Responses to reviewer #1

- General: Given the ambitions of charges of Paris Climate Agreement, the authors consider and quantify the climate impacts to maize, wheat, and rice in China, focusing on mean yield impacts, climate extremes, and variability. The authors take an ensemble approach using multiple climate models and the MCWLA family of crop models to conduct a large set of gridded simulations, allowing them to assess both the country level responses in each crop, but also consider the regional heterogeneity in response. The authors also consider these impacts with CO_2 fertilization turned off and on – a critical source of uncertainty and needed dimension in all climate-crop projections, particularly under high mitigation scenarios. In general, the authors find that though some negative yield impacts occur, particularly in maize, most declines are marginal and the potential national mean gains in crop yields, particularly wheat and rice, could considerably outweigh any deleterious effects of 1.5℃-2℃ temperature rises. Gains in crop yields are a result of both enhanced solar radiation and more optimal thermal regimes for photosynthesis, and the impacts of CO_2 fertilization further amplify regionalized yield gains. While the effects of extremes are important and locally impactful – the authors show extreme effects even with the productivity boosts of CO_2 fertilization - these too have limited national impact. The authors conclude that so long as heavy mitigation takes place to limit large global temperature increases, China could take advantage of more optimal growth conditions that come with 1.5℃-2℃.

In general, this study is strong and fairly comprehensive in considering many aspects of climate change and crop growth, following methodologies that are now becoming standard for climate-crop assessments (ensemble approaches, with/without CO_2 effects, assessing both mean changes and extremes, as well as variability). As such, I find this study to fit nicely into the growing body of climate-crop literature, and its focus on China is additive and widely useful. I particularly liked the clarity of the visualizations, as it was quite interesting to read not just about the country totals, but also consider the spatially distributed impacts, which follow clear gradients in surface attributes across China. I think this study also comes at a opportune time, in the context of several other 1.5℃-2℃ assessments resulting from the Paris charge and so this will be important to publish sooner rather than later.

While I think this study is mostly comprehensive and complete, I do have suggestions for minor edits and clarifications that could help the work become accessible to wider array of readers, and eliminate some outstanding questions. As such, I recommend this study for publication after some minor edits are addressed.

Thanks a lot for the positive comments. We have followed all the suggestions to improve the manuscript. New information and figures have been added to describe the study more clearly. In addition, the language of manuscript has been carefully checks to better convey the results. The detailed responses are as follows.

Line Specific Comments:

1. Page 2, Lines 10-15: Perhaps good to have a more updated reference on the CO_2 effects, as they have been more incorporated and studies in recent crop modeling exercises (e.g. see (Deryng et al., 2016))

   Added more updated references. Please see page 2 lines 14-17.

2. Page 2, Lines 28-35: Line beginning with "So far there. . ." needs a rephrase, as it is long and awkward. In fact there are several examples of this dotted throughout the manuscript, so I recommend that this work receives a thorough editing to help with clarifying the sentences, as this will help to better convey the results.

   Followed the suggestion and rephrased the sentence. Please see page 2 lines 31-34.
   In addition, we have polished the language throughout the manuscript.

3. Page 3, Lines 5-10: While the climate data has been well described, more information could be made available as to where the crop system information was sourced from. I'm guessing this came from national databases and statistics? It would help to know if someone wanted to reproduce components of this or use the same cultivation areas.

   We have added the sources for crop system information. We have clarified that the dataset of cultivation area information were obtained from Monfreda et al. (2008). The information for crop phenology could be found from http://data.cma.cn/en. In addition, crop yields in each growing season have been recorded by the National Bureau of Statistics of China (http://www.stats.gov.cn/english/). Please see page 3 lines 13-15.

4. Page 3, Line 13: The historical time period needs to be corrected to 2006-2015 (not 2115)

   Thanks for your careful check, we have revised it. Please see page 3 line 19.

5. Page 4, Line 5-10: The authors do cite prior studies here in their description of model validation and calibration, but I think there is room to add a couple of sentence regarding how regional or grid cell differences in management were handled (even if just summarized from prior studies). As one reads through the results, questions may arise of how management contributes to some of these patterns, particularly as one muses about impacts and adaptation. So having just a bit of explanation here on how management regimes change or how that was treated would be helpful (as this can be difficult to implement on a grid). If there is no space, it could be useful to put this in an appendix (with maybe some reference or table of the various parameter sets used).

We have added more description about the crop model. We have clarified that the MCWLA models adopted a simplified method using a yield gap parameter to account for the effects of pests, diseases and non-optimal management such as fertilization. The differences of calibrated yield gap parameter among different regions represented the heterogeneity of managements. We have also clarified that during model simulation, the irrigation was for maize and wheat was assumed as automatic irrigation of 50 mm if the ratio between transpiration and potential transpiration was lower than 0.5. For rice, full irrigation was assumed when necessary during simulation. Please see page 4 lines 8-10 and page 5 lines 4-6.

6. Pages 4-5, Lines 30-3: I think the section on how heat stress and drought were defined and/or classified within a time period needs a bit more explanation. As I understand it based on what’s written, it seems that within a time period, periods that past a threshold for drought or heat stress were binned separately from periods that did not meat that threshold, and then the difference was taken. These differences were then compared between time periods. Is this correct? I think how you classified these events needs more explanation, as it’s not quite clear from the short amount of text shown here.

Actually, as a mechanism model, the MCWLA model could identify the extreme events by considering multiple environment variables. The impacts of heat stress and drought stress were considered in MCWLA models by limiting the simulation processes of leaf growth, root growth, biomass accumulation and the calculation of harvest index. In this study, differences between the simulated yields with and without considering the limitation of extreme event stresses were used to quantify the impacts of extreme events. In addition, the differences of impacts between historical and future periods were used to evaluate the changes in the impacts of extreme events.

We have clarified the method of estimating impacts from extreme events in revised manuscript. Please see page 5 lines 21-29.

7. Page 5, Lines 10-30: I understand that the authors had a lot of power in their dataset, given the 70-member ensemble. I also appreciate that the under 1.5℃-2℃ conditions, differences in crop response are bound to be somewhat small. However, I don't see a mention at all with respect to significance, particularly when some of these areas are bound to be highly variable. There is an opportunity to discuss this in the variability section later on, but I think that comes too late.

   I do not think the significance needs to be over-emphasized as these changes are quite small, but it should still be addressed – and important point here being that under high mitigation scenarios, general yield variability owing to weather and CO_2 effects and other factors might still be a more dominant forcing than climate change itself. These ideas could be addressed more in your discussion as well, as they would be consistent with other studies (for example in Section 4.3) that talk about driving uncertainties in climate-crop assessments.

We have carefully revised the manuscript and figures to add information about significance. The significance of differences for climate factors and crop responses between 1.5℃ and 2℃ warming scenarios have been clarified. Please see revised Figure 2, 4, 5, 7, 8; page 6 line 8-9, 13-14; page 7 lines 11-12, 18-19, 24-25; page 8 lines 11-15; page 9 lines 1-3, 5-8, 14-16, 20-22.

8. Page 5, Line 30: I suggest that every where you use "slighter" in the manuscript, you replace it with "smaller" or something along those lines as the wording is a bit off.

We have followed your suggestion and revised the word "slighter" to "smaller" or "less".

9. Page 8, Line 2 and Figure 7: The two rows of picture in each sub-panel look exactly the same. I understand the authors said that CO_2 made little difference on the impact of extremes, however it is impossible to tell any difference in the figures. I think when dealing with small differences, it would be better to show a difference

plot between no CO_2 and with CO_2 so that the reader could better visualize how small or regionally different the change in impacts are.

Followed. A new figure (Figure A2) has been added in supplementary to clarify the differences. Please see Figure A2.

10. Page 8, Lines 22-30 and Figure 9: Can the authors clarify here: is this exactly what's written – the standard deviation in the yield changes or anomalies? Or is this the change in SD/variation between the historical and 1.5℃-2℃? I think it's the former, but I think it could also be helpful to show the latter as well. The first way speaks a bit to the uncertainty in the changes, while latter shows how the yield variability changes between scenario, and I was wondering about that as well.

    Yes, you are right. We showed the standard deviation in the yield changes. Please see page 10 line 2. In addition, we have followed your suggestion and showed the changes in yield variability between warming scenarios. Please see Figure A3 and page 10 lines 15-20.

11. Page 9, Line 25: Please break up this first sentence as it's a bit long to read in its current form

    Revised. Please see page 11 lines 20-23.

Please note that the supplement to the comment of reviewer #1 is not for our manuscript but for other manuscript. Thus we don't responses to it.

Impacts of climate change and climate extremes on major crops productivity in China at a global warming of 1.5℃ & 2.0℃

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Abstract. A new temperature goal of "holding the increase in global average temperature well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels" has been established in Paris Agreement, which calls for understanding of climate risk under 1.5℃ & 2.0℃ warming scenarios. Here, we evaluated the effects of climate change on growth and productivity of three major crops (i.e., maize, wheat, rice) in China during 2106-2115 at warming scenarios of 1.5℃ & 2.0℃ using a method of ensemble simulation with well-validated MCWLA family crop models, their 10 sets of optimal crop model parameters, and 70 climate projections from four global climate models. We presented the spatial patterns of changes in crop growth duration, crop yield, impacts of heat and drought stress, as well as crop yield variability and probability of crop yield decrease. Results showed that climate change would have major negative impacts on crop production, particularly for wheat in north China, rice in south China and maize across the major cultivation areas due to decrease in crop growth duration and increase in extreme events. By contrast, with moderate increases in temperature, solar radiation, precipitation, and atmospheric CO_2 concentration, agricultural climate resources such as light and thermal resource could be ameliorated which enhance canopy photosynthesis, and consequently biomass accumulations and yields. The moderate climate change would slightly deteriorate maize growth environment but result in much more appropriate growth environment for wheat and rice. As a result, wheat, rice and maize yields would change by +3.9% (+8.6%), +4.1% (+9.4%), and +0.2% (-1.7%), respectively, at a warming scenario of 1.5℃ (2.0℃). In general, the warming scenarios would bring more opportunities than risks for the crop development and food security in China. Moreover, although variability of crop yield would increase from 1.5℃ warming to 2.0℃ warming, the probability of crop yield decrease would decrease. Our findings highlight that the 2.0℃ warming scenario would be more suitable for crop production in China, but the expected increase in extreme events impacts should be paid more attention to.

1 Introduction

In the past decades, global warming has markedly shifted the spatial-temporal patterns of temperature and precipitation (Gourdji et al., 2013; Liu and Allan, 2013). Moreover, the warming trend is expected to go on in the following decades with the increase of greenhouse gas emissions (Zhao et al., 2017), especially in cultivated areas (Lobell et al., 2011).The effects of climate changes and climate extreme on growth and yields of crops have been highly concerned (Porter et al., 2014; Asseng et al., 2015). Researchers have extensively demonstrated crop responses to climate factors through conducting environment-controlled experiments (e.g., Ottman et al., 2012; Chen et al., 2016), analysing historical records (e.g., Lobell et al., 2011; Tao et al., 2012; Tao et al., 2014), and crop model simulations (Porter et al., 2014; Asseng et al., 2015). These studies have documented that increasing temperature could shorten crop growth duration and reduce crop yields at broad regions (Porter et al., 2014). Meanwhile, with climate warming, the frequency and intensity of climate extreme events, for example heat stress, are projected to increase, and substantially threaten the crop growth and food security, especially for some susceptible areas (Wahid et al., 2007; Asseng et al., 2011; Gourdji et al., 2013). Besides the negative impacts, the warmer environment could also improve the crop productions in some areas that suffered from heat deficit (Tao et al., 2008a; Tao et al., 2012; Tao et al., 2014; Zhang et al., 2014). In addition, elevated CO_2 concentration could inhibit the stomatal conductance and reduce the transpiration rates (Brown and Rosenberg, 1997, Burkart et al., 2011; Deryng et al., 2016), enhance photosynthesis, and consequently have fertilization effects on crop productivity (Ainsworth et al., 2008; Leakey, 2009; Vanuytrecht et al., 2012; Pugh et al., 2016).

With the progresses on impact mechanisms, crop model improvements and impacts assessment approaches such as ensemble simulations, climate change impact assessments have been elaborated in recent decade (Porter et al., 2014). The results of these studies have stressed the remarkable increase of extreme events and the decrease of major food crop yields, particularly under those scenarios with relatively higher temperature increase (Lobell et al., 2014; Porter et al., 2014). These results alerted the food crisis and highlighted the importance of mitigating the impacts of human activities on climate change. Recently, a new temperature goal of “holding the increase in global average temperature well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels” have been established in Paris Agreement for the purpose of significantly reducing the risks and impacts that caused by climate change (UNFCCC, 2015). This goal implied a more moderate climate scenario in the future, requiring more focuses on the impacts evaluation in a warming world with ambitious mitigation strategies, and thus called for climate change impact assessments under the 1.5℃ warming and 2.0℃ warming scenarios (Mitchell et al., 2016).

