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ORIGINAL PAPER

Increased heat stress risk for maize in arid-based climates as affected by climate change: threats and solutions

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Abstract

Heat stress in combination with drought has become the biggest concern and threat for maize yield production, especially in arid and hot regions. Accordingly, different optimal solutions should be considered in order to maintain maize production and reduce the risk of heat stress under the changing climate. In the current study, the risk of heat stress across Iranian maize agro-ecosystems was analyzed in terms of both intensity and frequency. The study areas comprised 16 provinces and 24 locations classified into five climate categories: arid and hot, arid and temperate, semi-arid and hot, semi-arid and temperate, and semi-arid and cold. The impact of heat stress on maize under a future climate was based on a 5-multi-model ensemble under two optimistic and pessimistic emission scenarios (RCP4.5 and RCP8.5, respectively) for 2040–2070 using the APSIM crop model. Simulation results illustrated that in the period of 2040–2070, intensity and the frequency of heat stress events increased by 2.37 °C and 79.7%, respectively, during maize flowering time compared to the baseline. The risk of heat stress would be almost 100% in hot regions in the future climate under current management practices, mostly because of the increasing high-risk window for heat stress which will result in a yield reduction of 0.83 t ha^{-1}. However, under optimal management practices,farmers will economically obtain acceptable yields (6.6 t ha^{-1}). The results also indicated that the high-risk windows in the future will be lengthening from 12 to 33 days in different climate types. Rising temperatures in cold regions as a result of global warming would provide better climate situations for maize growth, so that under optimistic emission scenarios and optimal management practices, farmers will be able to boost grain yield up to 9.2 t ha^{-1}. Overall, it is concluded that farmers in hot and temperate regions need to be persuaded to choose optimal sowing dates and new maize cultivars which are well adapted to each climate to reduce heat stress risk and to shift maize production to cold regions.

Keywords APSIM · Extreme temperature · Cultivar · Multi-model ensemble · Management practices

Introduction

Heat stress has recently become the biggest concern and threat for grain maize production, particularly in arid, semi-arid, and hot climates (e.g., Jin et al. 2017). Maize yield is largely specified during a short period of flowering stage determining grains set and the number of grains (Otegui and Bonhomme 1998). If maize crops experience temperatures above 35 °C during flowering stage, grain yield will be diminished by reduced ovary fertilization of pollinated spikelets (Dupuis and Dumas 1990; Ordónez et al. 2015). However, the amount of this reduction is strongly depended on the intensity and frequency of occurrence of extreme temperatures. For example, the effect of 30–35 °C temperatures on crops yields is quite different from that of 35–40 °C. This issue can be better understood in Sub-Saharan Africa maize agro-ecosystems where Lobell et al. (2011) reported that maize yield is reduced 1 to 1.7% per each degree day above 30 °C. Other researchers reported that 1% increase in extreme-heat-degree-days and consecutive-dry-days led to maize yield losses of 0.2% and 0.07%, respectively, in China (Wei et al. 2017). In the Northeastern USA, it was also estimated that maize crops will experience greater frequencies (30 days) of daily high temperature above 35 °C during

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silking-anthesis and reproductive stages under RCP8.5 at the end of twenty-first century (Prasad et al. 2018).

As the incident of extreme high temperatures are expected to be increased by the end of the current century (Jin et al. 2017; Hoegh-Guldberg et al. 2018), two major approaches have been investigating to tackle the negative impacts of heat stress on crops including "tolerance" (Lobell et al. 2015) and "escape" (Rodríguez et al. 2005). In the latter one, some useful strategies could help crops to avoid exposure to heat stress. These strategies vary from changing sowing dates (Liu et al. 2013), cultivar switching (Rahimi-Moghaddam et al. 2018) to even expanding cropping systems to cooler locations with high latitude (Gourdji et al. 2013). For instance, in the southwest of Iran which has hot climatic conditions, climate change increased the length of the high-risk window for extreme temperatures from 18.8 to 26.3 days for RCP4.5 and RCP8.5, respectively, which reduced grain yield considerably (18.3%). However, by choosing optimal sowing dates and cultivars, grain yield improved substantially by 0.6–1.1 t ha^{-1} (Rahimi-Moghaddam et al. 2018). In an another study, Zheng et al. (2012) reported that climate change made winter a bit warmer in the Australian Wheatbelt resulted in reducing the wheat growing season by up to 6 weeks. Under these conditions, the longer maturity cultivars showed better performance to adapt to future climates. Liu et al. (2013) also assessed negative effects of climate warming on maize yield in Northeast China and reported that adoption of longer season cultivars (with higher thermal time requirements) could overcome the negative effects of climate change and made a substantial increase in yield ranging from 13 to 38% over the past 27 years. In almost all the studies, crop simulation models have been applied to investigate the long-term assessment of adaptation strategies in different locations and seasons. Simulation modeling has provided opportunities for researchers to save time and reduce costs to solve research problems without needing multi-environment field experiments (e.g., Zheng et al. 2012; Lobell et al. 2015; Rahimi-Moghaddam et al. 2018).

