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The compound effects of drought and high temperature stresses will be the main constraints on maize yield in Northeast China

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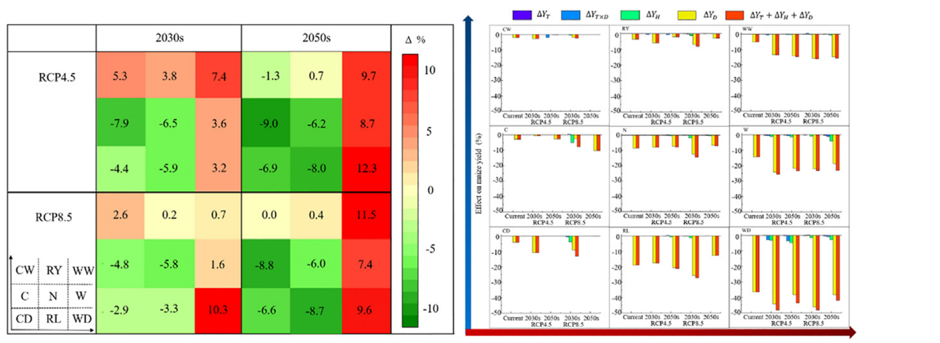
HIGHLIGHTS

- The effects of high temperature, drought, and interactions on maize yield were assessed.
- Maize belt in Northeast China was focused.
- The division of climatic year type reflects the comprehensive characteristics of temperature and precipitation.

GRAPHICAL ABSTRACT



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ABSTRACT

Compound climate extremes such as drought and high temperature have a greater impact on agricultural production than the individual extremes. An increasing frequency and intensity of the compound climate extremes has been observed and projected under climate change, yet partitioning the total impacts to individual ones on crop yield has not been well assessed. In this study, we assessed the compound and separate effects of drought and high temperature on maize yield under 9 climate-year types (CYTs) with different combinations of precipitation and temperature in Northeast China (NEC). The well-validated Agricultural Production Systems Simulator (APSIM) model was used to simulate the maize yield, driven by historical (1981–2017) and future climate data (2021–2060). The results show that CYTs of warm (warm-dry, warm-wet, warm) are prominent in the future under both Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios. However, CYT of warm-wet increased mostly (11.5%) under RCP8.5, while warm-dry increased most (12.3%) under RCP4.5. The magnitude of maize yield loss caused by the compound of high temperature and drought (18.75%) is higher than the individual ones (drought 17.32% and high temperature 1.27%). There are variations in the effects of stresses on maize yield among CYTs and the yield reductions by the compound effects of drought and high temperature were warm-dry > warm > rainless > warm-wet > normal > cold-dry > cold > rainy > cold-wet. In addition, the yield loss was negatively correlated with T_{max} and VPD_{max} but positively correlated with *Prec*. These findings imply the importance of fully considering the selection of heat and drought-resistant varieties and implementing supplementary irrigation for future climate mitigation strategies during maize production in NEC.

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1. Introduction

Under climate change, drought and high temperature have been the main stresses on agricultural production and threaten global food security with increasing temperature and variable precipitation (IPCC, 2019; Teuling, 2018; Zandalinas et al., 2020; Zhang et al., 2019). During 1964–2007, drought and heat around the world reduced cereal production by 9–10% (Lesk et al., 2016), and the maize yield reduction will increase from 7 to 31% in the future (Feng et al., 2019). With the synchronously increasing magnitude, duration, and frequency of drought and high temperature in the future, the combined events may lead to amplified impacts on agricultural production compared to individual events (Potopová et al., 2020). Therefore, it is greatly needed to understand the current and future individual and compound effects of drought and high temperature on crop production (Pullens et al., 2021).

As the second-largest maize consumer and producer in the world, China accounts for ~20% of global maize production. Meanwhile, China's maize production is sensitive to climate variations. A future warming climate, with frequent extreme drought and heat events, might more severely decrease crop yield (Liu et al., 2017; Yu and Zhai, 2020a; Yu and Zhai, 2020b). In Northeast China (NEC), maize grain production accounts for 30% of the nation's total (National Bureau of Statistics of China 2001–2019), which is known as the Golden-Maize-Belt and plays a vital role in securing food production in China (Liu et al., 2012a; Liu et al., 2012b; Ma et al., 2008). However, since maize production in NEC is mainly rain-fed, it is highly susceptible to the effect of climate change. During 1961–2017, increases in the drought frequency and intensity have already been reported (Wang et al., 2020a). The future yield reduction caused by drought was estimated to be approximately 36– 39%, with an increasing rate of yield loss over time (Xu et al., 2020). Moreover, the frequency of heatwaves in NEC has increased significantly, such as the 2018 Northeast Asia heatwave (Tao and Zhang, 2019). More concurrent drought and high temperature stresses have been observed which caused greater maize yield loss and may become a critical climate risk in NEC (Chen and Sun, 2015; Wang et al., 2020b; Zhang, 2003). Therefore, it is important to quantify the influence of drought and high temperature stresses on maize yield under current and future climate change in NEC.