China is one of the major countries producing the staple food including maize, rice and wheat. Crop productions in China have accounted for roughly 21%, 28% and 17% of global total production of maize, rice and wheat, respectively, during the past decade. However, so far there has no study on the impacts of 1.5℃ warming and 2.0℃ warming on crop production in China. Therefore little information is available on the question of “What may probably happen to the future crop production in China with moderate temperature increase?” Here, we tried to conduct a study to evaluate the influences of climate change and climate extremes on these major crop yields in China at the warming scenarios of 1.5℃ & 2.0℃. We aimed to provide the spatial patterns of changes in crop growth duration, crop yield, yield decrease probability, and impacts of heat and drought stress for three major crops under these warming scenarios across China at a spatial resolution of 0.5°×0.5°.

2 Materials and methods

2.1 Study area

This study focused on the cultivation area of maize, wheat and rice across China. The crop cultivation areas were shown in Fig. 1. The study was conducted at a grid scale with spatial resolution of 0.5°×0.5°. The maize was mainly sown in the northeast China, North China Plain (NCP) and some areas of southwest China (Fig. 1b). The major cultivation areas of winter wheat were across the NCP and Sichuan Basin, and the spring wheat was sown above the 40th degree of Northern Latitude (Fig. 1c). The rice was widely cultivated in the northeast, southwest and south China (Fig. 1d). The double rice (early rice and later rice) was cultivated in six provinces in south China, while single rice was cultivated in other regions. The dataset of cultivation area information were obtained from Monfreda et al. (2008). The information for crop phenology could be found from http://data.cma.cn/en. In addition, crop yields in each growing season have been recorded by the National Bureau of Statistics of China (http://www.stats.gov.cn/english/).

2.2 Data

The climate dataset used in this study were the outputs of the “half a degree additional warming, projections, prognosis and impacts (HAPPI) experiment”, which provided historical climate datasets during 2006-2015 and the projected climate scenarios that were 1.5℃ and 2.0℃ warmer than pre-industrial level during 2106-2115 (Mitchell et al., 2017). Data from four global climate models (GCMs) including the CAM4, ECHAM6, MIROC5and NorESM1with 1.5℃ warming and 2.0℃ warming scenarios were published by the National Energy Research Scientific Computing Center (NERSC) at http://portal.nersc.gov/c20c/data.html. These datasets had been bias corrected using the methods in Hempel et al. (2013) and Frieler et al. (2016) and the dataset EWEMBI (Frieler et al., 2016; Lange, 2016). These climate datasets were generated using ensemble simulations that driven with different initial conditions. In the datasets, the CAM4, ECHAM6 and NorESM1 provided 20 runs of simulation results and the MIROC5 provided 10 runs of simulation results. All these runs were input into crop models and treated equally. In this study, the period of 2006-2015 was regarded as historical period and the period of 2106-2115 was regarded as future period. The soil texture and hydrological properties data that used during crop model simulation were obtained from the FAO soil dataset as described in Tao and Zhang (2013a).

2.3 MCWLA model and its parameterization

The MCWLA model family, including MCWLA-Maize model (Tao et al., 2009a; Tao et al., 2009b), MCWLA-Wheat model (Tao and Zhang, 2013a) and MCWLA-Rice model (Tao and Zhang, 2013b), were used as tools to simulate crop growth in this study. The MCWLA models were designed for the crop growth simulation at a daily step and the crop yields estimation. Briefly, the MCWLA models take the temperature and photoperiods into account to drive the simulation of daily crop development. Meanwhile, the growth rates that driven by heat and the water stresses were considered during estimating the LAI growth. In addition, the models adopted the process-based representation of the coupled CO_2 and H_2O exchanges in the Lund–Potsdam–Jena (LPJ) model. The models adopted a simplified method using a yield gap parameter to account for the effects of pests, diseases and non-optimal management such as fertilization. The differences of calibrated yield gap parameter among different regions represented the heterogeneity of managements.

The MCWLA models have been widely used to simulate the effects of climate change and climate extreme on crop growth and yields at broad areas of the world (Asseng et al., 2013; Bassu et al., 2014; Asseng et al., 2015; Li et al., 2015; Tao et al., 2015; Shuai et al., 2016; Wang et al., 2016; Chen et al., 2017a; Chen et al., 2017b; Zhang et al., 2017). The simulation results in previous studies indicated that the MCWLA models could fairly well capture the effects of climate change, climate extreme and elevated CO_2 on crop growth and yields, including crop yield variability due to variations in temperature (Tao and Zhang, 2013a, b), heat stress (Asseng et al., 2015) and CO_2 concentration (Tao and Zhang, 2013a; Durand et al., 2017; Hasegawa et al., 2017).

In this study, the MCWLA models were used to simulate the yields of maize, wheat and rice in China at a grid scale under different climate scenarios. The model parameters have been well calibrated and validated in China by previous studies for maize (Tao et al., 2009a,b; Shuai et al., 2016), rice (Tao and Zhang, 2013a; Wang et al., 2016) and wheat (Tao and Zhang, 2013a; Chen et al., 2017b). In these studies, MCWLA models were calibrated and validated at a province scale. The Bayesian probability inversion, Markov chain Monte Carlo (MCMC) technique and particle swarm optimization algorithm have been applied to analyse uncertainties in parameter estimation and model prediction and to optimize the model. Model calibration and validation were based on the historical provincial yield statistics. Root-mean-square error (RMSE) and correlation coefficient (r) were used to evaluate the simulation accuracy of models. For each crop in each province, ten optimal sets of parameters that produced the minimum RMSE and appropriate r were selected. Using multiple sets of parameters, crop models could better represent the diverse cultivars and management practices in a region and thus can have a better estimate of regional yield, which have been addressed in previous papers (Tao et al., 2009a, b). The validation results of MCWLA models for maize, wheat and two growing seasons of rice in our study areas were summarized in Table 1.

2.4 Methods to evaluate the impacts of climate change and climate extreme

For each grid cell across the cultivation areas of each crop, the bias-corrected climate datasets were used as input data to drive the well-validated MCWLA models. According to the protocol of HAPPI, the emission scenario of 1.5℃ warming was close to that of RCP 2.6, and the emission scenario of 2.0℃ warming was weighted between RCP 2.6 and RCP 4.5 (Mitchell et al., 2017). In this study, the simulation during 2006-2015 used the CO_2 concentration of 390.5 ppm. Meanwhile, the CO_2 concentration during 2106-2115 was set as 416.1 ppm and 490.5 ppm for warming scenarios of 1.5℃ & 2.0℃, respectively. The irrigation was considered during model simulation. For maize and wheat, we assumed automatic irrigation in simulation settings, that is, an irrigation of 50 mm would be conducted if the ratio between transpiration and potential transpiration was lower than 0.5. For rice, full irrigation was assumed when necessary during simulation.

The annual average simulation results during 2006-2015 and 2106-2115 were compared at grid scale. Because we used 70 runs of climate data and 10 sets of parameters, thus we could obtain an ensemble of 70 climate projections ×10 sets of parameters =700 sets of comparison results for each grid under a single warming scenario. Then the median of these results was used to demonstrate the changes between the two periods for a certain variable such as crop growth duration and crop yield.

In this study, we evaluated the changes in growth duration, yield and the impacts of climate extreme events on crop yield for each grid with crop cultivation across China at the warming scenarios of 1.5℃& 2.0℃, respectively. For growth duration and yield in each grid under one set of climate data, the changes were identified as Eq. (1):

$$S_c = \frac{S_f - S_h}{S_h} \times 100\% \qquad (1)$$

Where S_c was the change percentage between two periods, S_h and S_f were annual average simulation result for the historical and the future period, respectively. Meanwhile, standard deviation (SD) of S_c for yield was also calculated at grid scale to represent yield variability. Moreover, we also computed the probability of yield decrease by calculating the percentage of simulation results that showed yield decrease among the 700 simulated results at each grid.

Furthermore, to evaluate the impact of climate extreme event, we selected heat stress on rice and wheat and the drought stress on wheat and maize as typical extreme events. The impacts of heat stress and drought stress were considered in MCWLA models by inhibited function limiting the leaf growth, root growth, photosynthesis, biomass accumulation and the calculation of harvest index. The impacts of climate extreme event on crop yield were quantified as the differences between the simulated yields with and without considering the limitation of extreme event stresses:

$$YL = \frac{Y_1 - Y_0}{Y_1} \times 100\% \qquad (2)$$

Where YL was the yield loss percentage caused by extreme events, Y_0 was the simulated yield using original MCWLA model which considered the impacts of the extreme event. Y_1 was the simulated yield with assumption that those extreme events would not limit the crop growth. We calculated the YL for both historical period and future period. The differences of YL between historical and future periods were used to evaluate the changes in the impacts of extreme event on crop yield.

Besides the analysis at a grid scale, we also aggregated the simulated yields to country scale using the cultivation areas-weighted-mean based on the crop cultivation ratios for each grid to present the impact of climate change on national food supply.

3 Results

3.1 Changes in critical climate factors at the warming scenarios of 1.5℃ & 2.0℃

The spatial patterns of projected annual changes in average temperature, precipitation and solar radiation during 2106-2115, relative to 2006-2015, were shown in Fig. 2. These changes were the median changes based on the 70 sets of climate projections. The spatial patterns of climate change at the warming scenarios of 1.5℃ & 2.0℃ were similar. Increase in temperature was projected by approximately 0.7 ~ 1.05℃ and 1.2 ~ 1.9℃, respectively, at the warming scenarios of 1.5℃ & 2.0℃ (Fig. 2a, b). The SD of temperature changes could generally range from 0.3 to 0.5 ℃ in most of areas in China (Fig. A1a, b). Significant differences in temperature changes could be in the whole China between two warming scenarios (Fig. 2b). Temperature would increase less in the northeast China, NCP, southwest China and the Qinghai-Tibet Plateau. As for precipitation, the median change showed that precipitation would increase up to 8% during 2106-2115 in most parts of China (Fig. 2c, d). However, precipitation variability was large with a SD up to 15% in most of cultivation areas (Fig. A1c, d). In general, the increase of precipitation at warming scenario of 2.0℃ would be larger than that at warming scenario of 1.5℃ except some areas in southwest China although the differences between two warming scenarios were not significant in general. For most of the cultivation areas of major crops in China, increase of precipitation would range from 2% ~ 6%. Increase of precipitation would be greater in the southeast China by more than 6%. Solar radiation would increase in nearly the whole country (Fig. 2e, f). Under 1.5℃ warming scenario, it was expected to increase by more than 7% in the southern parts of China, particularly the Sichuan, Chongqing, Guizhou and Hunan provinces. Moreover, solar radiation in these areas would increase more significantly under 2.0℃ warming scenario. In other regions, solar radiation would increase by less than 6%, which was similar under the two warming scenarios. In regions with a large increase in solar radiation, SD could be large too. In the study area, SD of solar radiation changes was projected to be 2% ~ 7% (Fig. A1e, f).

3.2 Impacts of climate change on major crops growth durations

Increase in temperature would accelerate crop development rate and consequently reduce crop growth duration. Results showed that increase in temperature would ubiquitously shorten the growth duration of the three major crops (Fig. 3). The most prominent decrease in maize growth duration could be expected in the northeast China, southwest China and Loess plateau by up to 6% and 10% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 3a, b). The decrease in maize growth duration would be relatively smaller (4% ~ 8%) in south China. In addition, the impacts of climate change on maize growth duration would be the smallest in the NCP where was expected to reduce by less than 2% in most of areas. The decrease in growth durations of wheat would be smaller than that of maize (Fig. 3c, d). In most of regions, wheat growth duration would decrease slightly by less than 4%, particularly in the NCP (less than 2%). Wheat growth duration could decrease more in the northeast, southwest and northwest China. Under 2.0℃ warming scenario, the decrease of growth duration would be approximately 2% more than that under 1.5℃ warming scenario in most of cultivation areas, except the

NCP. Rice phenology would change more apparently in the double rice region (Fig. 3e, f). Rice growth duration was projected to decrease by 4% ~ 8% and 6% ~10% at the warming scenarios of 1.5℃ & 2.0℃, respectively. By contrast, it was projected to reduce by less than 2% in other regions, with slight differences between the two warming scenarios.

