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Separating the impacts of heat stress events from rising mean temperatures on winter wheat yield of China

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Supplementary material for this article is available [online](#)

Abstract

Warming due to climate change has profound impacts on regional crop yields, and this includes impacts from rising mean growing season temperature and heat stress events. Adapting to these two impacts could be substantially different, and the overall contribution of these two factors on the effects of climate warming and crop yield is not known. This study used the improved WheatGrow model, which can reproduce the effects of temperature change and heat stress, along with detailed information from 19 location-specific cultivars and local agronomic management practices at 129 research stations across the main wheat-producing region of China, to quantify the regional impacts of temperature increase and heat stress separately on wheat in China. Historical climate, plus two future low-warming scenarios (1.5 °C/2.0 °C warming above pre-industrial) and one future high-warming scenario (RCP8.5), were applied using the crop model, without considering elevated CO₂ effects. The results showed that heat stress and its yield impact were more severe in the cooler northern sub-regions than the warmer southern sub-regions with historical and future warming scenarios. Heat stress was estimated to reduce wheat yield in most of northern sub-regions by 2.0%–4.0% (up to 29% in extreme years) under the historical climate. Climate warming is projected to increase heat stress events in frequency and extent, especially in northern sub-regions. Surprisingly, higher warming did not result in more yield-impacting heat stress compared to low-warming, due to advanced phenology with mean warming and finally avoiding heat stress events during grain filling in summer. Most negative impacts of climate warming are attributed to increasing mean growing-season temperature, while changes in heat stress are projected to reduce wheat yields by an additional 1.0%–1.5% in northern sub-regions. Adapting to climate change in China must consider the different regional and temperature impacts to be effective.

1. Introduction

The impact of climate warming on crop yields has been studied widely during the last few decades (Rosenzweig and Parry 1994, Semenov 2009, Lobell *et al* 2011, Challinor *et al* 2014, Asseng *et al* 2015, Liu *et al* 2019). Higher growing season temperatures, especially for hot areas, are likely to reduce crop yields with implications for crop production

and food security (IPCC 2014). Also, increasing extreme climate events due to shifting climate variability (IPCC 2012), such as heat stress, are projected to have increasing adverse impacts on crop production (Semenov and Shewry 2011, Teixeira *et al* 2013, Delphine *et al* 2014, Trnka *et al* 2014), even under moderate climate warming (e.g. 1.5 °C warming above pre-industrial) (Tebaldi and Lobell 2018). Adapting to these two impacts could be substantially

different (Challinor *et al* 2007). Therefore, investigating impacts of climate warming on crop production, including both increasing mean growing-season temperature and heat stress events, is critical to understand climate impacts and to adapt the cropping systems to climate change effectively, which is of great importance to ensure regional and global food security.

Determining the responses of crop production to climate variables has been conducted at different spatial scales. At global scale, Ray *et al* (2015) found that climate variability (including temperature and precipitation) explained about 32%–39% observed yield variability. Using a multivariable linear regression approach across the main wheat producing region of China, Liu *et al* (2014) found 29% of fluctuation in wheat yields can be explained by temperature variability, which is due to a combination of increasing mean growing-season temperature and heat stress. Generally, the quantified impact on crop yield in these studies was the combination of increasing growing-season mean temperature and extreme temperature events (heat stress). Even though most previous analysis examined the impacts of increasing mean growing-season temperature on crop yields (Lobell 2007, Xiong *et al* 2014), a few recent studies started to focus on the extreme temperature events. For example, with reported records of extreme weather disaster, Lesk *et al* (2016) showed that droughts and extreme heat significantly reduced national cereal production by 9%–10% during 1964–2007. However, isolating the individual impacts of increasing growing-season mean temperature and heat stress events from the compounding impacts of temperatures on crop production is yet to be resolved.

As an alternative for isolating climate impacts on crop yield from other non-climatic factors in cropping systems, crop models have the potential to separate the individual impact of a single climate factor (e.g. heat stress or increasing mean growing-season temperature). Recent studies have shown increased concern over the considerable uncertainty in the responses of crop models to extreme climate events and the implication of this uncertainty on the climate impact assessment (Rötter *et al* 2011, Lobell *et al* 2012, Barlow *et al* 2015, Liu *et al* 2016a). Meanwhile, international projects, such as the agricultural model intercomparison and improvement project (AgMIP), have given more attention to model comparison and improvement (Rosenzweig *et al* 2013). The efforts for model improvements, especially under heat stress conditions in the AgMIP-Wheat project, helped to improve the simulation of heat stress impact across crop models (Maiorano *et al* 2017, Wang *et al* 2017). In China, with detailed wheat observations under different heat stress events, we proposed process-based algorithms to quantify heat stress effects on wheat

phenology (Liu *et al* 2016c), leaf senescence and biomass growth (Liu *et al* 2017), and biomass partitioning and yield formation (Liu *et al* 2020). These studies resulted in an improved WheatGrow model with new algorithms that have reliable performance in both field and environment-controlled heat stress conditions (Liu *et al* 2020).

