institute Invergowrie, Dundee DD2 5DA, UK. ¹⁹Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK. ²⁰CGIAR-ESSP Program on Climate Change, Agriculture and Food Security, International Centre for Tropical Agriculture (CIAT), A.A. 6713 Cali, Colombia. ²¹European Commission, Joint Research Centre, via Enrico Fermi, 2749 Ispra 21027, Italy. ²²Cantabrian Agricultural Research and Training Centre (CIFA), 39600 Muriedas, Spain. ²³Department of Agronomy, University of Cordoba, Apartado 3048, 14080 Cordoba, Spain. ²⁴Department of Geography, University of Munich, Munich 80333, Germany. ²⁵Ecosystem Services and Management Program, International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria. ²⁶Institute of Soil Science and Land Evaluation, University of Hohenheim, 70599 Stuttgart, Germany. ²⁷AgWeatherNet Program, Washington State University, Prosser, Washington 99350, USA. ²⁸Department of Plant Agriculture, University of Guelph, Guelph, Ontario N1G 2W1, Canada. ²⁹Department of Geographical Sciences, University of Maryland, College Park, Maryland 20742, USA. ³⁰Texas A&M AgriLife Research and Extension Center, Texas A&M University, Temple, Texas 76502, USA. ³¹Department of Agroecology, Aarhus University, 8830 Tjele, Denmark. ³²Institute of Landscape Systems Analysis, Leibniz Centre for Agricultural Landscape Research, 15374 Müncheberg, Germany. ³³USDA, Agricultural Research Service, U.S. Arid-Land Agricultural Research Center, Maricopa, Arizona 85138, USA. ³⁴Centre for Environment Science and Climate Resilient Agriculture, Indian Agricultural Research Institute, IARI PUSA, New Delhi 110012, India. ³⁵Landscape & Water Sciences, Department of Economic Development, Jobs, Transport and Resources, Horsham, Victoria 3400, Australia. ³⁶The School of Plant Sciences, University of Arizona, Tucson, Arizona 85721, USA. ³⁷Natural Resources Institute Finland (Luke), FI-00790 Helsinki, Finland. ³⁸Department of Agronomy, Kansas State University, Manhattan, Kansas 66506, USA. ³⁹Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Karlsruhe Institute of Technology, 82467 Garmisch-Partenkirchen, Germany. ⁴⁰School of Geography, Earth & Environmental Science and Birmingham Institute of Forest Research, University of Birmingham, Birmingham B15 2TT, UK. ⁴¹CIMMYT Int., AP 6-641, 06600 Mexico DF, Mexico. ⁴²Center for Development Research (ZEF), Walter-Flex-Straße 3, 53113 Bonn, Germany. ⁴³Georg-August-University Göttingen, Grisebachstraße 6, 37077 Göttingen, Germany. ⁴⁴University of Natural Resources and Life Sciences, 1180 Vienna, Austria. ⁴⁵Computational and Systems Biology Department, Rothamsted Research, Harpenden AL5 2JQ, UK. ⁴⁶PBL Netherlands Environmental Assessment Agency, 3720 AH, Bilthoven, The Netherlands. ⁴⁷Department of Biological Systems Engineering, Washington State University, Pullman, Washington 99164, USA. ⁴⁸PPS, WSG and CALM, Wageningen University and Research, 6700AA Wageningen, The Netherlands. ⁴⁹Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Science, Beijing 100101, China. ⁵⁰CSIRO Agriculture & Food, St Lucia, Queensland 4067, Australia. ⁵¹CSIRO Agriculture & Food, Black Mountain, Australian Capital Territory 2601, Australia. ⁵²Department of Agronomy and Biotechnology, China Agricultural University, Yuanmingyuan West Road 2, Beijing 100193, China. *e-mail: yanzhu@njau.edu.cn

Methods

Grid-based simulations. Seven global gridded models simulated $0.5^\circ \times 0.5^\circ$ grid cells across all wheat-growing regions of the world from 1980 to 2099 under a RCP 8.5 scenario with a statistically downscaled version of HadGEM2-ES⁵⁰, with only a small trend in solar radiation at some locations (Supplementary Fig. 6). Here, a set of simulation experiments without effects of elevated CO₂ and under full irrigation treatments were used. Among the seven global gridded models, adaptation through cultivars, sowing dates or growing season had been employed in four of the models (Supplementary Table 3). The global yield impacts from models with and without adaptation are compared in Supplementary Fig. 10. Only one climate model and RCP were used as there were limited data available for grid-based simulations. The period 2029–2058 was selected as being on average 2 °C warmer globally than the baseline period of 1981–2010 and the impact was halved to adjust the temperature change to +1 °C for the analysis here. The temperature change considered here is 1 °C warming of the global mean temperature, including land and ocean surface. The change in simulated grain yields between these two temperature periods was used to estimate temperature impacts on wheat at global and national scales. Grid-based simulations for the direct comparison with point-based simulations were extracted from simulations assuming full irrigation. For national- and global-scale results, grid-based simulations were aggregated by area-weighted means, using rain-fed and irrigated wheat areas per pixel of MIRCA2000 (ref. 51) combining simulations under irrigated and rain-fed conditions. To make projections between the different grid-based models comparable, yield simulations were bias-corrected to national FAO levels by using FAO mean yields and superimposing projected relative changes. More details about the grid-based simulations can be found in ref. 9.