3.3 Impacts of climate change on major crops yields

The projected impacts of climate changes on the three major crops yields in China were investigated without (Fig. 4) and with taking CO_2 fertilization effect into account (Fig. 5). Without taking CO_2 fertilization effect into account, maize yield in most of the cultivation areas would decrease by less than 10% under 1.5℃ warming scenario (Fig. 4a). Under 2.0℃ warming scenario, yield decrease would be less than 15% in most of areas. The yield decrease would be larger than 15% at 5.6% of the grids with maize cultivation (Fig. 4b). Maize yield was expected to increase mainly in the northeast China and some portions in northwest China. The proportion of grids with yield increase would be 45.5% under 1.5℃ warming scenarios, and 35.1% under 2.0℃ warming scenarios. In 50.5% of grids with maize cultivation, yield changes between 1.5℃ and 2.0℃ warming scenarios were not significant (Fig. 4b). As for wheat, the areas with yield increase would be in the southern parts of the cultivation areas (Fig. 4c, d), where yield was expected to increase by less than 10% under the both warming scenarios. The regions with yield decrease were located in the northern parts of China and Yunnan province in southwest China, where yield was expected to decrease by up to 15% and 25% at the warming scenarios of 1.5℃ & 2.0℃, respectively. Under 2.0℃ warming scenario, the areas with yield increase would slightly shrink. Moreover, the yield decrease would obviously aggravate by approximately 5% in most of areas with yield decrease under 1.5℃ warming scenario. The differences of yield changes between 1.5℃ and 2.0℃ warming scenarios were generally significant expect some grids (~ 14.5%) in Gansu, Guizhou and Jiangsu provinces (Fig. 4d). For rice, there was a spatially explicit pattern of yield changes (Fig. 4e, f). Rice yield would increase by 5% ~ 15% or even larger than 30% in the northeast and southwest China. The yield increase in these areas would be greater at warming scenario of 2.0℃ than that at 1.5℃. However, in the central parts of rice cultivation areas and the double rice cultivation region, rice yield was projected to decrease widely by less than 10% and 15% at the warming scenarios of 1.5℃ and 2.0℃, respectively. The differences of yield changes between the two warming scenarios would be less significant in Sichuan Basin and some areas of northeast China than other rice cultivation areas.

When considering the CO_2 fertilization effect, the effects of CO_2 fertilization could enhance crop photosynthesis and increase crop productivity to some extent for all the three major crops (Fig. 5). For maize, the differences between the simulated yields with and without considering CO_2 fertilization effect were small (Fig. 4,a, b, Fig. 5a, b). The contribution of CO_2 fertilization effect to maize yields was generally less than 6%, and it would be a little more obvious at warming scenario of 2.0℃ than that at 1.5℃. In regions such as the NCP and middle and low reaches of Yangtze River (MLYR), maize yield would increase at more areas than those without CO_2 fertilization effect. Nevertheless, yield would still decrease in more than half of grids with maize cultivation. In comparison with maize, the yields of wheat and rice were more benefited from the elevated CO_2 concentrations. The contribution of CO_2 fertilization effect to wheat yield could reach 4% and 15% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 5c, d). With CO_2 fertilization effect, the decrease in wheat yield in the northeast China and NCP could be totally compensated. As a result, yield could be expected to increase by approximately 5% ~ 15% in most of the wheat cultivation areas (Fig. 5c, d). The increase of wheat yield under 2.0℃ warming scenario would be 5% larger than those under 1.5℃ warming scenario. In addition, wheat yield decrease in Inner Mongolia and Yunnan Provinces would be less than 10%, suggesting that the risks of yield decrease caused by climate change could be reduced by the rising of CO_2 concentration in these areas. As for rice, the contribution of CO_2 fertilization effect could be 2% ~ 5% and 8% ~ 16% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 5e, f). Yield decrease in the central China and double rice regions could be compensated and the widespread yield increase would be expected across the entire rice cultivation areas. Yield increase under 2.0℃ warming scenario would be 5% ~ 10% larger than that under 1.5℃ warming scenario. The elevated CO_2 concentrations would lead to more significant difference between yield changes under 1.5℃ and 2.0℃ warming scenarios for wheat and rice. In general, there were significant differences between simulation results under 1.5℃ and 2.0℃ warming scenarios in nearly the entire cultivation region (Fig. 5d, f). However, maize yield was less sensitive to the rising of CO_2 concentration. Significance of differences between yield changes under 1.5℃ and 2.0℃ warming scenarios was similar to those without considering CO_2 fertilization effect (Fig. 4b, 5b).

To evaluate the possible effects of climate change on country-level crop productivities, the simulation results at grid scale were aggregated to country scale. The yield changes for the three major crops at country scale under different climate scenarios were shown in Fig. 6. Without CO_2 fertilization effect, maize yields at country level would decrease by 0.1% and 2.6% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 6a, b). By contrast, wheat and rice would slightly benefit from climate change at warming scenario of 1.5℃ but suffer from negative impacts at warming scenario of 2.0℃ (Fig. 6a, b). Wheat yield would increase by 1.2% but decrease by 0.9% at the warming scenarios of 1.5℃ & 2.0℃, respectively. Rice yield would increase by 0.7% under 1.5℃ warming scenario but decrease by 2.4% under 2.0℃ warming scenario. When considering the CO_2 fertilization effect, crops would obtain a larger yield increase or less yield decrease (Fig. 6c, d). Maize yield would increase by 0.2% under 1.5℃ warming scenario and the yield decrease would reduce to 1.7% under 2.0℃ warming scenario. Wheat and rice yields would increase by 3.9 % and 4.1%, respectively, under warming scenario of 1.5℃ (Fig. 6c); and by 8.6% and 9.4%, respectively, under warming scenario of 2.0℃ (Fig. 6d).

3.4 Impacts of climate extremes on major crops yields

The influences of climate extreme events, including heat stress and drought stress, on yield have been explicitly accounted for in this study. The impacts of heat stress on wheat and rice (Fig. 7), and the impacts of drought stress on wheat and maize (Fig. 8) were shown here. Without considering CO_2 fertilization effects, wheat yield loss caused by heat stress would increase in the northern parts of China by up to 8% under warming scenario of 1.5℃ (Fig. 7a), particularly in the Inner

Mongolia, Loess Plateau and NCP, and it would become significantly larger at warming scenario of 2.0℃ (Fig. 7b). In other regions such as the southwest China, the risk of heat stress would not change obviously. In addition, the heat stress risk would not change significantly between 1.5℃ and 2.0℃ warming scenarios in these areas. As for rice, yield loss caused by heat stress would increase by less than 2% and 5% under 1.5℃ and 2.0℃ warming scenario, respectively, mainly in the MLYR (Fig. 7e, f). Under 2.0℃ warming scenario, the increase of heat stress risk would be more significant in these areas than those under 1.5℃ warming scenario. In other regions such as the northeast China and southwest China, the risk of heat stress would not change much comparing with historical period, and the increase of temperature from 1.5℃ warming to 2.0℃ warming scenario would not significantly increase the heat stress risk. When taking CO_2 fertilization effect into account, the results were quite similar to those without considering CO_2 fertilization effect (Fig. 7c, d, g, h, Fig A2), indicating that the rising of CO_2 concentration would not obviously influence the changes of heat stress risk.

The impacts of drought stress on wheat and maize yield were shown in Fig. 8. The impacts of drought stress on wheat yield would be more severe at nearly the entire cultivation areas (Fig. 8a, b). Under 1.5℃ warming scenario, wheat yield loss due to drought stress would increase by less than 4% in most of areas (Fig. 8a). Yield loss would increase by larger than 2% in 45.5% of the grids with wheat cultivation. Under 2.0℃ warming scenario, the yield loss would be significantly larger in northeast China, Inner Mongolia, and Guizhou Province than that under 1.5℃ warming scenario (Fig. 8b). Yield loss in the southern parts of the NCP would decrease obviously. In general, the yield loss would increase by more than 2% in 50.8% of the grids with wheat cultivation. As for maize, the impacts of drought stress would decrease in the southeast China by approximately 2% (Fig. 8e, f). By contrast, in most parts of maize cultivation areas, maize yield loss due to drought stress would increase by up to 8%, mainly in the Loess Plateau, NCP and some areas in northeast China and southwest China. Grids with yield loss increase by more than 2% would be expected in 31.6% at the warming scenarios of 1.5℃. Impacts of drought would significantly aggravate under 2.0℃ warming scenario, particularly for Loess Plateau, NCP and northernmost China. 53.5% of all grids would suffer from yield loss increase by more than 2%.

Elevated CO_2 concentration would reduce impacts of drought stress on crop growth, consequently reduce yield loss. Yield loss would be reduced more significantly under warming scenario of 2.0℃ than 1.5℃. For wheat, the percentage of grids with increased yield loss of more than 2% would reduce to 18.8% at warming scenario of 1.5℃ (Fig. 8c). Meanwhile, yield loss under 2.0℃ warming scenario was expected to decrease in nearly 60% of the grids (Fig. 8d). By contrast, decrease of yield loss could be found in only 5.7% of grids when CO_2 fertilization effect was not taken into accounted. For maize, yield loss due to drought stress could be expected to decrease in a larger area, particularly the northeast China and southwest China (Fig. 8g, h). The Loess Plateau would still be the hotspot areas suffered from increased drought stress, however the increase of yield loss would be less than 6% generally.

3.5 Variability in the projected yield changes

The SD of the projected yield changes between historical and future periods was shown in Fig. 9. For maize, the SD would be relatively larger in the south China and some marginal areas of the northeast China, where it could be larger than 20%. By contrast, it was generally less than 10% in most parts of the northeast China, NCP, Loess Plateau and southwest China (Fig. 9a, b). The SD under 2.0℃ warming scenario would generally be larger than that under 1.5℃ warming scenario except the areas with relatively smaller SD in NCP and Loess Plateau. For wheat, under both warming scenarios, the SD of simulated yield changes was less than 9% in most of the cultivation areas. However, it could be up to 12% and 18%, respectively, in the NCP and Inner Mongolia (Fig. 9c, d). The SD under the two warming scenarios was similar in most of cultivation areas, while SD under 2.0℃ warming scenario would increase in some areas of the NCP and southern parts of cultivation areas. As for rice, the simulated yield changes in double rice region and most parts of the southwest China were relatively stable with SD generally less than 9% under the both warming scenarios (Fig. 9e, f); by contrast, the SD would range from 9% to more than 20% in the northeast China, central China and the Sichuan Basin (Fig. 9e, f). The SD in MLYR at warming scenario of 2.0℃ would be larger than that at warming scenario of 1.5℃. In other regions, the variability of rice yield changes was similar under the two warming scenarios.

Changes in coefficient of variation (CV) of simulated yields were used to show the changes in variability of simulated yields between 1.5℃ and 2.0℃ warming scenarios (Fig. A3). For maize, CV would increase mainly in the northernmost China and southeast China by 4% ~ 8%. In other regions, the changes of CV were generally within ±2%. As for wheat, the changes in CV were generally within ±2% in the entire study area, indicating small changes between the two scenarios. For rice, CV of simulated yields would decrease mainly in the northeast and southwest China by more than 2% or even 4%. In other regions, the changes of CV were within ±2%.

The SD of the changes in yield loss that due to heat stress and drought stress were shown in Figs. A4 and A5, respectively. The CO_2 fertilization effect would not obviously affect the SD of projected changes in yield loss. However, the changes in warming scenario from 1.5℃ to 2.0℃ would more or less affect the projected changes in yield loss. For heat stress, the projected changes in wheat yield loss showed a large variability in the northern parts of the study area, while the variability for rice was large in double rice region in south China, with SD ranging from 4% to 10% in these areas.By contrast, SD in other areas were generally less than 2%. For drought stress, the SD of projected changes in wheat yield loss could be larger than 8% in the northeast China, NCP and southwest China. The SD of projected changes in maize yield loss was larger in the NCP and Loess Plateau than other cultivation areas, with a SD of 4% ~ 6%.

3.6. Probability of yield decrease at the warming scenarios of 1.5℃ & 2.0℃

Based on the large number of ensemble simulations, the probability of major crops yields decrease was estimated and presented in Fig. 10. For maize, yield would decrease with probability of more than 60% at warming scenario of 1.5℃ in the southwest China, southeast coast areas, some portions in the north China, NCP, and northeast China (Fig. 10a). Moreover, the probability of yield decrease in these areas would increase at warming scenario of 2.0℃ (Fig. 10b). In contrast, the probability of maize yield decrease would be less than 40% in the MLYR, and the northeast China (Fig. 10a). In addition, the yield decrease probability in these areas would decrease to less than 30% at warming scenario of 2.0℃ (Fig.10b). For wheat, probability of yield decrease was projected to generally less than 30% in more than half of the wheat cultivation areas at warming scenario of 1.5℃ (Fig.10c). However, yield would decrease with probability of more than 60% in the southwest China, north China, and some portions in marginal areas in northeast China. At warming scenario of 2.0℃, the probability of yield decrease would reduce in the areas with low decrease probability (Fig. 10d). 66% of grids would have yield decrease probability less than 30%, while number of grids with yield decrease probability larger than 70% would not change much. For rice, the probability of yield decrease was projected to be less than 30% generally across most of the cultivation areas under 1.5℃ warming scenario, and the probability would be even less under 2.0℃ warming scenario. But in some areas in the MLYR, the probability of yield decrease could keep ranging from 40% ~ 60% and 40% ~ 50% at the warming scenarios of 1.5℃ & 2.0℃, respectively.