The objectives of this study were to 1) assess the changing characteristics of crop growing-related meteorological elements, such as the air temperature, precipitation and maximum vapor pressure deficit (VPD_{max}) in NEC under climate change and 2) assess the individual and compound effects of drought and high temperature on maize yield in the future. To clarify the effect variations under different types of climate, the assessment was conducted in 9 climate-year types (CYTs) with different combinations of precipitation and temperature.

2. Materials and methods

2.1. Study region

The study region is the potential planting area of maize in NEC, where the sum of daily average temperature above 10 °C was consecutively more than 2100 °C d (Liu et al., 2012a), It is comprised of Heilongjiang (north), Jilin (center), and Liaoning (south) Provinces (Fig. 1).

2.2. Climate and soil data

Climate data during 1981–2017 in the weather stations in NEC (Fig. 1), including the daily maximum, minimum, and average temperatures, sunshine duration, relative humidity, actual vapor pressure, and precipitation, are available from China Meteorological Administration climate data-sharing service system (http://data.cma.cn/). For the future climate projections, we used the output databases of HadGEM2-ES models under two Representative Concentration Pathway (RCP4.5 and 8.5) scenarios. Soil data were obtained from the China Soil Scientific Database, which is operated by the Institute of Soil Science, Chinese Academy of Sciences (http://vdb3.soil.csdb.cn/). In Agricultural Production Systems Simulator (APSIM), the input of soil profile properties includes the soil bulk density (*BD*), drained upper limit (*DUL*), 15 bar lower limit (*LL15*), total nitrogen (*N*), soil organic carbon (*SOC*), and pH values in different soil layers.

2.3. Crop model

APSIM (http://www.apsim.info/apsim/) is an agricultural system modelling platform that can simulate the growth process and final yield of a variety of crops under different climate, soil, and management conditions (Holzworth et al., 2014; Gaydon et al., 2017). According to the maize trial data from the 14 agrometeorological experimental stations and the climatic data from the nearest meteorological stations, the APSIM-Maize model was validated as a well-perform in each station (Zhao, 2020). In this study, the APSIM-Maize model was used to simulate the yield of maize with the daily climate data and calibrated parameters

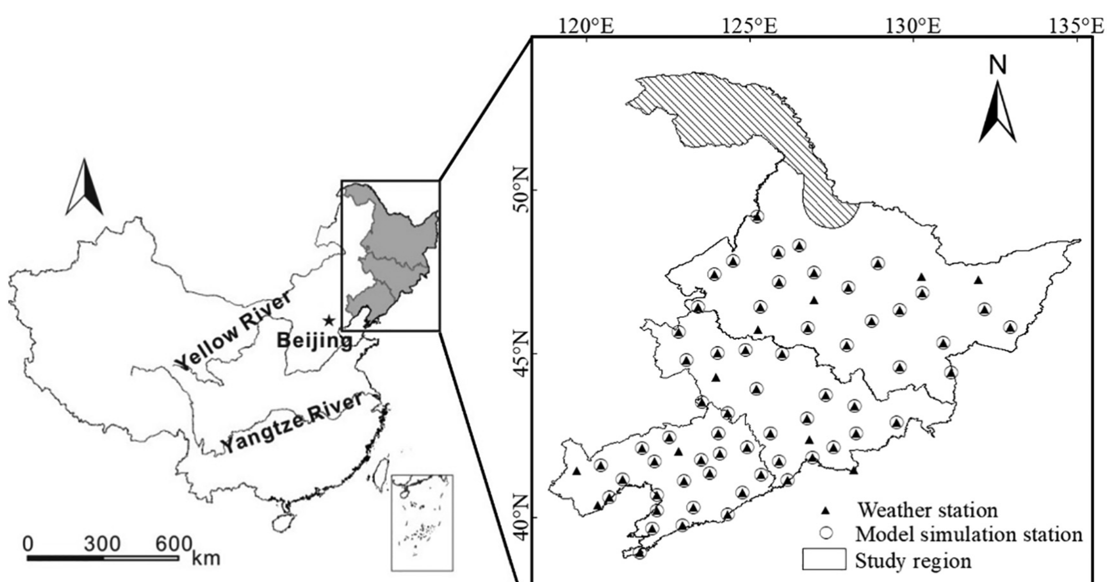

Fig. 1. Geographical location of the weather stations, model simulation station and potential maize growing region in three provinces of Northeast China.