Iranian maize agro-ecosystems with dominant arid climates cover an area of 234,000 ha under cultivation and ranked third in annual grain maize production in the Middle East with ~ 2 megatons (FAO 2014). Therefore, any changes in the production of maize agro-ecosystems due to future global warming could have an important impact on the turnover of the crop in national and global markets. Accordingly, the primary aims of this study were to investigate the risk of heat stress in different climates in agro-ecosystems under present and future climate changes considering both (i) the frequency of occurrence of extreme temperatures during sensitive phenological stages, and (ii) the intensity of extreme temperatures. The secondary objectives were to assess the effect of heat stress on maize production in the study areas and the role of adaptation strategies, including changes in sowing date, cultivar switching, and expansion of cropping systems to cooler locations in mitigating the impact of global warming and reducing the risk of heat stress.

Materials and methods

Study locations, climate, soil, and management data

To represent the Iranian maize cropping system, 16 out of 31 provinces were selected, and the major production areas (24 locations) were chosen in each province. The locations were classified into five climate regions (arid and hot, arid and temperate, semi-arid and hot, semi-arid and temperate, and semi-arid and cold) according to the Köppen climate methodology (Table 1 and Fig. 1) (Kottek et al. 2006; Karki et al. 2016). To do this, mean annual precipitation (MAP), temperature of the hottest month (T_{hot}), temperature of the coldest month (T_{cold}), and value of $P_{threshold}$ parameters were considered (Kottek et al. 2006; Karki et al. 2016). Details of the subdivision of Köppen climatic classifications and the five climate regions are shown in Table S1.

Other than genetic coefficients (Table S2), the APSIM model required climate, soil, and management inputs to run. Historical daily climate data for the period 1980–2010 were gathered for the study locations from the Meteorological Organization of Iran (Table 1). Climatic data included solar radiation (MJ m^{-2} d^{-1}), maximum and minimum temperatures (°C), and rainfall (mm).

Soil characteristics were collected from a database generated by the Agricultural Meteorological Organization of Iran. In addition, some published reports and papers (i.e., Nouri et al. 2016; Rahimi-Moghaddam et al. 2019) were used to complete and improve the database. The soil data required to drive and run the module of soil water balance in the crop model included soil depth, bulk density, drained upper limit (DUL), crop lower limit (CLL), and saturated water content (SAT). As the collected data only contained the particle size distribution, bulk density, and organic carbon, the SPAW (soil–plant-air–water) model (Saxton et al. 1986) was applied for estimating DUL, CLL, and SAT and, ultimately, plant available water-holding capacity (PAWC). The soil properties of all study locations are presented in Table S3.

Local management practices were obtained by local experts from the Ministry of Agriculture and Agricultural and the Natural Resources Research and Education Centers in each province and at each location. Farmers' practices included sowing season, sowing date, number of irrigations, and cultivar (Table 1). Two late-maturing (SC704; as the most dominant and commercial maize cultivar in Iran) and early-maturing (SC260) cultivars were used. The cultivars are not only different in terms of their length of growing

Table 1 Regions, climate types, locations, and climatic properties in Iran's maize agroecosystems