Taking CO_2 fertilization effect into account, at country scale, the SD of simulated yield changes ranged from 1.5% to 4% under different ensemble members (Fig. 6c, d). Meanwhile, the SD under 2.0℃ warming scenario would be generally larger than that under 1.5℃ warming scenario. For maize, wheat and rice, respectively, the probability of yield decrease was 46.1%, 18.3% and 4.3% under 1.5℃ warming scenario, and 70%, 0.6% and 0% under 2.0℃ warming scenario.

4 Discussion

4.1 Impacts of climate change on future crop productivity in China

The results showed there was a similar spatial pattern between changes of growth duration and that of yield decrease without CO_2 fertilization effect. For example, wheat in the northern parts of China, rice in the double rice cultivation regions, and maize across China. These results suggested that growth duration should play a critical role in affecting crop yields. Beside changes in growth duration, varieties in temperature and solar radiation would also impact the crop yields by affecting photosynthesis process. Moderate increase in mean temperature and the increase in solar radiation would promote the yield increase by enhancing crop canopy photosynthesis and consequently biomass accumulation and yield (Tao et al., 2013). These positive effects could underlie the crop responses of yield increase in current study. For example, in cultivation areas of maize with growth duration decrease by less than 2%, the yield would generally increase, which should be due to the increase of solar radiation and the warmer environment that close to optimal temperature for photosynthesis. As for wheat in southern parts of cultivation areas, although the growth duration would obviously decrease because of the relatively large increase in temperature, the yield loss could be compensated by the positive effects of increasing temperature and solar radiation on photosynthesis. For rice, the contribution of increased temperature and solar radiation would be more distinct for rice production in the southwest and northeast China where growth duration would decrease by less than 2%. The large increase of rice yield in these areas indicated a more appropriate environment, particularly a more suitable thermal scenario, for photosynthesis (Tao et al., 2008b; Zhang et al., 2017).

According to the simulation results, impacts from extreme events would still be a critical limitation factor for crop growth in the future. Although their impacts might be slightly mitigated in some areas, the projected increases of stress impacts were always remarkable. The increase of impacts of heat stresses on wheat in the northern parts of China and on rice in south China would significantly aggravate the yield loss in these areas, suggesting the requirement for improving adaptation strategies with higher priority. Meanwhile, the increase of drought impacts indicated that water requirement would widely increase risk of water crisis in most of the cultivation areas.

The elevated atmospheric CO_2 concentration, which is a critical reason for global warming, has also positive impacts on crop yields. The interactions among moderate increase in temperature, solar radiation and CO_2 concentration would enhance photosynthesis (Sage et al., 1995; Hikosaka et al., 2006; Sage and Kubien, 2007; Zhu et al., 2008). The combination of these effects would consequently benefit the biomass accumulations and yield. In this study, the CO_2 fertilization effects have compensated yield decrease of wheat and rice in most of the cultivation areas. As for maize, although less sensitive to the elevated CO_2 concentration, the CO_2 fertilization effect could reduce yield loss to some extent. In addition, the rising CO_2 could also be expected to effectively reduce drought stress because of the stomatal ‘anti-transpirant’ response of plants and the increase of root density and canopy closure which would reduce the transpiration rates at leaf level and meanwhile increase the water availability (Polley et al., 2007; Jiahong et al., 2010). However, for hotspot areas of drought stress aggravation, particularly the wheat production in the north China and the maize production in Loess Plateau, the increase of irrigation should be inevitable and more input in agricultural infrastructure would be necessary.

4.2 Risks and opportunities in regard to crop production in China with climate change

Climate change will substantially alter the growing environment of crops and consequently change the yield potential and yield expectation in future periods (Gourdji et al., 2013; Nelson et al., 2014; Rosenzweig et al., 2014; Assenget al., 2015). In past decade, the negative impacts of climate change have been critically focused on since the foreseeable population growth and more frequent extreme events may infer pessimistic conclusion of food shortage (Wheeler and Von Braun, 2013; Trnkaet al., 2014). In this study, the projected yield changes under 1.5℃ and 2.0℃ warming scenarios presented possible risks to crop production but also suggest opportunities and potentials for agricultural development. The negative impacts were generally resulted from the decrease of growth duration and aggravation of impacts of extreme events. However, the negative impacts under moderate warming scenarios would be very limited at country scale, suggesting low risks for crop production and food security. Moreover, the negative impacts of warming scenarios could be compensated by the increase of solar radiation and temperature, the more appropriate temperature environment in some relatively colder areas, and the fertilization effects of elevated atmospheric CO_2 concentration. As a consequence, yield would increase with high probability for rice and wheat under both warming scenarios. The yield of maize, which was not sensitive to CO_2 fertilization effects, would slightly decrease in a 1.5℃ warmer world and decrease more under 2.0℃ warming scenario. However, the contribution of climate change to increasing wheat and rice productivity would be always much larger than the decrease of maize productivity, indicating that the national overall food supply would benefit from climate change.

We concluded that the 1.5℃ or 2.0℃ warming scenario would bring more opportunities than risks to food supply in China, particularly for wheat and rice. When comparing the effects between warming scenarios of 1.5℃ and 2.0℃, although the variability of yield changes would be larger under 2.0℃ warming scenario, the probability of wheat and rice yield decrease would be less, and their yields would increase much more at warming scenario of 2.0℃ than that at 1.5℃.

4.3 Uncertainties of the study

The uncertainties in the simulation results have been explicitly quantified in this study. Uncertainties in GCMs and model parameterization are critical sources of uncertainties in simulation results (Elliott et al., 2014; Lobell et al., 2014; Tao et al., 2018). In order to provide more accurate evaluation on climate change impacts, the input data, the quality of crop model and climate projection should be further elaborated. Here, we used multiple sets of parameters to account for the uncertainties in cultivars and management in province scale. More elaborate parameters for smaller scale might help better clarify and reduce the uncertainties from model itself. In addition, the parameter that calibrated basing on current crop datasets may lead to new uncertainties when discussing the future crop responses. The changes in cultivars and development of adaptation methods in future may lead to more optimistic results than current study, given the rapid update of adaptive cultivars. The combination of assessing results across multiple sectors, such as the accurate prediction of changes in climate factors, cultivars, and adaptation capacity, could be expected to help better quantify the future risks and opportunities on agricultural development and provide more accurate and effective suggestions for government and farmers.

5 Conclusions

In current study, using the well-validated MCWLA family crop models, their 10 sets of optimal parameters, and 70 climate projections from four GCMs, we evaluated the potential changes of major crop growth and yields during 2106-2115 relative to 2006-2015 under 1.5℃ and 2.0℃ warming scenarios. Results showed that the decrease of crop growth duration and the increase of extreme events impacts would be critical reasons for yield decrease in the future. Meanwhile, agricultural climate resources such as light and thermal resource could be ameliorated which enhance canopy photosynthesis, biomass accumulations and yield and could partly compensate the yield decrease or even contribute to the yield increase. In general, without considering CO_2 fertilization effects, the food supply at country scale would not change much under the 1.5℃ warming scenario, while the crop production for all three kinds of major crops would tend to reduce slightly under the 2.0℃ warming scenario. The maize production in most of cultivation areas, wheat production in north and southwest China, and the rice production in south China, would be hotspots that encounter adverse impacts caused by climate change. The combination of moderate increase in temperature, solar radiation, precipitation, and the CO_2 fertilization effects, would result in more appropriate growth environment for wheat and rice and slightly deteriorate the growth environment of maize. Totally, the benefits from climate change would be larger than crop loss caused by the adverse factors in moderate warming environment. Thus we could expect that the 1.5℃ and 2.0℃ warming scenarios would bring more opportunities than risks for agricultural production and food supply in China in general. Moreover, because of the larger increase in crop productivity and the less probability of yield loss, the 2.0℃ warming scenario might be more suitable for crop production in China than the 1.5℃ warming scenario.

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Table

Table 1. Validation of the MCWLA family models for maize, wheat and rice in different provinces of China.

Province code	Province Name	Mean RMSE (kg/ha) and (*r*) of validation results			
		Maize	Wheat	Early rice	Late rice
1	Heilongjiang	571.3 (0.45*)	497.9 (0.36*)	371.0 (0.36*)	-
2	Jilin	887.5 (0.41*)	-	585.4 (0.34*)	-
3	Liaoning	689.9 (0.55*)	-	498.0 (0.59*)	-
4	Inner Mongolia	1433.9 (0.51*)	542.1 (0.31*)	-	-
5	Hebei&Beijing&Tianjin	785.7 (0.38*)	290.1 (0.46*)	-	-
6	Shanxi	555.1 (0.39*)	224.7 (0.84*)	-	-
7	Shannxi	1074.5 (0.41*)	364.3 (0.35*)	-	-
8	Ningxia	1714.0 (0.26*)	795.2 (0.32*)	-	-
9	Gansu	352.0 (0.39*)	584.9 (0.44*)	-	-
10	Shandong	805.7 (0.49*)	430.0 (0.50*)	-	-
11	Henan	675.4 (0.38*)	219.7 (0.53*)	-	-
12	Jiangsu	1578.6 (0.16)	254.5 (0.56*)	639.7 (0.33*)	-
13	Anhui	833.0 (0.30*)	315.5 (0.66*)	478.3 (0.27)	-
14	Hubei	882.3 (0.32*)	196.9 (0.24)	558.5 (0.53*)	-
15	Sichuan&Chongqing	255.9 (0.54*)	345.7 (0.27)	529.5 (0.13)	-
16	Zhejiang	929.2 (0.30*)	242.1 (0.29)	490.5 (0.59*)	533.9 (0.41*)
17	Jiangxi	386.6 (0.26*)	-	255.8 (0.63*)	316.0 (0.34*)
18	Hunan	679.8 (0.38*)	-	432.0 (0.53*)	447.0 (0.45*)
19	Guizhou	395.8 (0.12)	183.1 (0.23)	456.2 (0.32*)	-
20	Yunnan	969.0 (0.22)	611.3 (0.10)	368.0 (0.26)	-
21	Fujian	355.9 (0.35*)	-	486.5 (0.22)	331.9 (0.34*)
22	Guangdong	334.0 (0.38*)	-	391.5 (0.51*)	420.9 (0.21)
23	Guangxi	387.6 (0.44*)	-	323.7 (0.36*)	306.3 (0.42*)