Wheat planted in approximately 25% of the area for grain crops in China (National Bureau of Statistics of China 2018), has been one of most important staple food crops for grain supply and national food security. Due to climate change, warming growing season temperatures have been detected in most of wheat producing regions of China (Tao *et al* 2014). In addition, heat stress events have been a main environmental stress factor for wheat production in China during the last decades (Liu *et al* 2014). However, a systematic investigation of the impact of mean temperature increase and heat stress events on wheat of China is yet to be conducted at regional scale, especially for future climate warming scenarios.

The main objectives of this study were (a) to determine the spatial and temporal change of heat stress events across the main winter wheat producing region of China under different climate change scenarios, and (b) to separate the impact of heat stress from rising growing-season temperature from the compounding impacts of temperature on winter wheat of China under historical and future climate scenarios.

2. Materials and methods

2.1. Study region

The main winter wheat producing region of China covered the 14 main winter wheat production provinces and municipalities (figure 1), which accounts for more than 87% and 91% of the total wheat planting area and production in China, respectively (National Bureau of Statistics of China 2018). Based on the eco-climate conditions, the whole region was divided into four sub-regions, including two northern sub-regions, the north sub-region (NS) and the Huang-Huai sub-region (HHS), and two southern sub-regions, the middle-lower reaches of Yangzi River sub-region (MYS) and the southwest sub-region (SWS) (figure 1). In each sub-region, there are two or three eco-zones based on topography and production conditions, as shown in figure 1.

Due to the data availability, 129 agrometeorological experimental stations (AESs) from the national AES network of China were chosen to determine spatial variation of heat stress events and to evaluate the impacts of heat stress and increasing growing season temperature (figure 1(b)). These stations are distributed throughout the entire study region.

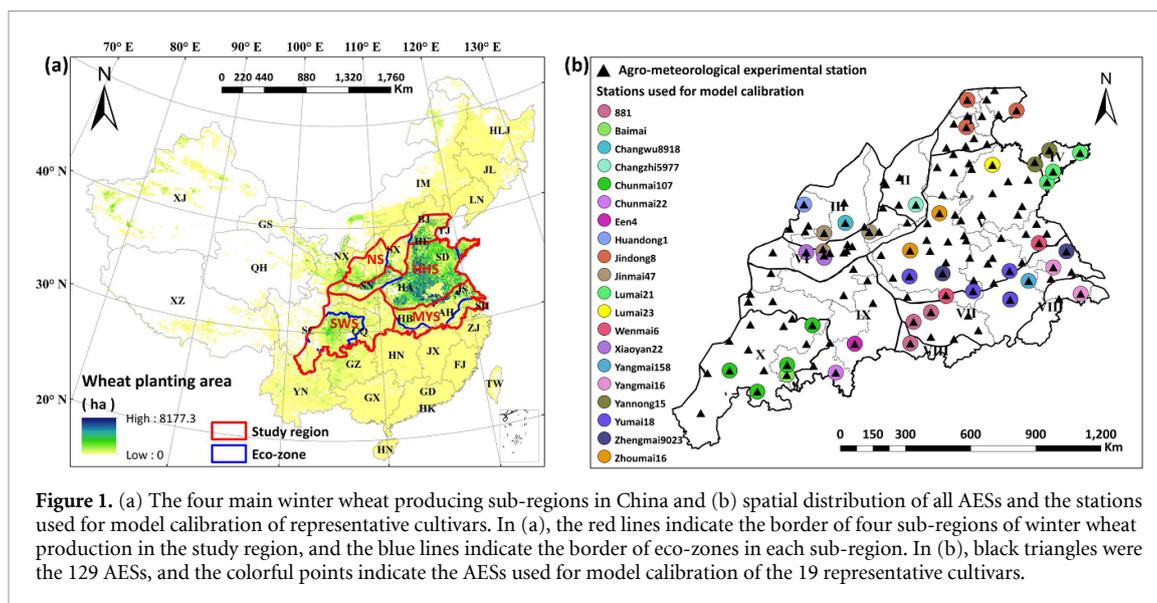


Figure 1. (a) The four main winter wheat producing sub-regions in China and (b) spatial distribution of all AESs and the stations used for model calibration of representative cultivars. In (a), the red lines indicate the border of four sub-regions of winter wheat production in the study region, and the blue lines indicate the border of eco-zones in each sub-region. In (b), black triangles were the 129 AESs, and the colorful points indicate the AESs used for model calibration of the 19 representative cultivars.

2.2. Climate data

The climate scenarios used in this study included historical (Baseline, 1980–2010), 1.5 °C and 2.0 °C above pre-industrial level (1.5 °C half a degree additional warming, prognosis and projected impacts (HAPPI) and 2.0 °C HAPPI), and RCP8.5 (2050s) scenarios. Here, two HAPPI scenarios were considered as low-warming scenarios (~ 0.6 °C and 1.1 °C above current global mean temperature, respectively) (Morice *et al* 2012), and the RCP8.5 scenario was considered as the high-warming scenario (~ 2.0 °C above current global mean temperature). For the historical period, observed daily climate data at 129 AESs (31 years from 1980 to 2010) were obtained from the China Meteorological Data Sharing Service System (<http://data.cma.cn/>), including daily maximum and minimum air temperatures, sunshine hours, and precipitation.