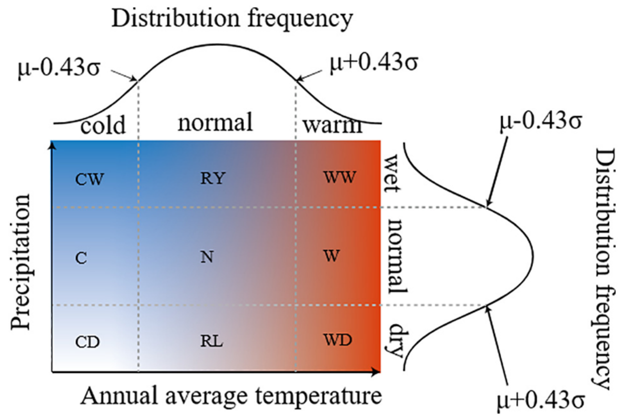

Fig. 2. Division of different CYTs in the maize growing season.

in our previous study (Zhao and Yang, 2018). In APSIM, the influence of drought and heat stress is complicated through its effects on crop phenological (life cycle), morphological (leaf development and senescence) and physiological processes (photosynthesis and grain formation), as well as soil water and nitrogen processes that supply water and nitrogen to the plants (Jin et al., 2017). Here, we only focused on the direct impact (the yield reduction) of drought and high temperature stress on maize production.

To qualify the yield reduction in maize caused by drought and high temperature stresses, we set three major stresses and introduced three switches to control the inclusion of each group. The three stresses are drought, high temperature, and heat at the flowering stage. Drought and high temperature stresses reduce yield through reducing the biomass production and grain filling rate, while heat stress at the flowering stage may restrict the kernel formation (Jin et al., 2017). We denoted Y_{THD} as the simulated yield with all enabled stresses (i.e., the default APSIM simulation) and Y^{THD} as the simulated yield without any of the aforementioned stresses. In APSIM model structure, there was no interaction between heat stress at the flowering stage and the other two. However, high temperature stress may exacerbate drought stress because it increases potential biomass production and, hence the water demand. The effect of high-temperature stress on yield denoted as ΔY_T, can be calculated as follows:

$$\Delta Y_T = \frac{Y_T^{HD} - Y^{THD}}{Y^{THD}} \tag{1}$$

Similarly, we calculated the heat at the flowering stage (ΔY_H) and drought stress (ΔY_D) effects as follows:

$$\Delta Y_H = \frac{Y_H^{TD} - Y^{THD}}{Y^{THD}} \tag{2}$$

$$\Delta Y_D = \frac{Y_{THD} - Y_{TH}^{D}}{Y^{THD}} \tag{3}$$

The interaction of drought and high temperature ($\Delta Y_{T\times D}$) stress was quantified as follows:

$$\Delta Y_{T\times D} = \Delta Y_T - \frac{Y_{THD} - Y_{HD}^{T}}{Y^{THD}} \tag{4}$$

$$= \frac{Y_D^{TH} - Y^{THD}}{Y^{THD}} - \Delta Y_D \tag{5}$$

The total climatic yield gap due to climate extremes was as follows:

$$\Delta Y_T + \Delta Y_H + \Delta Y_D = \frac{Y_{THD} - Y^{THD}}{Y^{THD}} \tag{6}$$

Other physiological stress switches were not considered in this study.

2.4. Crop growing-related meteorological element

Three crop growing-related meteorological elements, including the mean maximum daily temperature (T_{max}), maximum daily vapor pressure deficit (VPD_{max}), and cumulative precipitation (*Prec*) during the maize growing season (May to September) were selected for NEC in the current and future to clarify their spatial distributions.

The vapor pressure difference (*VPD*) (kPa) refers to the difference between the saturated water vapor pressure and the actual water vapor