*$p<0.1$; - no cultivation

Figures

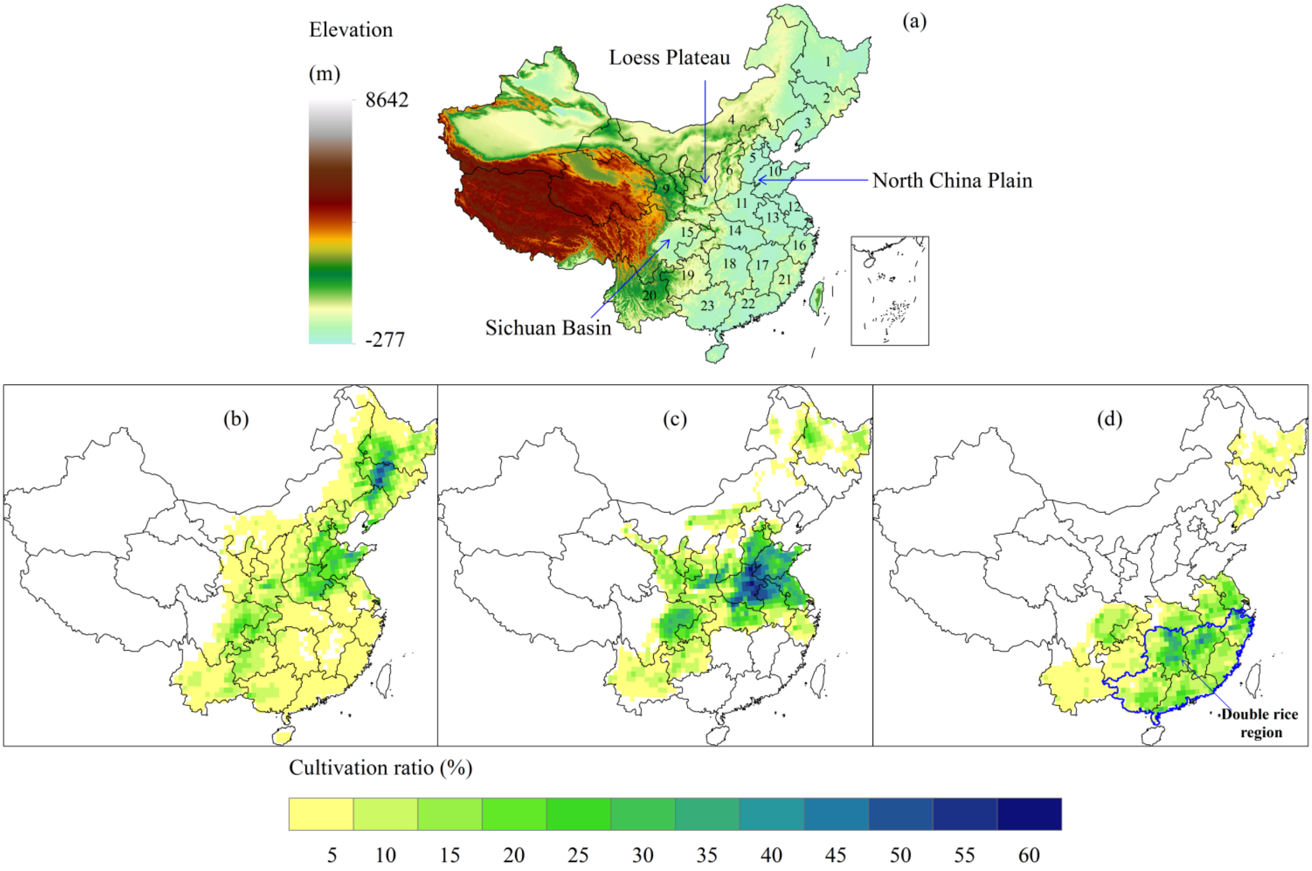

Figure 1: Terrain (a) and cultivation fractions of maize (b), wheat (c) and rice (d) in China. ***Province codes: 1, Heilongjiang; 2, Jilin; 3, Liaoning, 4, Inner Mongolia; 5, Hebei&Beijing&Tianjin; 6, Shanxi; 7, Shannxi; 8, Ningxia; 9, Gansu; 10, Shandong; 11, Henan; 12, Jiangsu; 13, Anhui; 14, Hubei; 15, Sichuan&Chongqing; 16, Zhejiang; 17, Jiangxi; 18, Hunan; 19, Guizhou; 20, Yunnan; 21, Fujian; 22, Guangdong; 23, Guangxi.***

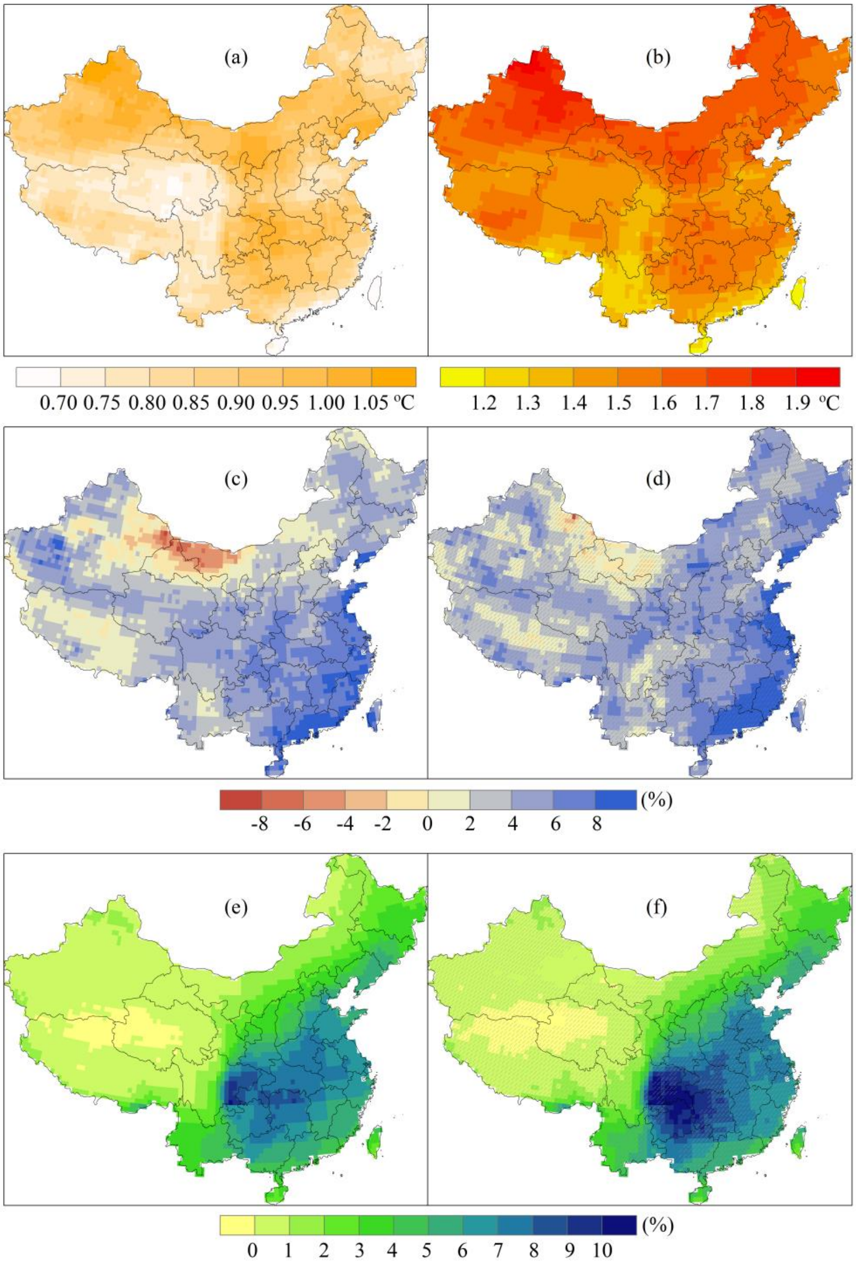

Figure 2: Median changes of mean temperature (a, b), precipitation (c, d), and solar radiation (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f) scenarios relative to 2006-2015. Hatching indicates the areas where the differences between 1.5℃ and 2.0℃warming scenarios are not significant (*$P>0.05$*).

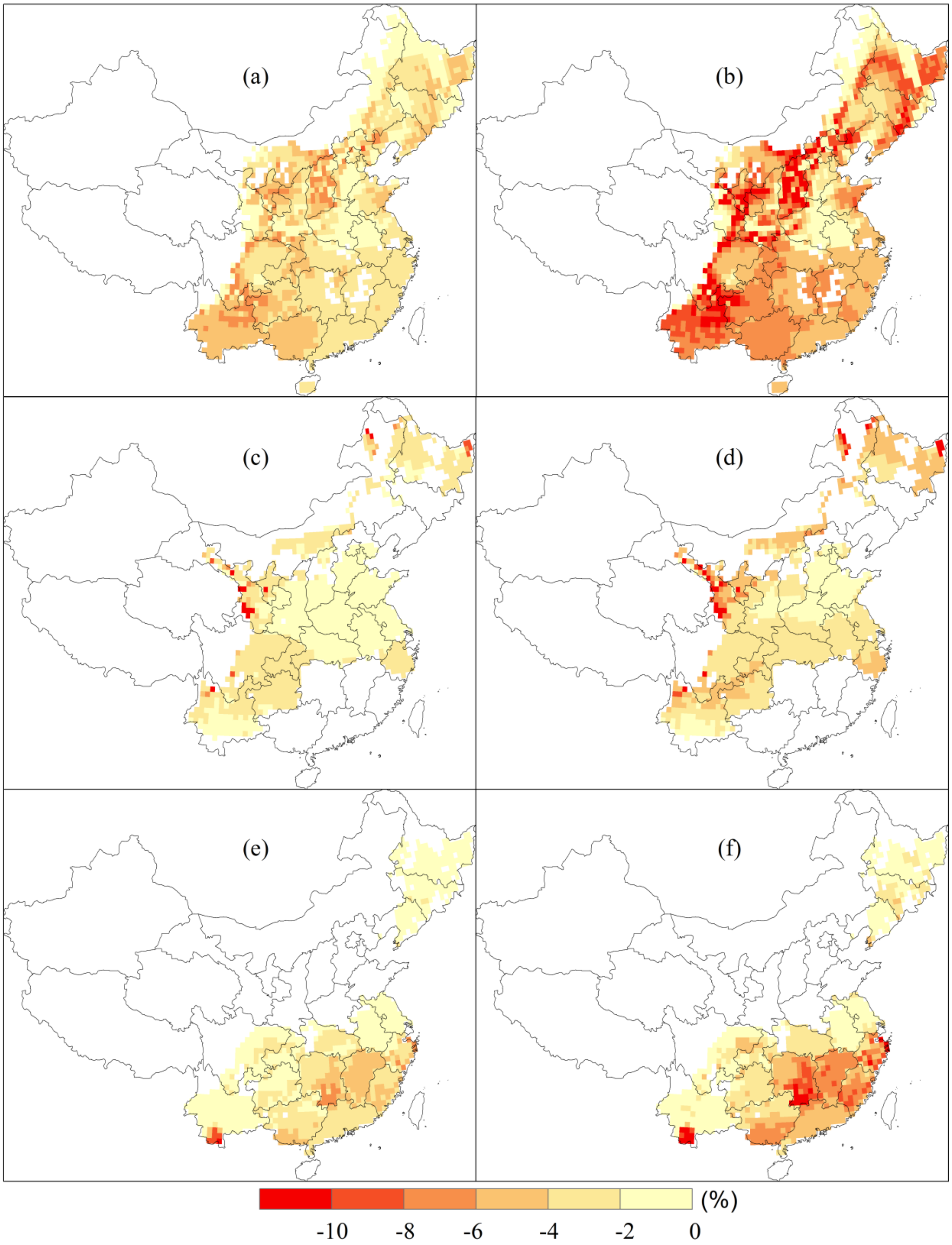

Figure 3: Median changes of growth duration for maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f) scenarios relative to 2006-2015.

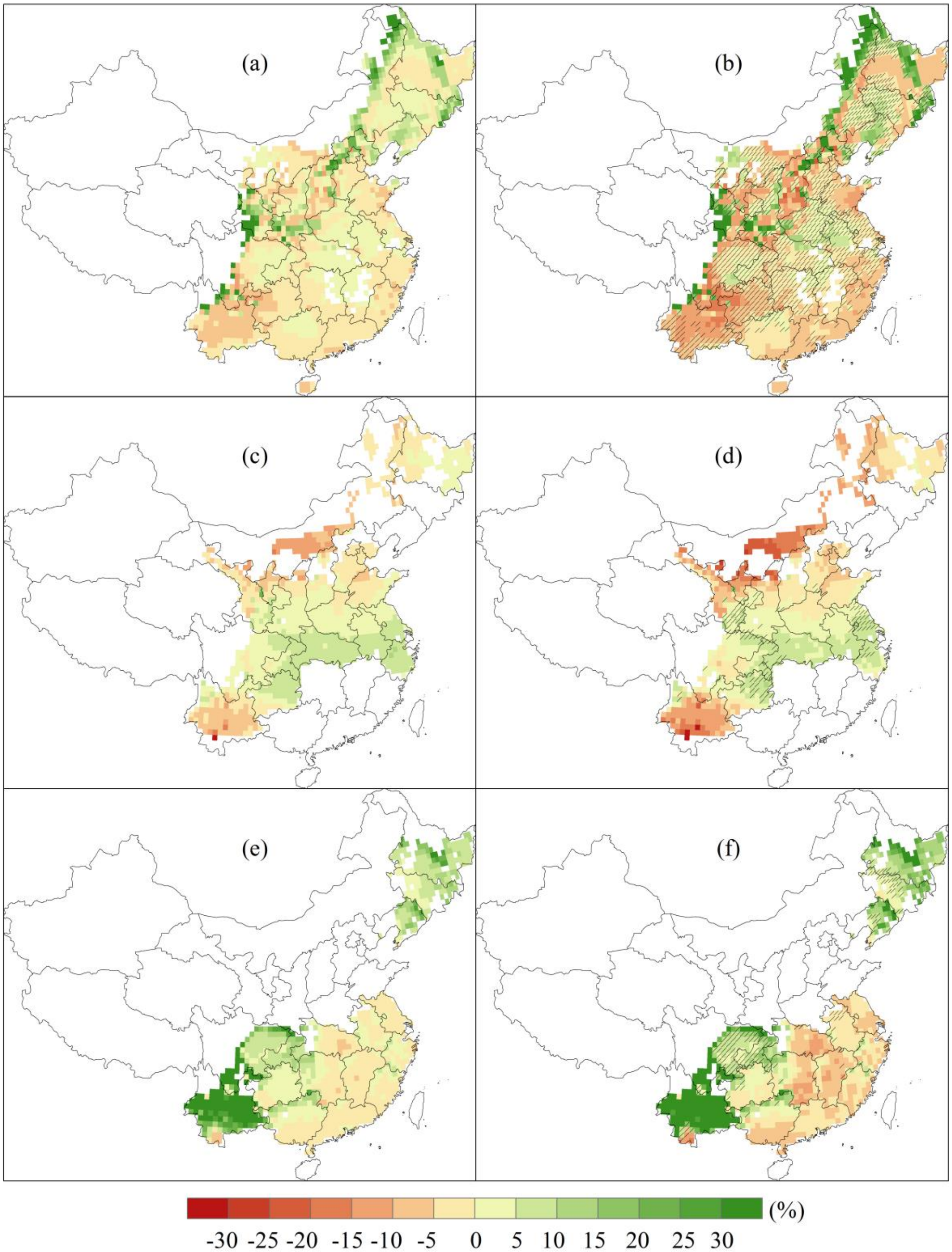

Figure 4: Median changes of projected yield for maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming(b, d, f) scenarios relative to 2006-2015, without taking CO_2 fertilization effect into account. Hatching indicates the areas where the differences between 1.5℃ and 2.0℃warming scenarios are not significant (*P>0.05*).