1.5 °C HAPPI and 2.0 °C HAPPI scenarios were obtained from the HAPPI project (Mitchell *et al* 2017). RCP8.5 scenario came from the outputs from Coupled Model Intercomparison Project Phase 5. For each station, and for each future climate scenario, the daily climate data for crop modeling were generated using the enhanced delta method, based on observed daily climate data during the historical period and future outputs from global climate models (GCMs) (Ruane *et al* 2015, 2018). Due to data availability at the time when the study was conducted, four GCMs (CanAM4, CAM4, MIROC5 and NorESM1) and seven GCMs (GFDL-CM3, GISS-E2-R, HadGEM2-ES, MIROC5, MIROC-ESM-CHEM, MPI-ESM-MR, and NorESM1-M) were used for the two HAPPI and RCP8.5 scenarios, respectively.

2.3. Crop modeling

The WheatGrow model (V3.1) was used to simulate wheat phenology and grain yield under different climate scenarios. The dynamic of wheat development

and growth was simulated by daily time step in WheatGrow. Several model evaluation have been conducted across the major wheat producing region of China (Lv *et al* 2013, Liu *et al* 2016a).

Properly reflecting the impacts of rising mean temperature and heat stress in the crop model is critical for the accuracy of impact assessment. In the WheatGrow model, rising mean temperature can affect wheat development rate and leaf photosynthesis directly, and change leaf area dynamics and grain filling rate indirectly. The evaluation of WheatGrow model under various growing season temperatures indicated reasonable responses (Asseng *et al* 2015). The recent model improvements for WheatGrow included the incorporation of the heat stress effects on wheat phenology (Liu *et al* 2016c), leaf senescence and biomass growth (Liu *et al* 2017), and biomass partitioning and grain yield formation (Liu *et al* 2020). The detailed effects of heat stress simulated by the improved WheatGrow model included that heat stress at anthesis and grain filling could shorten grain filling duration, limit leaf photosynthesis, accelerate leaf senescence, decrease biomass partitioning to grain, and finally reduce grain set and grain size. Model evaluation with observed heat stress experiments indicated reliable performance in both field and environment-controlled conditions (Liu *et al* 2020). Therefore, the improved version of WheatGrow was used to quantify the heat stress impacts on wheat yields under different climate scenarios.

Crop data from multi-year field experiments at the 129 AESs were collected for model calibration and validation. Data records collected for crop modeling included cultivar, phenology date (sowing, emergence, anthesis, and maturity), management practice, and grain yield. Nineteen representative wheat cultivars scattering across the whole study region were selected (figure 1), to have reliable spatial representation of the cultivar types. More details about model

calibration and evaluation can be found in supplementary methods.

After model calibration and evaluation, we run the simulations for the 30 year period for each AES and climate scenario. For stations that used the representative cultivars during the baseline period, the corresponding representative cultivars were used for three warming scenarios. The nearest representative cultivar in each eco-zone was used for stations without any of the 19 representative cultivars. Sowing date for warming scenarios was same as the baseline period, as no adaptation through shifting sowing date was considered here. In our simulations, we did not consider the CO₂ fertilization effects or simulate water or nitrogen stress, as we only focused on temperature impacts on potential wheat yield.

2.4. Heat stress indices

To quantify the occurrence of heat stress under different climate scenarios, three heat stress indices, including accumulated heat stress days (AHSDs), heat stress intensity (HSI), and heat degree-days (HDDs), were used to reflect different dimensions of heat stress, and these measurements were based on daily maximum air temperature between anthesis and maturity. Here, AHSD was the number of days when $T_{\max} \geq T_h$ after anthesis, and HSI was calculated as average T_{\max} for days when $T_{\max} \geq T_h$ after anthesis. HDD is the accumulated heat degree days from anthesis to maturity (see supplementary methods), and was used to consider both heat stress duration and intensity. All three indices were calculated from anthesis to maturity, as almost all heat stress events in winter wheat of China were observed after anthesis, according to the preliminary analysis (Liu *et al* 2014). T_h is the threshold temperature for heat stress. The review from Sánchez *et al* (2014) on cardinal temperatures in wheat suggested that maximum temperature are generally highest during grain filling (with an average of 35.4 °C and 31 °C for grain filling and anthesis), showing a wider range of cardinal temperatures than for anthesis. But several studies also used around 30 °C as threshold temperature for wheat (Porter and Gawith 1999, Farooq *et al* 2011, Semenov *et al* 2014). Generally, slightly different high temperature threshold can be found for cultivars from different growing environment (cultivar eco-type). For winter wheat in China, Deng *et al* (2009) suggested 30 °C as the appropriate threshold temperature for heat stress during the reproductive period. In our previous heat stress experiments for improving WheatGrow model, heat stress treatments (21 °C/31 °C) at both anthesis and grain filling resulted into lower measured leaf photosynthesis rate and biomass, compared with CK (17 °C/27 °C) (Liu *et al* 2017). Therefore, the threshold parameter T_h of 30 °C in the improved WheatGrow model was used for winter wheat of China in the main wheat producing region, which can

facilitate the model application across the whole study region.

Here, we used the simulated phenology date from WheatGrow to calculate the heat stress indices under historical and warming scenarios. In addition, heat stress indices for the baseline period calculated with simulated wheat phenology and observed wheat phenology were also compared to validate the model performance.