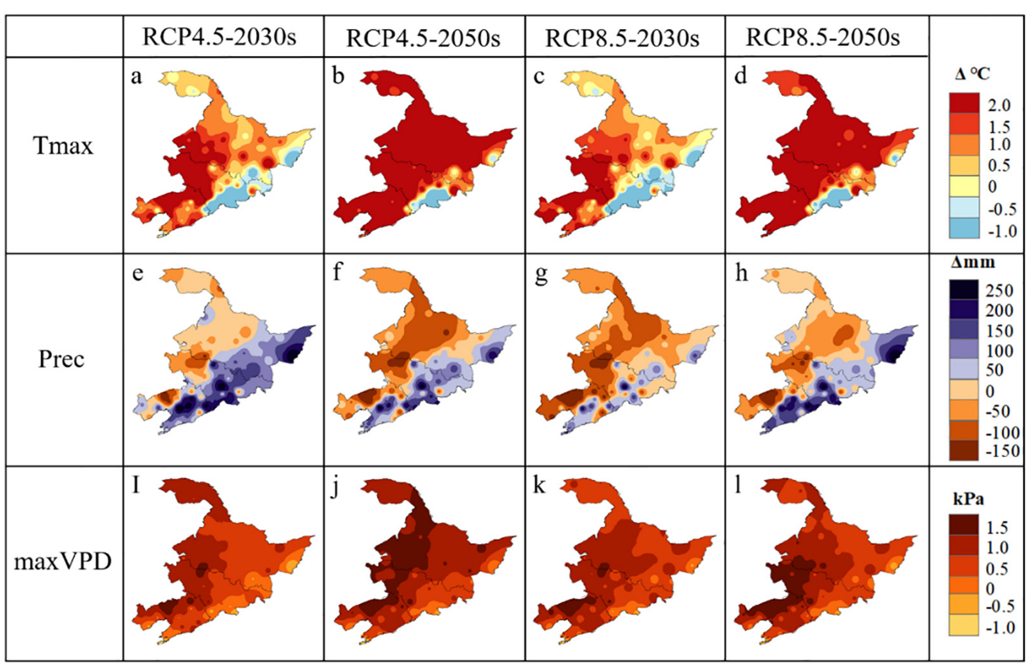

Fig. 3. Spatial distribution characteristics of VPD_{max}, T_{max}, and Prec in maize growing seasons of the RCP4.5 and RCP8.5 in the 2030s and 2050s compared to the current climate.

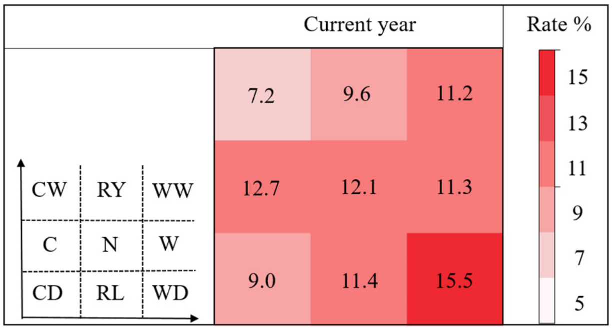

Fig. 4. The proportion of Climate Year Type (CYT) in the maize growing season in the current (1981–2017) climate (where N is normal, W is warm, C is cold, RY is rainy, RL is rainless, CD is cold-dry, CW is cold-wet, WD is warm-dry and WW is warm-wet).

pressure in the air at a certain temperature. The *VPD* affects the stomatal closure of plants, thus controlling physiological processes such as transpiration and photosynthesis, and therefore has an important influence on crop growth and performance. The calculation method of *VPD* is as follows (Zotarelli et al., 2020):

$$e^0(\mathrm{T}) = 0.6108e^{\frac{17.27T}{T+237.3}} \tag{7}$$

$$e_s = \frac{e^0(T_{\max}) + e^0(T_{min})}{2} \tag{8}$$

$$e_a = e_s \times R_h/100 \tag{9}$$

$$\mathrm{VPD} = e_s - e_a \tag{10}$$

where T_{max} and T_{min} are the daily maximum and daily minimum temperatures (°C), respectively, and R_h is the relative humidity (%), e^0(T) is the saturation vapor pressure at air temperature T (kPa), e_s is the saturation vapor pressure (kPa) and e_a is the actual vapor pressure (kPa).

2.5. Climate year type

To clarify the effect variations under different types of climate, the assessments were conducted under different CYTs. Each growing season was determined to be cold, normal, or warm with daily mean air temperature and dry, normal, or wet with accumulated precipitation. According to the classification method by Liu et al. (2017), the probability density of the standard normal distribution of air temperature and precipitation is evenly divided into three classes at $X = \mu \pm 0.43\sigma$ (X is a coefficient for class thresholds). The corresponding thresholds of the different types mentioned above are $\mu - 0.43\sigma$ and $\mu + 0.43\sigma$ (Fig. 2), where μ and σ are the mean value and standard deviation of precipitation and temperature in the maize growing season, respectively.

The combinations of precipitation and temperature can be divided into 9 different CYTs: normal (N), warm (W), cold (C), rainy (RY), rainless (RL), cold-dry (CD), cold-wet (CW), warm-dry (WD), and warm-wet (WW).