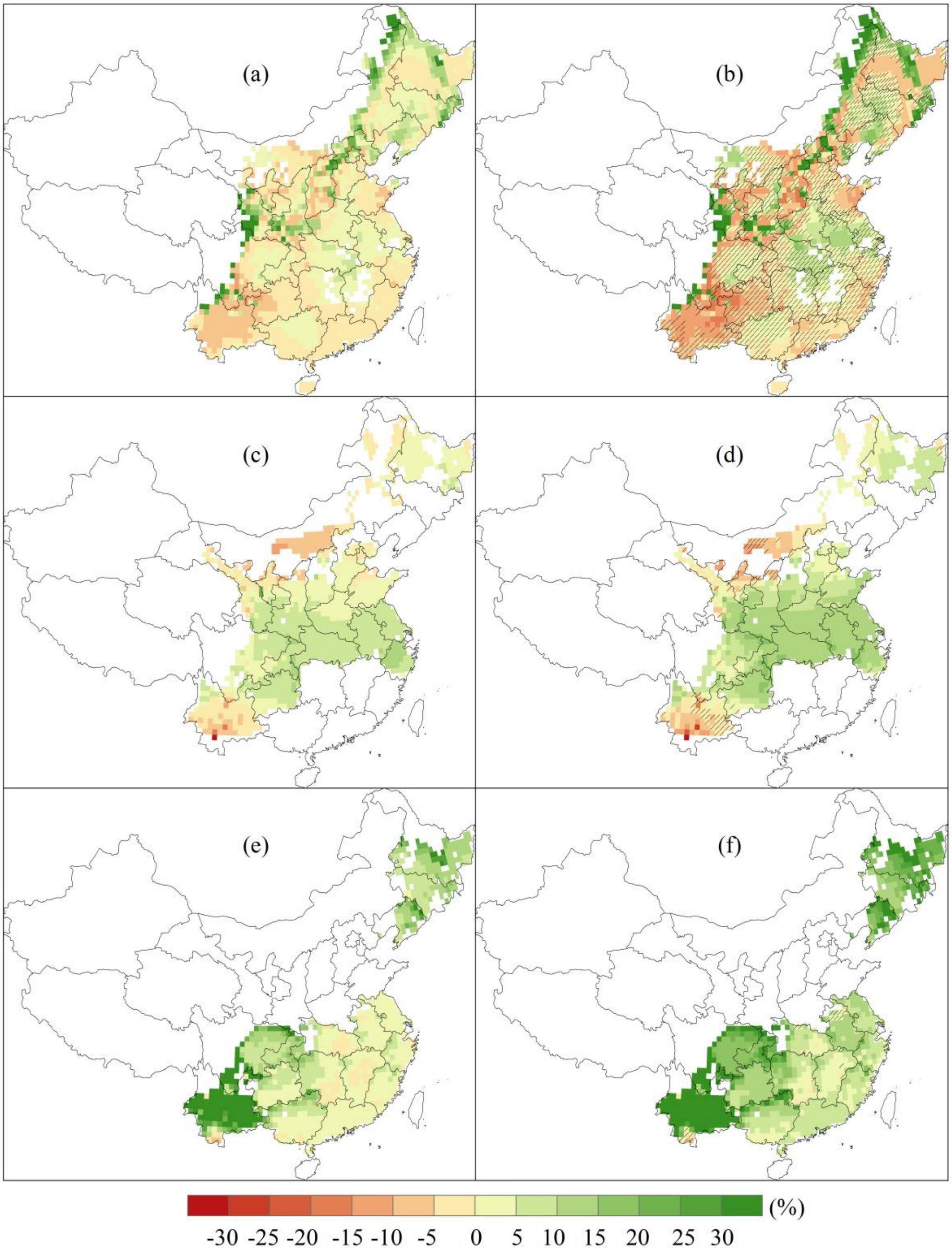

Figure 5: Median changes of projected yield for maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f)scenarios relative to 2006-2015, taking CO_2 fertilization effect into account. Hatching indicates the areas where the differences between 1.5℃ and 2.0℃warming scenarios are not significant (*P>0.05*).

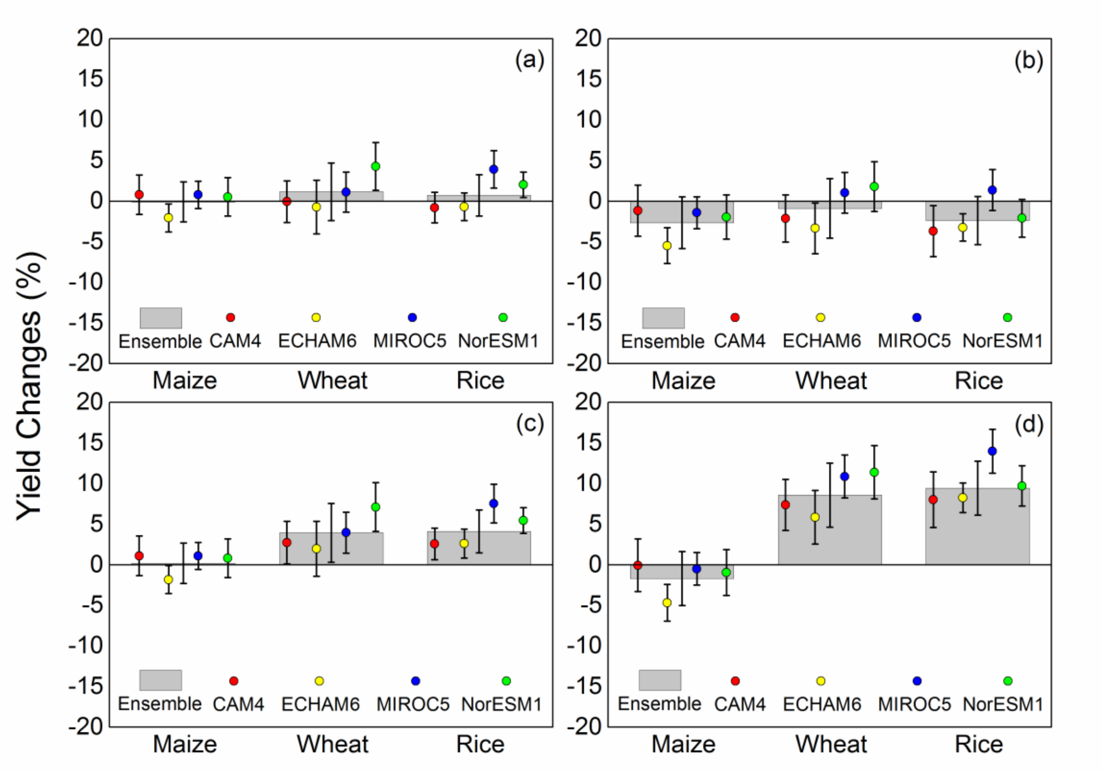

Figure 6: Projected yield change using climate projection from different GCMs at country scale during 2106-2115 at warming scenarios of 1.5℃ (a, c) and 2.0℃ (b, d) relative to 2006-2015, without (a, b) and with (c, d) CO_2 fertilization effect.

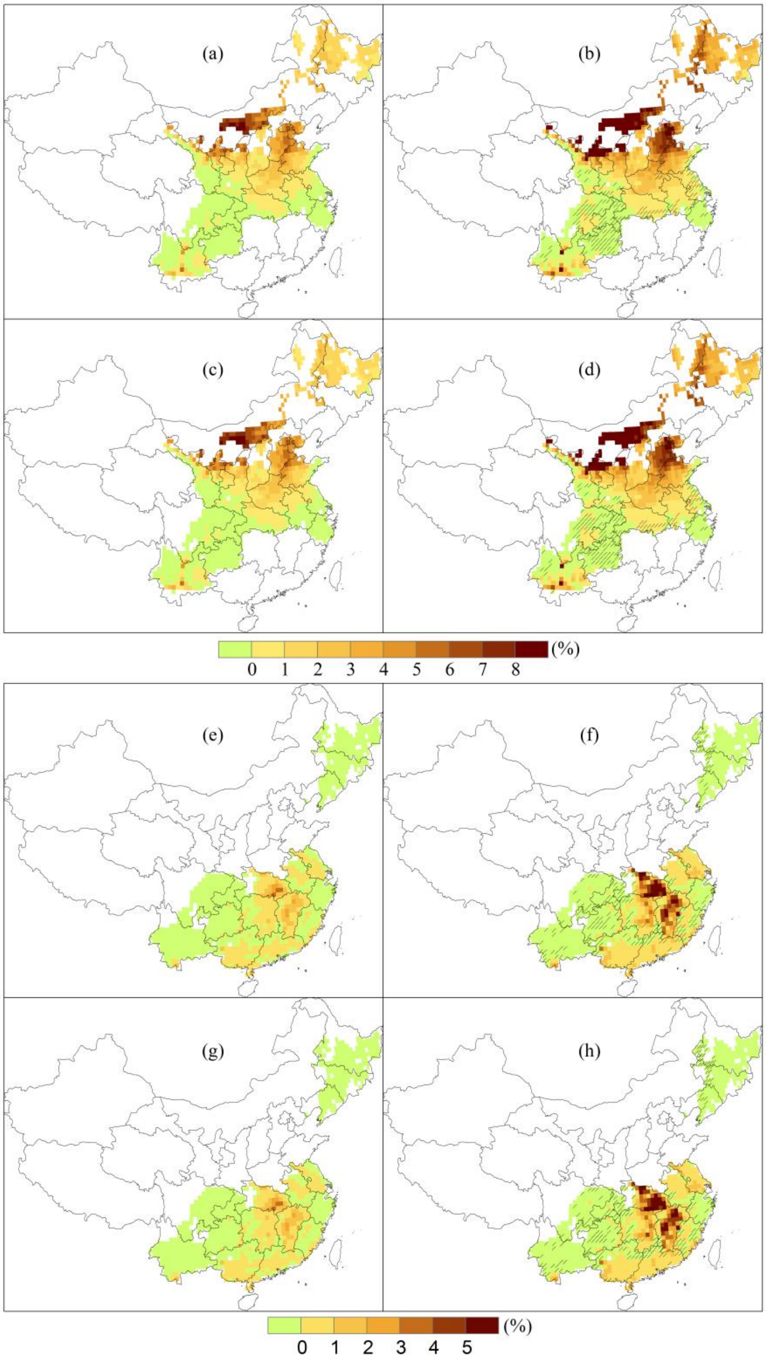

Figure 7: Median changes of yield loss caused by heat stress for wheat (a, b, c, d) and rice (e, f, g, h) during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming (b, d, f, h) scenarios relative to 2006-2015, without (a, b, e, f) and with (c, d, g, h) CO_2 fertilization effect. Hatching indicates the areas where differences between 1.5℃ and 2.0℃ warming scenarios are not significant (*P>0.05*).