Point-based simulations. Thirty models, 29 crop simulation models and one statistical regression model, were used to simulate wheat grain yields for 30 representative locations in high-rainfall and irrigated wheat-growing regions around the world (together representing about 70% of global wheat production) with the estimated baseline period of 1981–2010 and baseline +2 °C. Three models (CERES, EPIC and LPJmL) in point-based simulations were used in grid-based simulations. No CO₂ fertilization effects or any adaptation was considered in the point-based simulations. The impact was halved to adjust the temperature change to +1 °C for the analysis here. Local temperature impacts on yields were adjusted to global temperature change and upscaled via FAO statistics. Temperature impacts on national scales were assessed for 97 countries. Each country was assigned as being similar to one or more representative locations, so the temperature impacts of each country were the average impacts of the corresponding representative locations. More details can be found in ref. 8.

Statistical regressions. All estimated temperature impacts from statistical regressions were from literature reports^{10,11,45,49}, except for one new statistical regression analysis for the USA that we present here (Supplementary Methods). All temperature impacts were adjusted to global temperature change following the

approach by ref. 8. Details of these regression studies and impacts adjustments are summarized in Supplementary Table 1.

Meta-analysis and experimental data. Meta-analysis and experimental data from the literature are cited here for further comparison after adjusting them to global temperature change where possible. Meta-analysis and experimental data from the literature were cited here for further comparison after adjusting them to global temperature change. An adjustment factor to global temperature used for the statistical regressions was also used here. The temperature factors are listed in Supplementary Table 1.

Comparison at a national scale. Temperature impacts for 97 countries from both grid-based and point-based simulations were compared. Due to the limited number of country-scale estimates of temperature impacts on wheat yields with statistical regression analysis, we compared the regression results with the two simulation approaches for the top five wheat-producing countries (Supplementary Table 1).

Comparison at local scales. Yield simulations from 30 single grid cells from the grid-based method were chosen that were centred around the 30 global representative locations from the point-based method. Full irrigation treatments were applied in point-based and grid-based simulations. The baseline and increased temperature periods for the 30 grid cells were determined individually by matching the 30-year average annual temperature of each grid to the 30-year average annual temperature of the corresponding location from point-based simulations. The baseline and increased temperature periods for each of the 30 grid cells and temperature differences between the two methods are shown in Supplementary Table 4. Most locations had very similar temperature input data in the two comparison periods for grid-based and point-based simulations. Outliers (Supplementary Table 4) were found where the input data differed substantially but these did not cause outliers in yield impacts. The yield impact outlier at the Sudan location was caused by very low simulated yields (Fig. 4). The simulated yields for baseline and increased temperature periods were used to calculate temperature impacts at the local scale. These were also adjusted to global temperature change with the same method at global and national scales. The temperature and radiation data from the critical growing period of wheat from 90 days before maturity to maturity were compared. Maturity dates were the dates supplied from observations for each location in the point-based method⁸.

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Corrigendum: Similar estimates of temperature impacts on global wheat yield by three independent methods

Bing Liu, Senthil Asseng, Christoph Müller, Frank Ewert, Joshua Elliott, David B. Lobell, Pierre Martre, Alex C. Ruane, Daniel Wallach, James W. Jones, Cynthia Rosenzweig, Pramod K. Aggarwal, Phillip D. Alderman, Jakarat Anothai, Bruno Basso, Christian Biernath, Davide Cammarano, Andy Challinor, Delphine Deryng, Giacomo De Sanctis, Jordi Doltra, Elias Fereres, Christian Folberth, Margarita Garcia-Vila, Sebastian Gayler, Gerrit Hoogenboom, Leslie A. Hunt, Roberto C. Izaurralde, Mohamed Jabloun, Curtis D. Jones, Kurt C. Kersebaum, Bruce A. Kimball, Ann-Kristin Koehler, Soora Naresh Kumar, Claas Nendel, Garry J. O’Leary, Jørgen E. Olesen, Michael J. Ottman, Taru Palosuo, P. V. Vara Prasad, Eckart Priesack, Thomas A. M. Pugh, Matthew Reynolds, Ehsan E. Rezaei, Reimund P. Rötter, Erwin Schmid, Mikhail A. Semenov, Iurii Shcherbak, Elke Stehfest, Claudio O. Stöckle, Pierre Stratonovitch, Thilo Streck, Iwan Supit, Fulu Tao, Peter Thorburn, Katharina Waha, Gerard W. Wall, Enli Wang, Jeffrey W. White, Joost Wolf, Zhigan Zhao and Yan Zhu

In the version of this Article originally published, multiple errors were made in the author affiliations. References 49 and 51 were mislabelled. A source of funding was also omitted. These errors and omissions have been corrected in all versions.