2.5. Yield impact assessment

There were obvious differences in the mechanisms between the impacts of rising mean temperature and impacts of heat stress. Increasing growing season temperature can result in substantial impacts on crop production, by shortening crop growth duration, affecting leaf area and photosynthesis, and finally change biomass accumulation and partitioning, and grain yield formation (Porter and Gawith 1999). As summarized by Ye *et al* (2020), when increasing temperatures exceed the crop optimal temperature, the impacts of temperature increase on physiological processes and yield formation of wheat could be detrimental, such as on growth rate, photosynthetic rate, canopy senescence, and grain filling rate. While in cooler growing regions, increasing growing season temperature could be beneficial for wheat yield, due to its enhancement on leaf photosynthesis and biomass accumulation (Ottman *et al* 2012). Heat stress usually accelerate leaf senescence, shorten grain filling period, decrease grain set at anthesis, reduce grain filling rate by damaging leaf photosynthesis, and change the biomass partitioning.

It is known that the impacts of heat stress on crop yield may correlate to average temperature impacts, because both impacts can affect same growth process, e.g. phenology, leaf area and photosynthesis, and biomass accumulation. It is difficult to disentangle these two effects directly. However, through scenario analysis with improved WheatGrow model, we first quantified the heat stress effects directly by manipulating the climate data, using similar approach with Lobell *et al* (2015). And the overall impacts of temperature change from baseline period to warming scenarios (including impacts from both rising temperature and heat stress) can also be determined by the simulated wheat under two climate scenarios directly. Therefore, the impacts from rising mean growing temperature can be determined indirectly, by removing the heat stress impacts from the overall impacts of temperature change.

The relative heat stress impacts on wheat yield during historical period (Heat impacts_hist) and future period (Heat impacts_future) were calculated as follows:

$$\begin{aligned} & \text{Heat impacts_hist} \\ &= 100 \times \left(\frac{Y_{\text{hist}} - Y_{\text{hist_noheat}}}{Y_{\text{hist}}} \right) \quad (1) \end{aligned}$$

$$\text{Heatimpacts_future} = 100 \times \left(\frac{Y_future - Y_future_noheat}{Y_future} \right) \quad (2)$$

where Y_hist and Y_future were simulated yields with climate data during the historical period (1980–2010) and under future warming scenarios, respectively. Y_hist_noheat and Y_future_noheat were simulated yields with adjusted historical climate data and adjusted future climate data, respectively. Here, adjusted historical and future climate data were obtained by changing daily T_{max} above T_h to 30 °C in historical and future climate data, to make sure there was no heat stress during wheat growing season.

The overall impacts of temperature change from historical period to warming scenarios (Δ Temperature impacts) was calculated as follows:

$$\Delta\text{Temperature impacts} = 100 \times \left(\frac{Y_future - Y_hist}{Y_hist} \right). \quad (3)$$

The overall impacts of temperature change on wheat yield for future climate warming scenarios can be dissected into two parts: (a) the impacts of increasing mean growing-season temperature (Δ Warming impacts) and (b) the impacts of changes in heat stress (Δ Heat impacts), described as follows:

$$\Delta\text{Temperature impacts} = \Delta\text{Heat impacts} + \Delta\text{Warming impacts}. \quad (4)$$

The impacts of changes in heats stress for future period (%):

$$\Delta\text{Heat impacts} = \text{Heatimpacts_future} - \text{Heatimpacts_hist}. \quad (5)$$

Therefore, the impacts of increasing mean growing-season temperature can be determined as follows:

$$\Delta\text{Warming impacts} = \Delta\text{Temperature impacts} - \Delta\text{Heat impacts}. \quad (6)$$

The average and maximum heat stress indices and yield impacts during the 30 year period were calculated for each AES and each climate scenario first. Then we used the ArcGIS 9.3 software to display the spatial variation of heat stress indices and yield impacts as maps with the inverse distance weighted method. For future climate warming scenarios, we first calculated the impacts under each GCM, then reported the average results of different GCMs for each future climate scenario, because several previous studies showed that ensemble of multi models could reduce the uncertainty due to GCMs (Asseng *et al* 2013).

3. Results

3.1. Spatial variation of heat stress under historical and warming scenarios

During the historical period, patterns of spatial variation for heat stress indices determined with observed and simulated phenology from WheatGrow were similar (figure S5) (available online at stacks.iop.org/ERL/16/124035/mmedia). This indicated that simulations from WheatGrow can reproduce the spatial variation of wheat phenology well across the whole wheat producing region of China.

As shown in figure 2, substantial spatial variation of heat stress was observed across the main wheat producing region of China. Three heat stress indices showed similar spatial distribution across the study region under historical and future warming scenarios. More heat stress can be observed in the two northern sub-regions (NS and HHS) than the two southern sub-regions (SWS and MYS) (figure 2).

Compared with historical period, heat stress under three warming scenarios (1.5 °C HAPPI, 2.0 °C HAPPI, and RCP8.5) was projected to increase in NS, HHS, and east MYS, and decrease in most of the regions in SWS and west MYS (figure S6). A greater increase can be found in southwestern NS and northern HHS, with an average increase of 4 d, 0.6 °C, and 16 °C d for AHSD, HSI, and HDD, respectively.