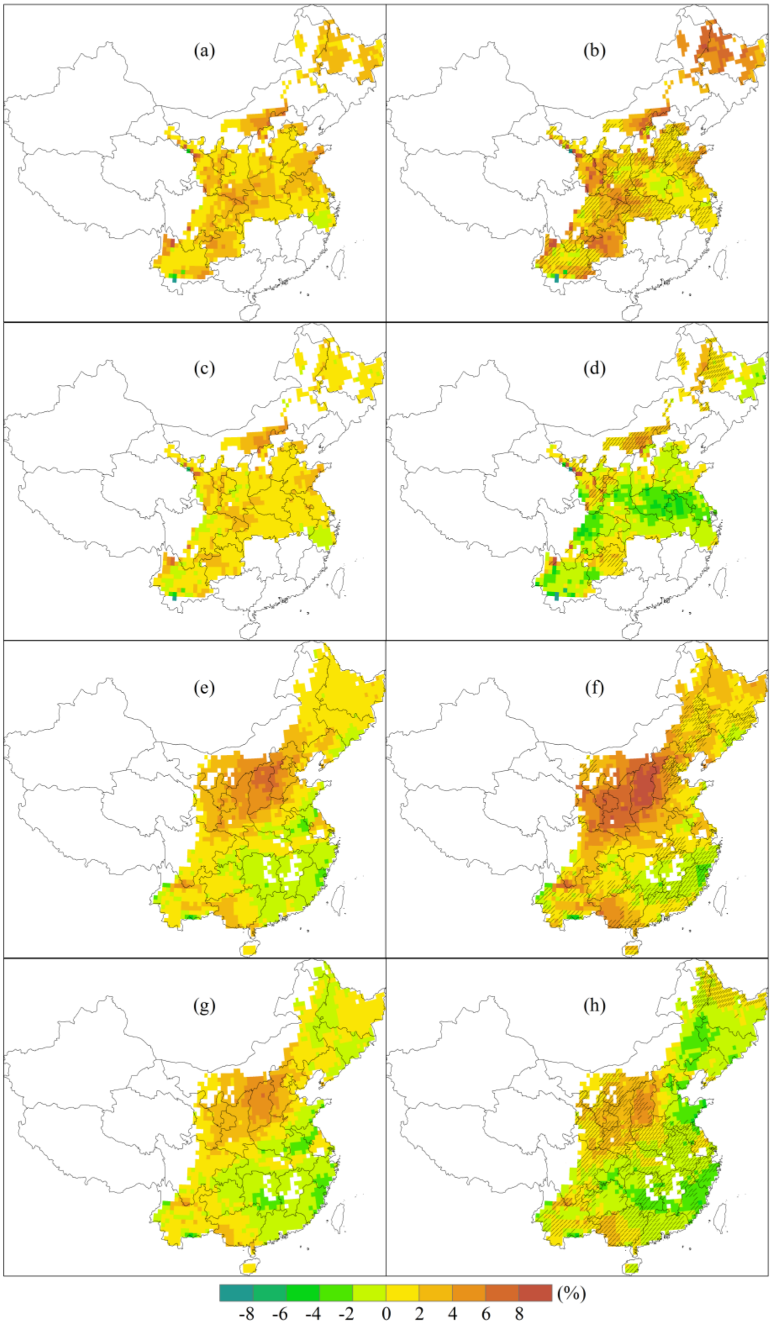

Figure 8: Median changes of yield loss caused by drought stress for wheat (a, b, c, d) and maize (e, f, g, h) during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming scenarios (b, d, f, h) relative to 2006-2015, without(a, b, e, f) and with (c, d, g, h) CO_2 fertilization effect. Hatching indicates the areas where differences between 1.5℃ and 2.0℃ warming scenarios are not significant (*P>0.05*).

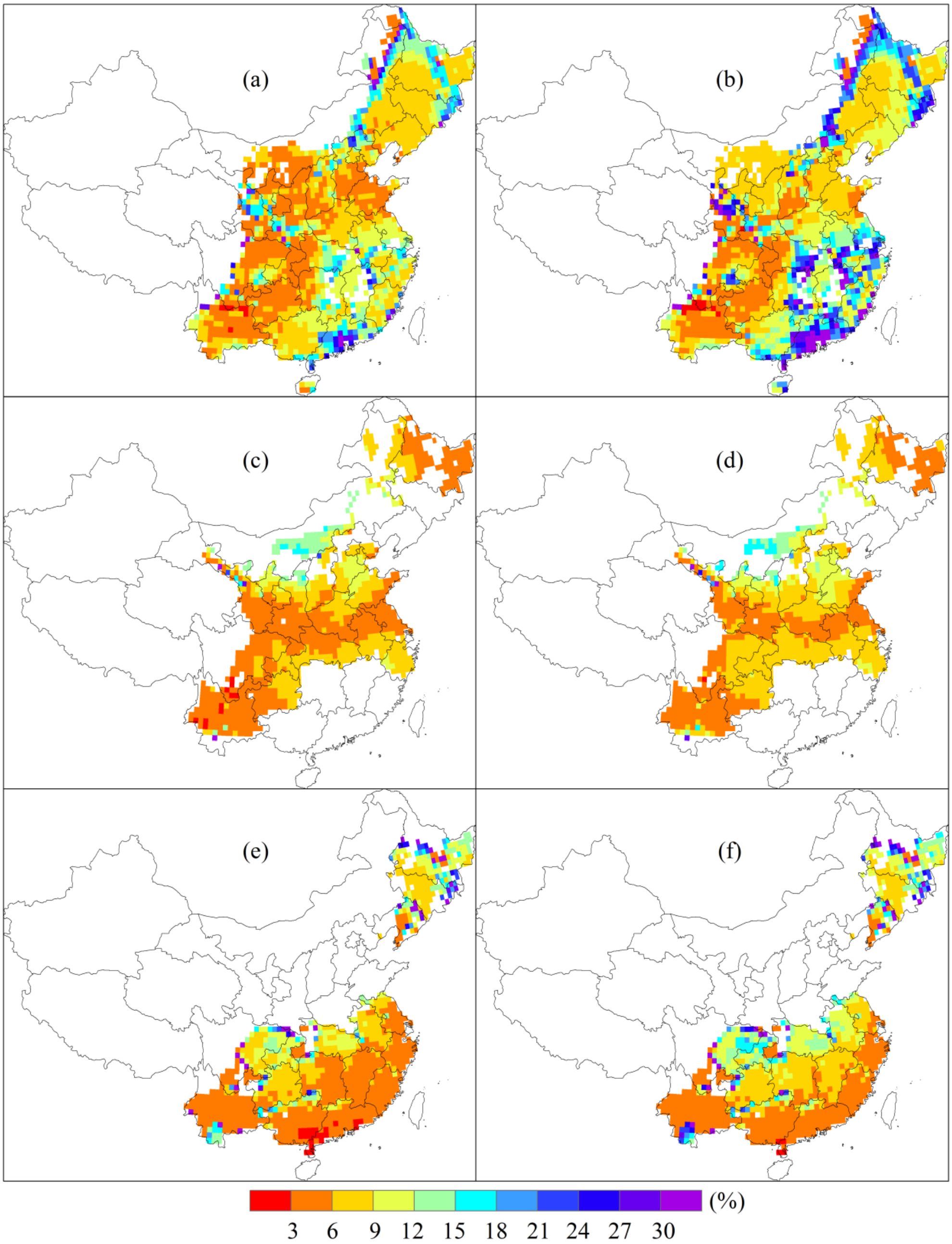

Figure 9: Standard deviation of the projected yield changes for maize (a, b), wheat (c, d), and rice (e, f) under 1.5℃ warming (a, c, e) and 2.0℃ warming(b, d, f) scenarios, taking CO_2 fertilization effect into account.

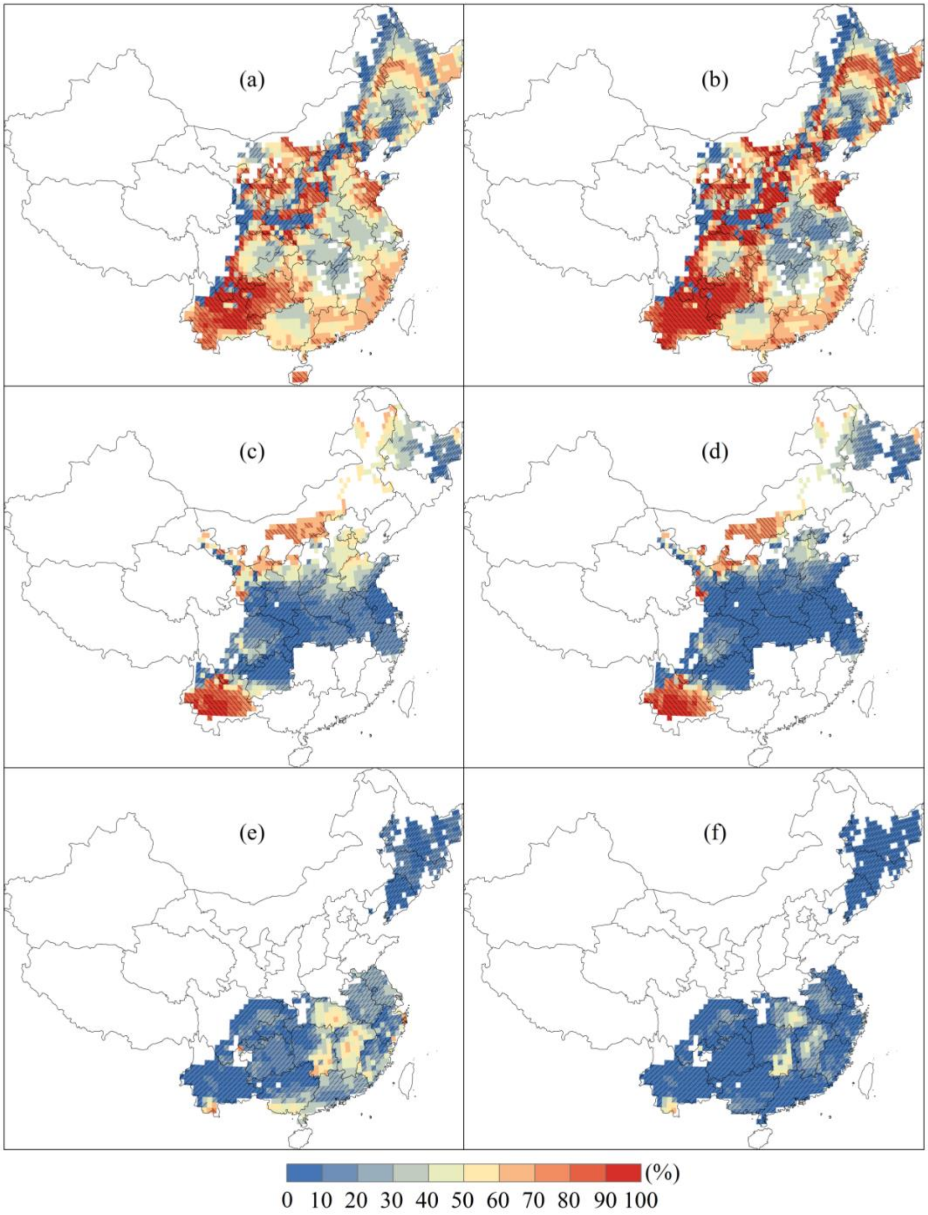

Figure 10: Median of projected yield decrease probability for maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f) scenarios, taking CO2 fertilization effect into account. Hatching indicates the areas where more than 70% of the ensemble simulations agree on the sign of yield change.