3. Results

3.1. Changes in T_{max}, Prec, and VPD_{max} in maize growing season

Compared with that in the current climate (1981–2017), the T_{max} during the NEC maize growing season in the 2030s (2021–2040) and 2050s (2041–2060) is expected to increase by 0.5 °C and 1.7 °C, respectively, under RCP4.5 and by 0.6 °C and 1.8 °C, respectively, under RCP8.5 (Fig. 3). In the 2030s, the region with the largest T_{max} increase under RCP4.5 and RCP8.5 is in the southwest. In the 2050s, except for a small part of the southeast, the T_{max} increase range is uniform under RCP4.5 and RCP8.5. The T_{max} increase in the 2050s is greater than that in the 2030s.

Compared with that in the current climate, the *Prec* during the NEC maize growing season is expected to increase by 84 mm and 44 mm in the 2030s and 2050s, respectively, under RCP4.5 and by 19 mm and 62 mm, respectively, under RCP8.5 (Fig. 3). Under RCP4.5, *Prec* increases in the southeast and decreases in the northwest of the study region in the 2030s, and *Prec* decreases in the early 2050s. Under RCP8.5, *Prec* in the southeast of the study region increases, while decreases in the northwest. Under RCP4.5, there was a decreasing trend, while an increasing trend under RCP8.5.

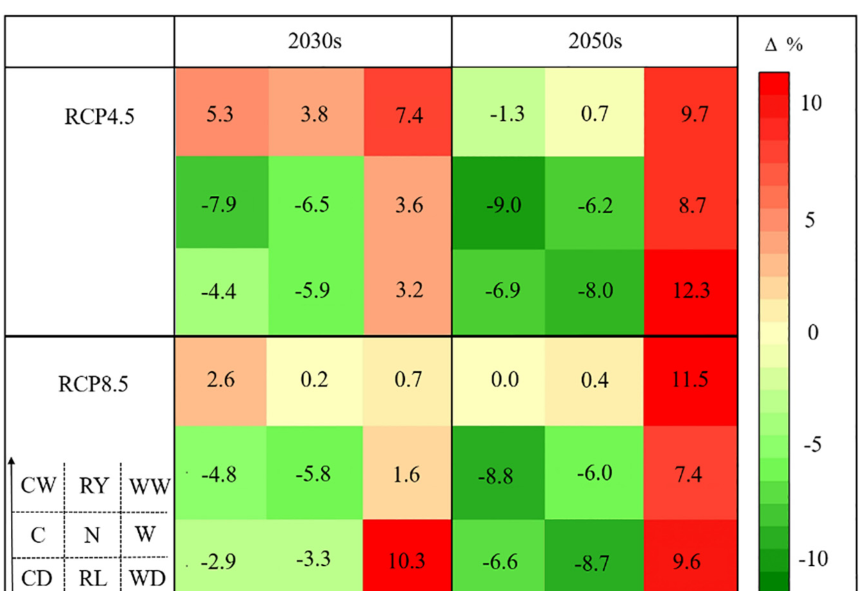

Fig. 5. Variation rate of Climate Year Type (CYT) in the maize growing season of the 2030s and 2050s under RCP4.5 and RCP8.5 compared to the current climate (where N is normal, W is warm, C is cold, RY is rainy, RL is rainless, CD is cold-dry, CW is cold-wet, WD is warm-dry and WW is warm-wet).

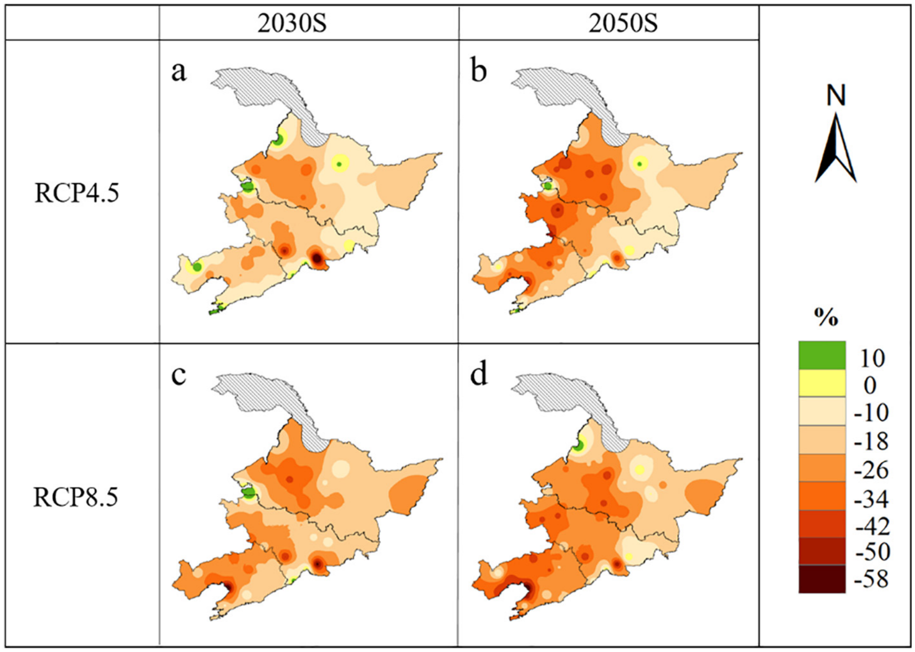

Fig. 6. Spatiotemporal changes in maize yield in the 2030s and 2050s under RCP4.5 and RCP8.5 compared to the current climate.