Generally, heat stress was projected to increase more under 2.0 °C HAPPI than 1.5 °C HAPPI in NS, HHS, and MYS, while no significant changes can be found for SWS between 2.0 °C HAPPI and 1.5 °C HAPPI. From 2.0 °C HAPPI to RCP8.5, all heat stress indices were projected to increase in MYS. In NS and HHS, AHSD and HDD were projected to decrease, while a slight increase can be expected for HSI, from 2.0 °C HAPPI to RCP8.5. For SWS, AHSD was projected to decrease slightly from 2.0 °C HAPPI to RCP8.5, and no significant change was found for HSI and HDD between the two warming scenarios (figure S6).

3.2. Impacts of heat stress on wheat yield under historical and warming scenarios

Figures 3 and S7 show the quantified average and maximum impacts of heat stress on wheat yield during the 30 year period, respectively. Under all four climate scenarios, estimated negative heat stress impacts (2.0%–4.0%) at northern sub-regions were larger than at the southern sub-regions. Larger negative impacts of heat stress were estimated for NS than HHS. The highest negative impacts were observed in the border area of north Hebei (HE), south Shaanxi (SN), and northwestern Henan (HA), where the average and maximum yield reductions due to heat stress can be 2.9% (236 kg ha⁻¹) and 29% (1899 kg ha⁻¹) during the historical period. For two southern sub-regions, heat stress impacts were usually less than 1.0%.

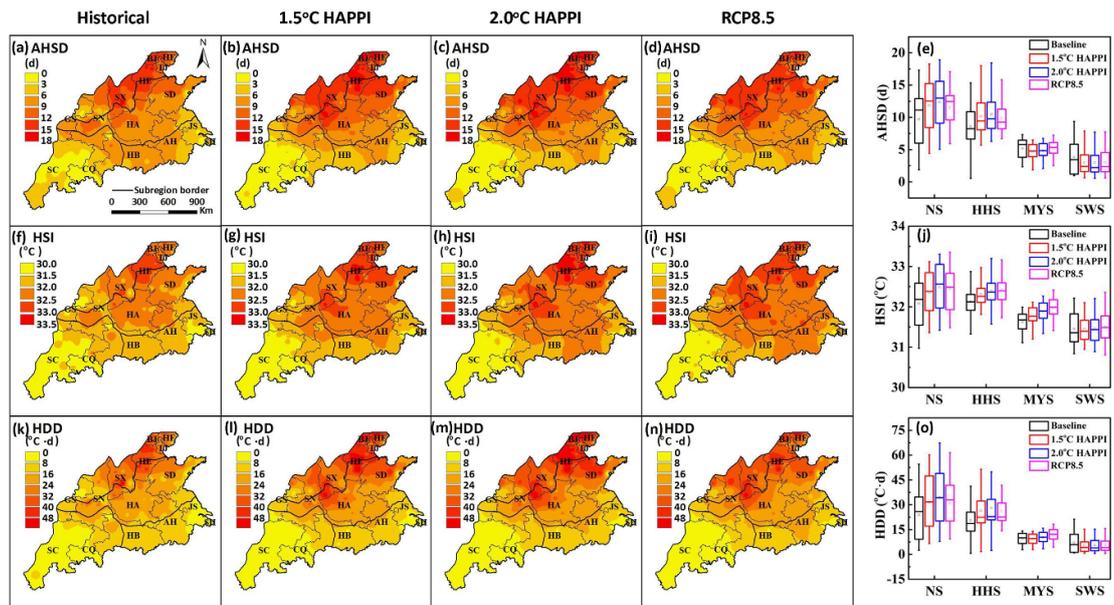


Figure 2. Spatial variation of projected heat stress indices averaged over the 30 year period under historical (a), (f), (k), 1.5 °C HAPPI (b), (g), (l), 2.0 °C HAPPI (c), (h), (m), and RCP8.5 (d), (i), (n) across the main winter wheat producing region of China. AHSDs: accumulated heat stress days (d), HSI: heat stress intensity (°C), HDD: heat degree days (°C d). NS: northern winter wheat sub-region, HHS: Huanghuai winter wheat sub-region, MYS: middle and low Yangtze Valleys winter wheat sub-region, SWS: southwest winter wheat sub-region. The box plots on the right are the distribution of the corresponding indices for all sites in each sub-region under different scenarios. The horizontal lines and small boxes in the middle of the boxes are the average and median of all stations.