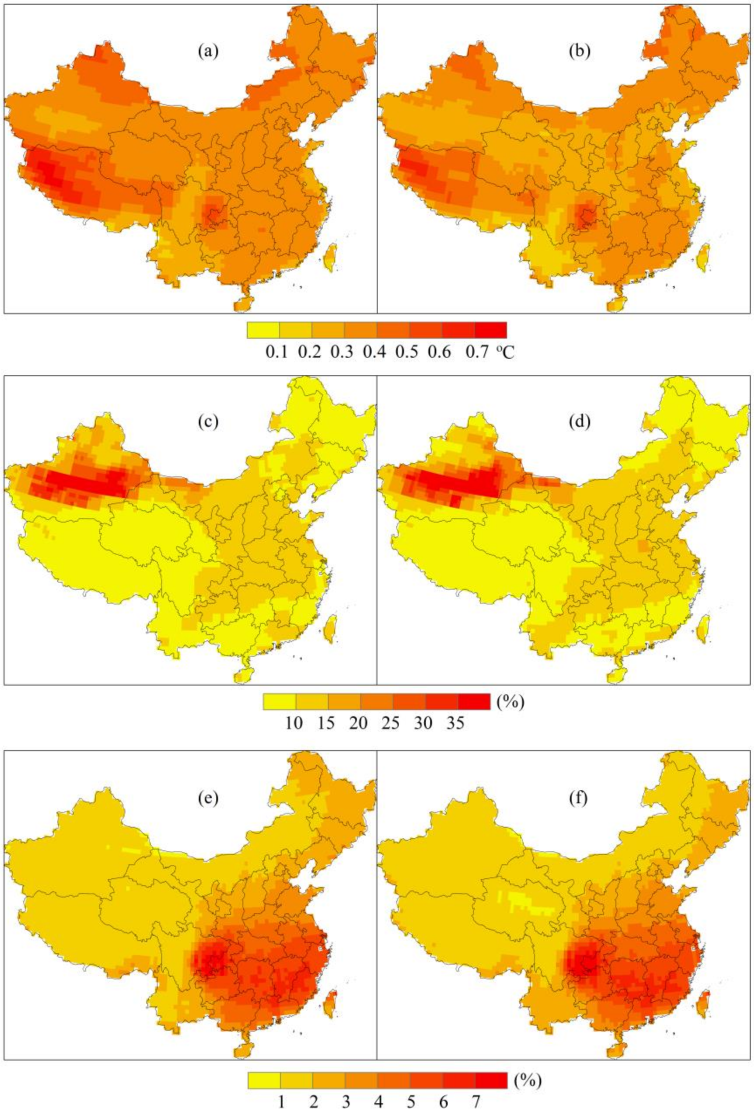

Figure A1: Standard deviation of projected changes in mean temperature (a, b), precipitation (c, d), and solar radiation (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f) scenarios relative to 2006-2015.

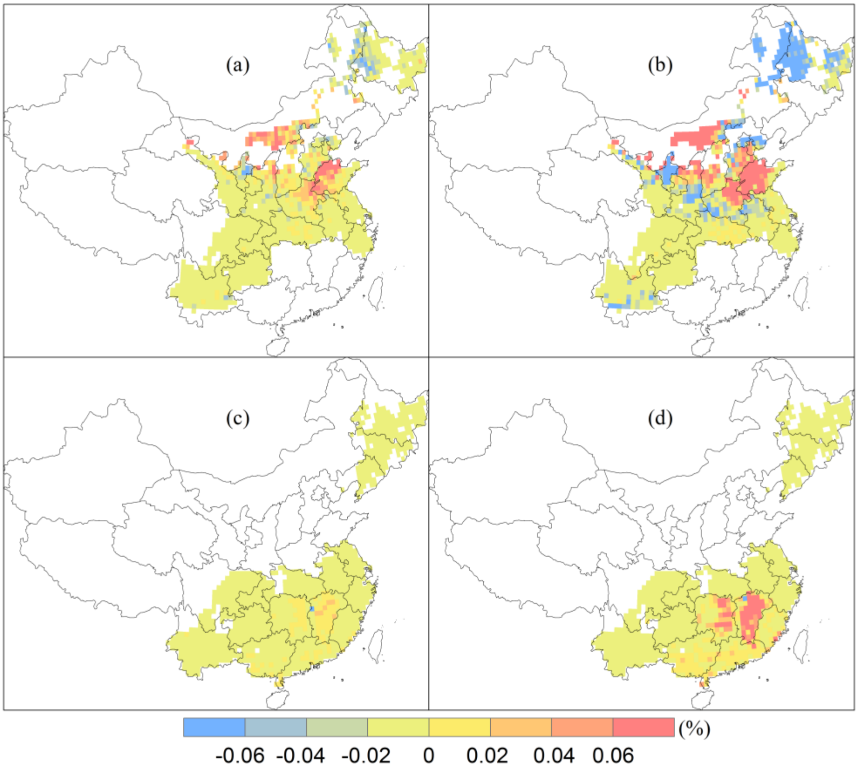

Figure A2. (a) Differences between Fig. 7a and Fig. 7c; (b) Differences between Fig. 7b and Fig. 7d; (c) Differences between Fig. 7e and Fig. 7g; (d) Differences between Fig. 7f and Fig. 7h.

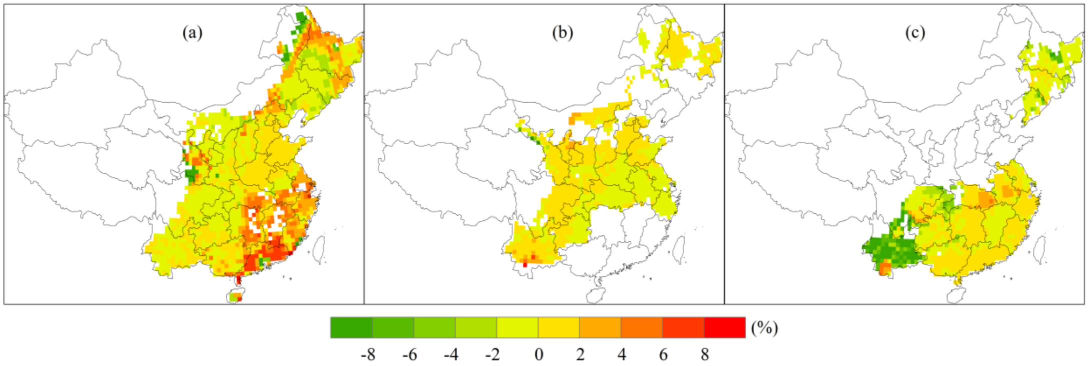

Figure A3. Changes in variation coefficient of simulated yields between 1.5℃and 2.0℃ warming scenarios for maize (a), wheat (b) and rice (c).

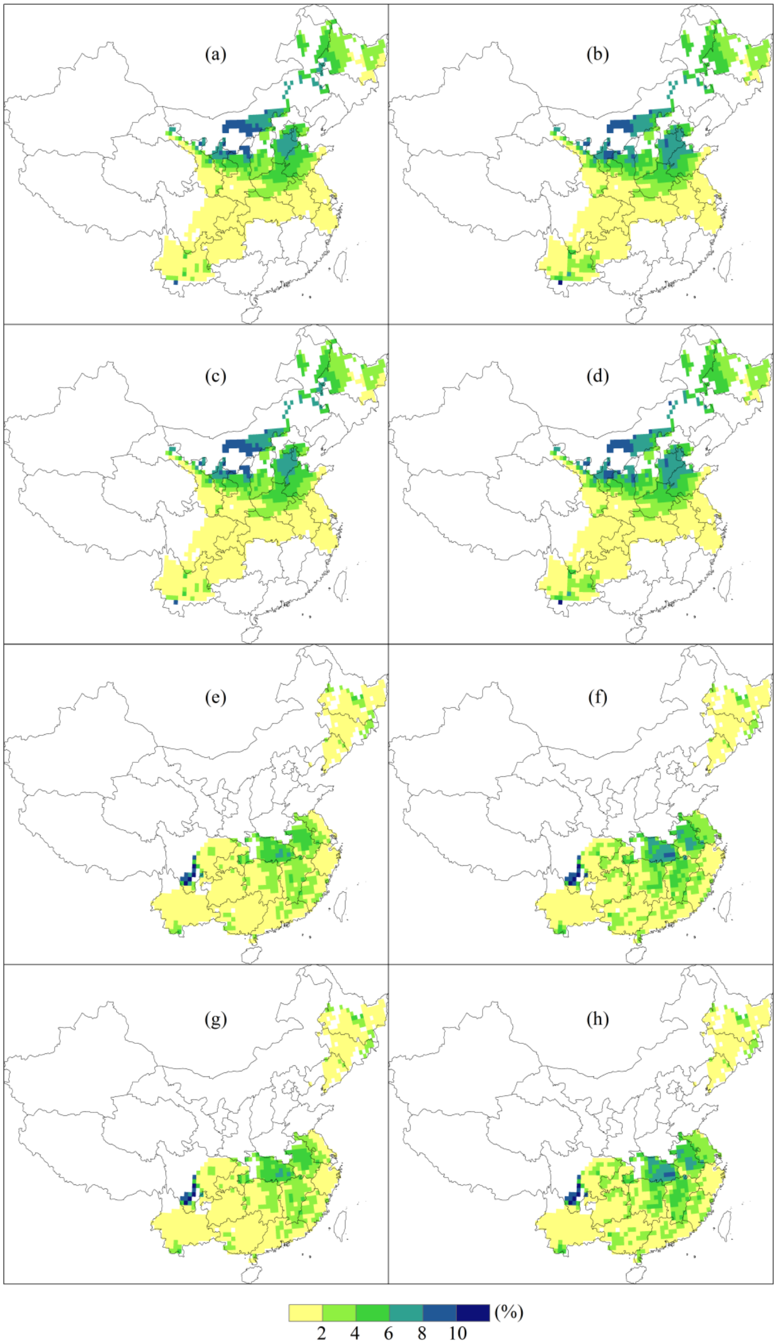

Figure A4. Standard deviation of changes in projected yield loss caused by heat stress for wheat (a, b, c, d) and maize (e, f, g, h) during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming scenarios (b, d, f, h) relative to 2006-2015, without (a, b, e, f) and with (c, d, g, h) CO_2 fertilization effect.

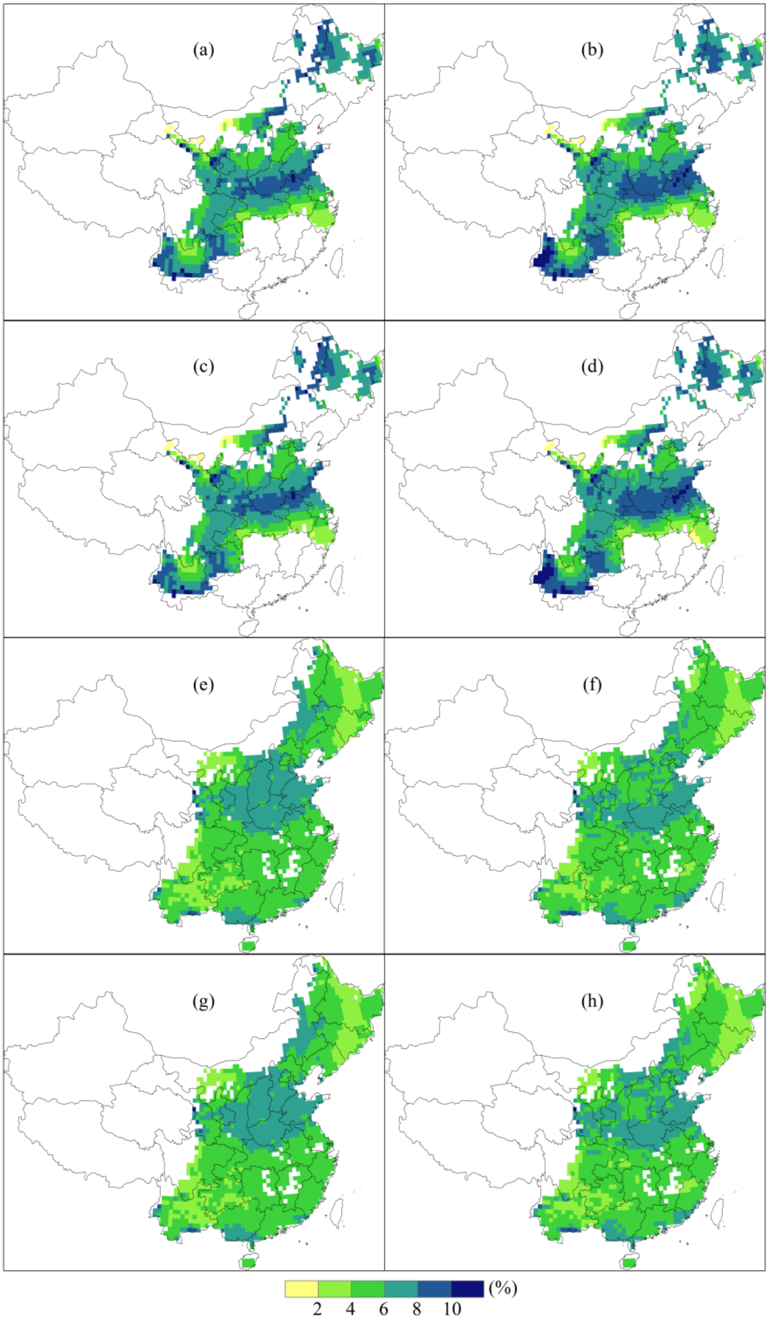

Figure A5. Standard deviation of changes in projected yield loss caused by drought stress for wheat (a, b, c, d) and maize (e, f, g, h) during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming scenarios (b, d, f, h) relative to 2006-2015, without(a, b, e, f) and with (c, d, g, h) CO_2 fertilization effect.

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