Compared with that in the current climate, the VPD_{max} during the NEC maize growing season is expected to increase by 0.67 kPa and 0.94 kPa in the 2030s and 2050s, respectively, under RCP4.5 and by 0.79 kPa and 0.87 kPa, respectively, under RCP8.5 (Fig. 3). The changes in VPD_{max} showed an increasing trend under both RCP scenarios.

3.2. Variation in CYT in the future

Currently (1981–2017), warm-dry conditions are the most common CYT (Fig. 4). In the 2030s, the warm-wet CYT has the highest increase (7.7%) among all the nine CYTs under RCP4.5, while warm-dry increases mostly by 10.7% under RCP8.5 (Fig. 5). In the 2050s, under RCP4.5, the warm-dry CYT increased the most, with an increased rate of 12.3%, and it was followed by the warm-wet CYT, with an increased rate of 9.7%. Under RCP8.5, the warm-wet CYT increased the most, with an increased rate of 11.7%, followed by the warm-dry CYT, with an increased rate of 10.0% (Fig. 5).

3.3. Spatiotemporal changes in maize yield under future climate change

Compared with that in the current climate, the NEC maize yield in the 2030s and 2050s is expected to decrease by 13.09% and 18.76%, respectively, under RCP4.5 and 18.96% and 22.07%, under RCP8.5 (Fig. 6). The largest reduction is distributed in the northwestern portion of NEC. In particular, the reduction area spreads to the whole mid and western portions in the 2050s under RCP8.5.

3.4. Shifts in the influence of different stresses

The average regional maize yield loss in the current climate derived was 0.01% to 11.57%, and could almost fully be attributed to the compound of drought and high temperature, the heat stress at the flowering stage and the individual drought stress, which will also be the main limitations on maize yield in the future (Fig. 7). Furthermore, the maize yield loss caused by all the studied individual and compound stresses will increase by 0.01% to 19.40% in the future. Under RCP4.5, drought will reduce the maize yield by 15.63% in the 2030s and 17.98% in the 2050s, respectively, while the compound of the three stresses will reduce by 16.49% and 19.40%, under RCP8.5, higher maize yield loss will be caused by both drought and the compound stresses in the 2030s than the 2050s. Compared 0.06% of yield loss in the current situation, heat stress at the flowering stage will reduce the maize yield by 1.27% on average in the future.

Furthermore, there are variations in the effects of stresses on maize yield under different CYTs (Fig. 8). Under the CYTs of warm-dry, the individual and compound of the three stresses cause more yield loss than other CYTs under the current and future climate, particularly under RCP4.5. Compared to the current climate, all the stresses will reduce more maize yield under the CYTs of warm-dry, warm, and warm-wet in the future.

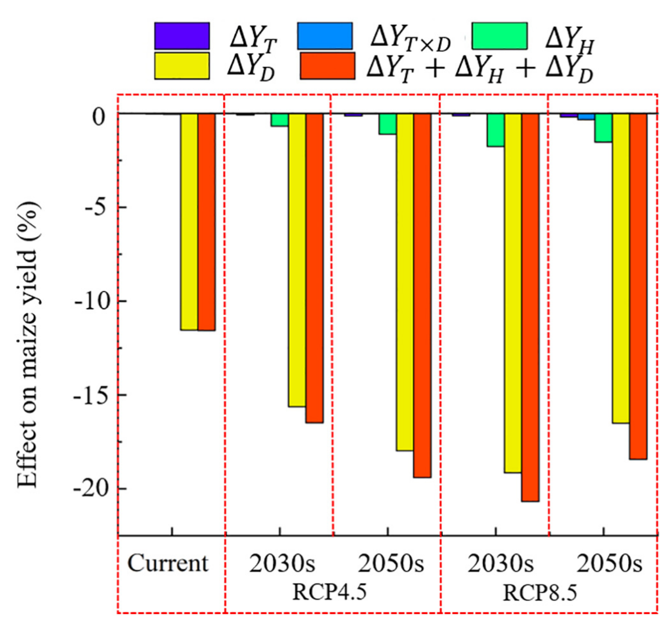

Fig. 7. Shifts in the influence of different stresses, where ΔY_T is the yield loss caused by high temperature, $\Delta Y_{T\times D}$ is the yield loss by the interaction of temperature and drought, ΔY_D the yield loss caused by drought, ΔY_H is the yield loss caused by the heat stress at the flowering stage and $\Delta Y_T + Y_H + Y_D$ is the yield loss caused by the compound of all stresses.