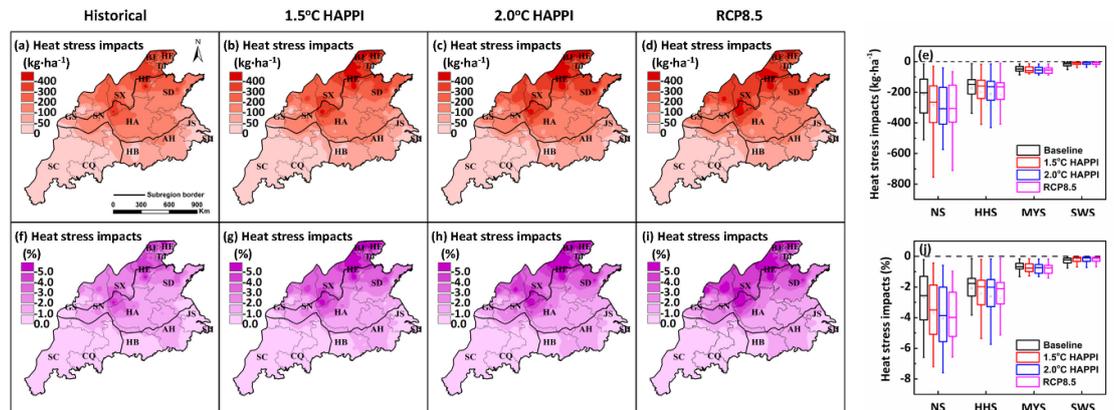


Figure 3. Estimated absolute ((a)–(e), kg ha⁻¹) and relative ((f)–(j), %) yield impacts of heat stress on wheat yields averaged over the 30 year period under historical (a), (f), 1.5 °C HAPPI (b), (g), 2.0 °C HAPPI (c), (h), and RCP8.5 (d), (i) scenarios across the main wheat producing region of China. NS: northern winter wheat sub-region, HHS: Huang-Huai winter wheat sub-region, MYS: middle and low Yangtze Valleys winter wheat sub-region, SWS: southwest winter wheat sub-region. The box plots on the right are the distribution of the corresponding indices for all sites in each sub-region under different scenarios. The horizontal lines and small boxes in the middle of the boxes are the average and median of all stations.

3.3. Impacts of temperature change on wheat yield under warming scenarios

Consistently negative impacts were projected for the overall impacts of temperature change (Δ Temperature impacts) and the impacts of increasing mean growing season temperature (Δ Warming impacts) across the main winter wheat producing region of China under three warming scenarios (figures 4 and S8). Among four sub-regions, the highest negative impacts of temperature change

and increasing growing season temperature were projected for SWS, where yield reduction due to temperature change and increasing growing season temperature could be 6%–12%. The projected absolute and relative impacts of temperature change and increasing growing season temperature for other three sub-regions (NS, HHS, and MYS) were usually less than 6% and 400 kg ha⁻¹. Projected negative impacts of temperature change and increasing growing season temperature usually