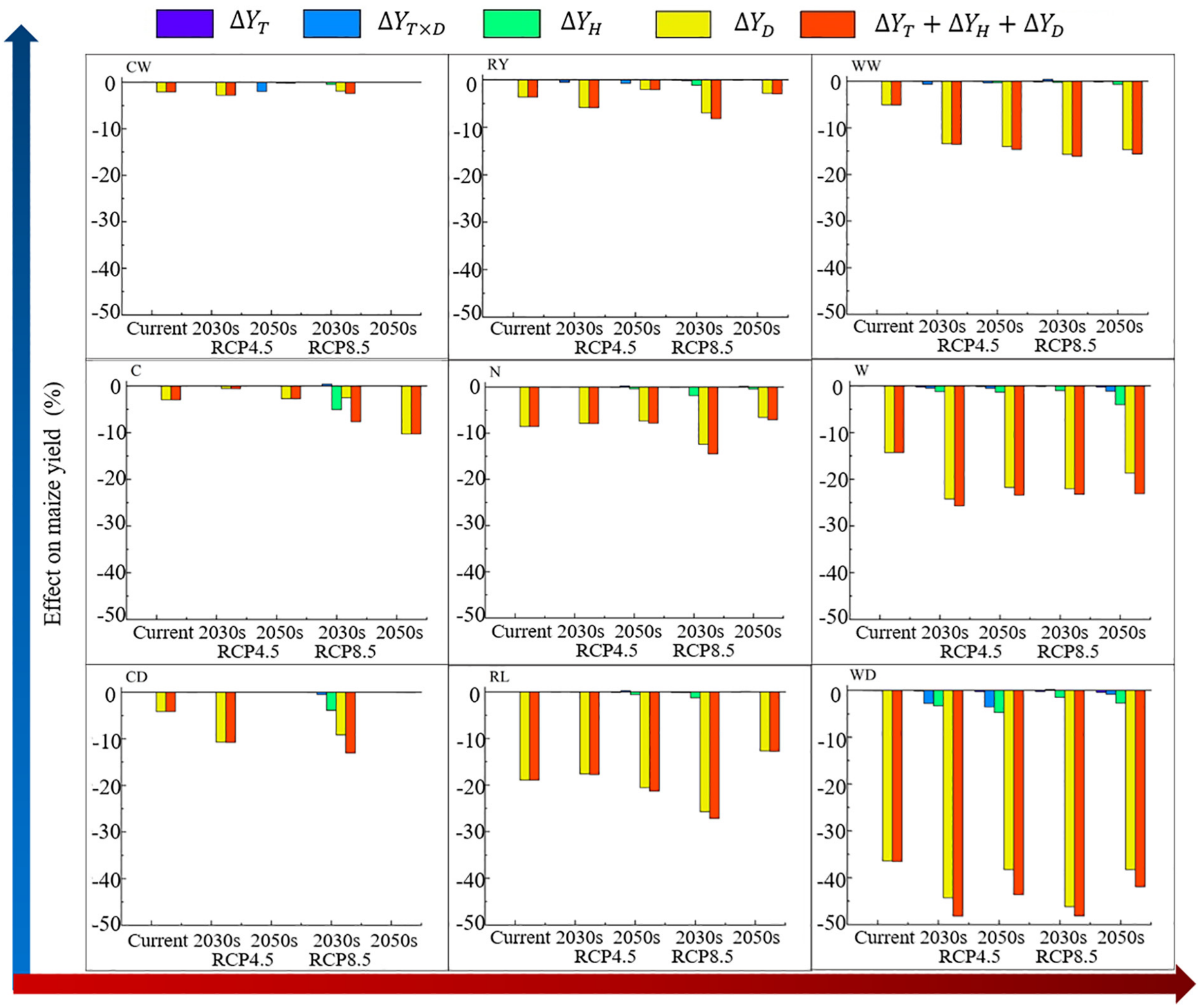

Fig. 8. Shifts in the influence of different stresses under different CYTs. (Precipitation increases upward (Y-axis), temperature increases to the right (X-axis); where N is normal, W is warm, C is cold, RY is rainy, RL is rainless, CD is cold-dry, CW is cold-wet, WD is warm-dry and WW is warm-wet).

3.5. Correlation coefficient between yield loss and meteorological elements

According to the correlation analysis between the yield loss and the changes of crop growing-related meteorological elements (Fig. 9), the effects of drought, high temperature, and the compound of drought and high temperature on maize yield were negatively correlated with the change in T_{max} and VPD_{max}, but positively correlated with the change in *Prec*. The interaction effect of drought and high-temperature stress on yield was positively correlated with T_{max}.

	ΔTmax	ΔPrec	ΔmaxVPD	Correlation coefficient
$\Delta Y_T + \Delta Y_H + \Delta Y_D$	-0.41**	0.206**	-0.357**	0.30
$\Delta Y_{T\times D}$	0.01	0.034	-0.043	
ΔY_T	-0.351**	0.271**	-0.414**	0.0
ΔY_H	-0.174*	0.063	-0.235**	
ΔY_D	-0.394**	0.198**	-0.333**	-0.45

Fig. 9. Correlation coefficients between yield loss under different stresses and changes of crop growing-related meteorological elements (* indicates statistical significance at $p < 0.05$, ** indicates statistical significance at $p < 0.01$).

4. Discussion

Previous studies reported that the high temperature in NEC during 1981–2017 increased from an average of 23.1 °C in the northern portion to an average of 28.0 °C in the southern portion (Liu et al., 2012b), while precipitation decreased from the southeast (average of 860 mm) to northwest (average of 320 mm) (Liang et al., 2011; F. Zhang et al., 2020; Z. Zhang et al., 2020). Furthermore, a higher VPD_{max} was found in the northwest than in the southeast. Compared with the current climate, T_{max}, *Prec*, and VPD_{max} under RCP4.5 and RCP8.5 showed an increasing trend.

Under the background of global warming, the temperature in China is generally increasing, particularly in the northern part of the country (Yang et al., 2011). In the current study, the future climate in NEC is characterized by an increase in warm (warm-dry, warm-wet, and warm) and a decrease in cold (cold-dry, cold-wet, and cold) CYTs (Fig. 5), which is consistent with previous research results (Liu et al., 2017). Research has shown that over the next 30–90 years, most of the land area will experience serious and widespread drought (Dai, 2012). As a result, drought and high-temperature stresses affect crop growth, development, and yield formation (Prasad et al., 2008). According to the comparison among simulated maize yield under the current and future climate, we found the compound effect of drought, high temperatures, and heat stress at the flowering stage will serve as the main constraint on maize production in NEC under both RCP scenarios. Moreover, drought, high temperature, the compound of drought, high temperature, and the heat at the flowering stage will have increased effects on maize yield, and the compound stresses will reduce the maize yield by 18.75% in the future. The compound effect of drought and high temperature on yield reduction was smaller than that of individual drought because temperature stress may reduce potential biomass production and hence the water demand.

According to the spatial distribution characteristics of the yield reduction, the areas of maize yield reduction under RCP4.5 and RCP8.5 were mainly distributed in the western part of the spring maize planting region where VPD_{max} increased, temperature increased and precipitation decreased (Fig. 3) and in regions with increased drought as assessed by other indices (Du et al., 2013).

Precipitation and temperature were used to assess agricultural drought alone to estimate its effect on crop yield (Gunda et al., 2016; Wan et al., 2021; Zhang and Zhang, 2016; Zhang et al., 2016). As drought and high-temperature stresses affect crop growth, development, and yield, we determined the effects of these stresses on yield in different CYTs. Based on the results of the effects of different CYTs, the compound of drought and high temperature, the heat at the flowering stage, and individual drought were still the main causes of changes in maize production in NEC. In warm CTYs, the individual effect of drought and the compound effect of drought and high temperature, and heat at the flowering stage are expected to impact production most severely, with an average reduction rate of 27.16%. In the process of maize production, water supplements and sowing date should be made promptly to ensure maize yield and national food security.

5. Conclusions

Under global warming, CYTs of warm (warm-dry, warm-wet, warm) are prominent in the future and the precipitation will be significantly reduced, in particular in the northwestern part of NEC. Under the current and future climate scenarios, the compound effect of drought, high temperatures, and heat stress at the flowering stage serve as the main constraint on maize production in NEC, and the yield loss caused by the compound effect shows an increasing trend. There are variations in the effects of stresses on maize yield under different CYTs, the highest yield loss was found in the CYT of warm-dry. In the future planting of maize in NEC, it is necessary to fully consider the selection of varieties that are resistant to high temperature and drought and to provide irrigation and water supplementation in key growth stages to ensure the yield of maize.

CRediT authorship contribution statement

Jin Zhao: Supervision, Conceptualization, Methodology, Investigation, Review & Editing. **E. Li:** Formal analysis, Software, Writing - Original Draft, Data Curation. **Johannes W.M. Pullens:** Writing - Review & Editing. **Xiaoguang Yang:** Supervision, Conceptualization, Resources, Reviewing and Editing.

Declaration of competing 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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