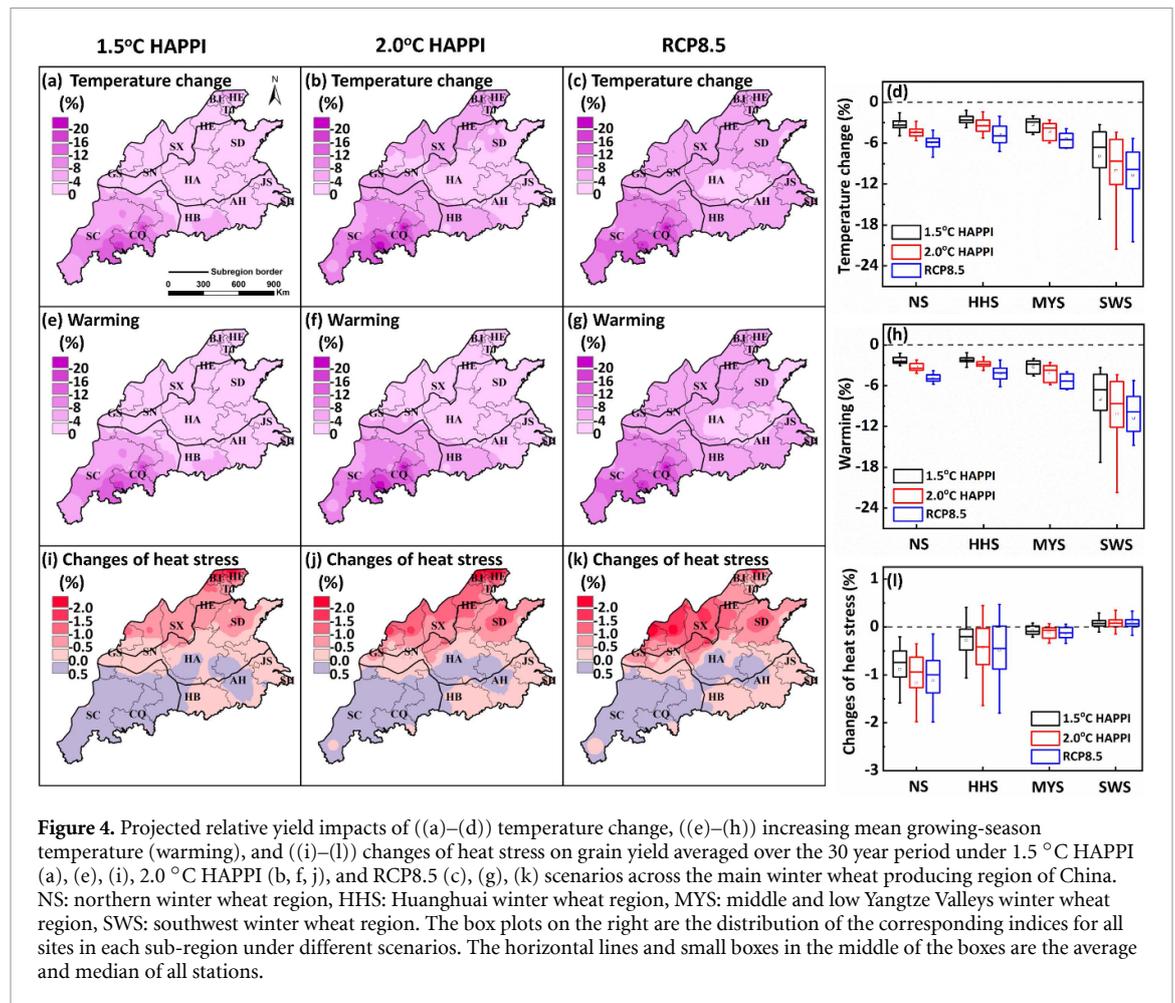


Figure 4. Projected relative yield impacts of ((a)–(d)) temperature change, ((e)–(h)) increasing mean growing-season temperature (warming), and ((i)–(l)) changes of heat stress on grain yield averaged over the 30 year period under 1.5 °C HAPPI (a), (e), (i), 2.0 °C HAPPI (b, f, j), and RCP8.5 (c), (g), (k) scenarios across the main winter wheat producing region of China. NS: northern winter wheat region, HHS: Huanghuai winter wheat region, MYS: middle and low Yangtze Valleys winter wheat region, SWS: southwest winter wheat region. The box plots on the right are the distribution of the corresponding indices for all sites in each sub-region under different scenarios. The horizontal lines and small boxes in the middle of the boxes are the average and median of all stations.

increase with warming levels under three warming scenarios (figures 4 and S8). In general, the projected impacts of increasing average growing season temperature (Δ Warming impacts) were larger than the impacts of heat stress changes (Δ Heat impacts) under the three warming scenarios (figure 4).

There was large spatial variation for the projected impacts of heat stress changes (Δ Heat impacts) across the study region. Compared to historical scenario, the projected changes of heat stress under the three warming scenarios will further decrease wheat yield in NS, and north HHS, with an average increase of 1.0%–1.5% (80–120 kg ha⁻¹) in yield reduction for most of northern sub-regions. However, no significant change (less than 0.5%) in heat stress impacts on yield was projected under climate warming scenarios in MYS and SWS. The increase in the projected negative impacts of heat stress in NS and HHS were similar under RCP8.5 and 2.0 °C HAPPI, and slightly larger than that under 1.5 °C HAPPI. In general, no significant increase in heat stress impacts on yield was projected from two low-warming scenarios (1.5 °C HAPPI and 2.0 °C HAPPI) to a high-warming scenario (RCP8.5).

4. Discussion

4.1. Estimated impacts of heat stress on wheat yields

The increasing heat stress events due to increasing temperatures have been projected under future climate warming across many regions (Semenov and Shewry 2011, Gourdji et al 2013, Teixeira et al 2013, Trnka et al 2014). In this study, we quantified the spatial variation of heat stress events under historical and three future warming scenarios across the main winter wheat producing region of China, and examined the impacts of heat stress events on yield with the improved WheatGrow model.

Large disparities in extreme heat stress impacts across the main winter wheat producing regions were observed. All three heat stress indices and yield responses show more serious impacts of heat stress in cooler northern sub-regions than in warmer southern sub-regions. The hot spots of heat stress events and its yield impacts under baseline period included Henan, Hebei, Shaanxi, and parts of Shandong, and these findings aligned with previous reports (Coordinated Research Group of Hot-Arid Wind for

Wheat in North China 1988, Shi *et al* 2007, Cheng *et al* 2011). In addition, the average and maximum impacts of heat stress events on yield across the main winter wheat producing regions show similar ranges with estimates from field-based yield observations and statistical regressions at regional scale (Shi and Shi 2016). For example, Deng *et al* (2009) summarized that there would be a 5%–20% of yield reduction due to heat stress in north China, depending on the interannual variability of heat stress events.

Under three warming scenarios, heat stress events and yield impacts were projected to increase in NS, HHS, and MYS, and to decrease slightly in SWS. However, when wheat phenology in the future warming scenarios is kept the same as in the historical period, heat stress events would increase substantially (figure S9). This indicated that the advanced wheat phenology, especially for anthesis date due to climate warming, has shifted the wheat reproductive period to the relatively cooler period (figure S4), which helps to avoid the increasing heat stress events under climate warming to some extent, this explained that the warming scenarios did not result in much higher negative impacts of heat stress on wheat yields. Similar analysis by Rezaei *et al* (2015) has indicated that earlier heading caused by the warmer temperature can prevent exposure to extreme heat events around anthesis. Therefore, warming impacts on wheat phenology could affect the impacts of extreme temperature substantially and should be considered in the integrated assessments of climate change impact.

4.2. Estimated impacts of increasing temperature on wheat yields

Here, the negative impacts of temperature increase from the baseline period to three warming scenarios could be attributed mainly to the increasing mean growing-season temperatures. The negative impacts of increasing average growing season temperature, as indicated by previous studies (You *et al* 2009, Ottman *et al* 2012, Asseng *et al* 2015), was due to the shortening of the growth duration and a decrease in crop biomass production.

However, the impacts of increasing average growing season temperature and changes of heat stress on wheat yield varied across the main winter wheat producing region. The different warming impacts of increasing average growing season temperature among four sub-regions, could be due to the differences in growing season temperature under baseline period. As indicated by Liu *et al* (2016b), warmer regions usually suffer more yield loss with increasing mean growing season temperature than cooler regions. For the main wheat producing region of China, Ye *et al* (2020) have shown much lower the growing season temperature under baseline period in the northern sub-regions than southern sub-regions.

Additional increase of growing season temperature in regions with lower baseline growing season temperature means lower reductions in crop growth duration and biomass accumulation. In addition, extreme temperature events may have more negative impacts compared to increasing average growing season temperature under some specific circumstances. For example, due to the interannual variability of extreme temperature events, the maximum impacts for heat stress could be up to –10% in the extreme conditions during the 30 year period, which might be higher than the negative impacts of increasing average growing season temperature. Therefore, more attention should be paid on extreme temperature events and average growing season temperature simultaneously, because yield interannual variability could have profound impacts on local food security.

4.3. Uncertainties and limitations

The uncertainties of the impacts quantified here could come from the climate model, crop model and the scenarios. For climate model, we reported results from ensemble of multi-GCMs here, to reduce the uncertainty due to GCM. Even though the Wheat-Grow model has been improved under heat stress, uncertainty from individual models were usually large, compared with multi-model ensemble (Asseng *et al* 2013). In addition, future climate change projections usually mean increasing temperature and elevated CO₂ occurred simultaneously, therefore temperature impacts including heat stress would be changed under elevated CO₂ conditions. Canopy temperature can represent the real temperature crop experienced better than air temperature. Elevated CO₂ could result into lower stomatal conductance, and then reduce the transpiration cooling effects on canopy temperature and exposure to heat stress (Shimono *et al* 2013). But elevated CO₂ also means larger leaf area index, and could increase transpiration to some extent (Burkart *et al* 2011). Generally, there is still lots of uncertainty on how these effects interact with each other on canopy temperatures. In addition, although (Webber *et al* 2017) tested different wheat models for canopy temperature and yield impacts under different heat stress conditions, current wheat crop models were not evaluated for canopy temperature and yield impacts under combined elevated CO₂ and heat stress conditions. Therefore, this study only focused on temperature impacts on potential wheat yield, and consideration the interactions between rising temperature, heat stress and elevated CO₂ into the crop models (Cai *et al* 2016, Fitzgerald *et al* 2016, Chavan *et al* 2019), would be needed for better quantifying climate warming and elevated CO₂ impacts together in the future. We acknowledge that the potential effects we quantified could be different from natural conditions in future climate change scenarios.

4.4. Implications for adapting to climate warming

Different climate variables could have different impacts on various processes in crop growth and yield formation. Therefore, adaptation strategies should differ for different climate variables (Challinor *et al* 2007). For example, early sowing or early anthesis dates could help to avoid heat stress (Gouache *et al* 2012), but will shorten the wheat growing period and could be detrimental for biomass accumulation and grain yield. In contrast, extending the duration of the reproductive period, which is beneficial for grain filling, may potentially compensate for the negative impacts of increasing mean growing-season temperature. However, this could also expose wheat to a higher risk of heat stress events due to later maturity. In addition, planting heat tolerant cultivars as suggested in many studies (Gouache *et al* 2012, Stratonovitch and Semenov 2015) to stabilize wheat yield under heat stress, might also negatively affect wheat yields, due to the tradeoff between average yield potential and the ability to resist extreme heat across cultivars, as indicated by Tack *et al* (2015) and Wang *et al* (2021).

Therefore, we need to develop region-specific adaptation strategies based on the spatial variation of the projected impact of temperature change, to balance the impact of increasing mean growing-season temperature and changes in heat stress. For example, stabilizing the wheat phenology under climate warming should be the priority in SWS where much higher negative impacts from increasing mean growing-season temperature on wheat yield were projected than other three sub-regions. However, in the northern sub-regions (NS and HHS), where wheat yield was more sensitive to increasing heat stress events, adaptation strategies should consider the increase of average growing season temperature together with heat stress. Even more attention should be paid to heat stress impact in some specific growing seasons when heat stress could emerge as a major risk for wheat production. This suggests that the interannual variability of heat stress should not be ignored for adaptation strategies.

5. Conclusions

Heat stress and its yield impact were more severe in the cooler northern sub-regions than the warmer southern sub-regions with historical and future warming scenarios. Heat stress was estimated to reduce wheat yield in most of northern sub-regions by 2.0%–4.0% (up to 29% in extreme years) under the historical climate. Climate warming, without considering elevated CO₂ effects, is projected to increase heat stress events in frequency and extent, especially in northern sub-regions. Surprisingly, higher warming did not result in more yield-impacting heat stress compared to low-warming, due to an advanced phenology with mean warming and finally avoiding heat

stress events during grain filling in summer. Most negative impacts of climate warming scenarios are attributed to increasing mean growing-season temperature, while changes in heat stress are projected to reduce wheat yields by an additional 1.0%–1.5% in the northern sub-regions. Adapting to climate change in China must consider the different regional and temperature impacts to be effective.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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