Region	Climate type	Location	No	Longitude	Latitude	Elevation (m)	Area under cultivation (ha)	Common sowing date	Sowing season	Number of irrigation	Annual mean temperature (°C)	Annual cumulative rainfall (mm)
AH	Arid and hot	Behbahan	1	50.2	30.6	313	4100	15- Jul	Summer	16	24.9	254.7
		Darab	2	54.3	28.8	1098.2	8000	30-Jun	Summer	14	22.1	257.4
		Dehloran	3	47.1	32.8	213	8265	22-Jun	Summer	15	26.2	270
		Dezful	4	48.4	32.4	143	25,585	15-Jul	Summer	14	24.5	318.7
		Fasa	5	53.8	28.9	1450	5100	21-Jun	Summer	13	19.3	289.9
		Iranshahr	6	60.7	27.2	591.1	1000	2-Aug	Summer	13	26.8	111.9
		Jiroft	7	57.8	28.6	601	100	22-Jul	Summer	14	25.1	176.2
		Khash	8	61.2	28.2	1394	3000	22-Jun	Summer	7	20.1	151.1
		Shush	9	48.2	32.2	83	31,990	15- Jul	Summer	14	25.9	224.4
		Shushtar	10	48.8	32.0	67	2370	15- Jul	Summer	16	27.1	282.1
SH	Semi-arid and hot	Gachsaran	13	50.8	30.5	720	1376	6-Jul	Summer	16	22.6	445.5
AT	Arid and temperate	Baft	11	56.6	29.2	2280	250	4-May	Spring	11	15	247.1
		Kerman	12	56.9	30.3	1753	100	19-May	Spring	12	15.9	148
ST	Semi-arid and temperate	Gazvin	14	50.1	36.3	1279.2	8660	1-May	Spring	15	14.1	314.4
		Kermanshah	15	47.0	34.3	1400	18,240	4-May	Spring	10	14.5	441.6
		Kuhdasht	16	47.4	33.5	1195	1300	30-Mar	Spring	12	16.1	374.2
		Nahavand	17	48.1	34.2	1644	3237.5	20-Apr	Spring	14	13.9	402.5
		Parsabad	18	47.9	39.6	31.9	10,635	30-Apr	Spring	10	15.2	271.2
		Shiraz	19	52.7	29.5	1585	770	20-Apr	Spring	12	17.8	334.7
SC	Semi-arid and cold	Ahar	20	46.7	38.5	1360	250	25-May	Spring	8	11.2	286.5
		Mahabad	21	45.7	36.7	1320	1600	21-Apr	Spring	8	13.1	403.8
		Sanandij	22	46.9	35.3	1500	30	20-May	Spring	12	13.6	449.5
		Shahr-e Kord	23	50.7	32.3	2061	230	22-May	Spring	12	11.5	330.6
		Zanjan	24	48.3	36.8	1638	30	20-May	Spring	9	11.2	295.6

AH, arid and hot; *AT*, arid and temperate; *SH*, semi-arid and hot; *ST*, semi-arid and temperate; *SC*, semi-arid and cold. Refer to the Fig. 1 for more details of regions. *No.*, the name number of each location in Fig. 1

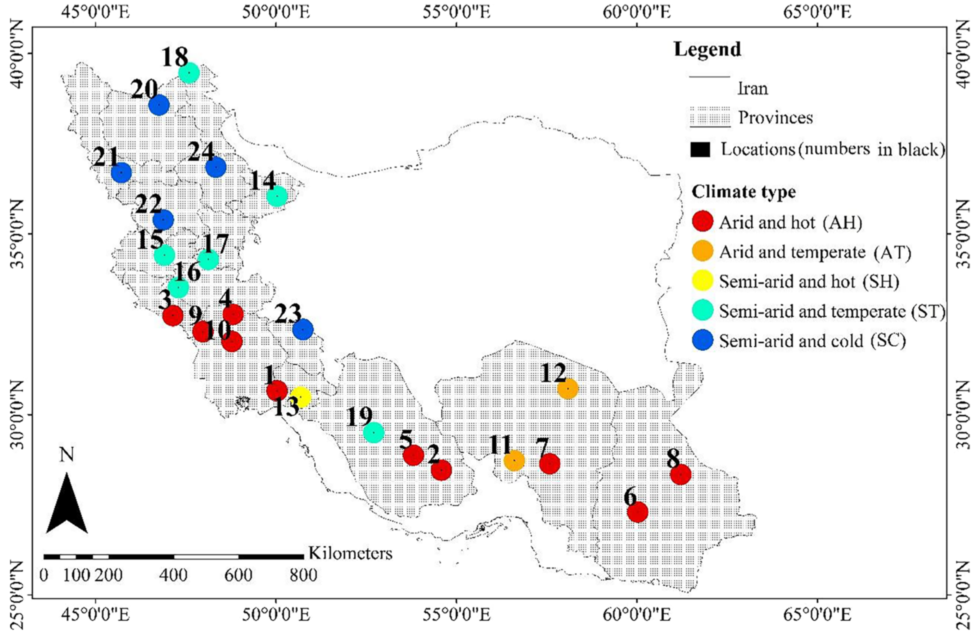

Fig. 1 Geographical details of locations in 16 provinces of Iran and their climate types. The name of locations (numbers in black) are given in Table 1. Twenty four locations were classified into five climate regions (i.e., AH, AT, SH, ST, and SC) over maize agroecosystems in Iran according to the Köppen climate classification

season (i.e., thermal time accumulations in different growth stages) but also in their potential in producing biomass and grain yield (i.e., genetic coefficients of maximum number of grains per head and grain growth rate) (Table S2). In the study locations, grain maize is commonly planted in spring and summer seasons depending upon the climate type and region (Table 1). Farmers in the hot regions usually sow maize during the summer season (from 21 June to 2 August), while planting in the spring sowing season (from 30 Mar to 22 May) is dominant in temperate and cold regions.

Maize simulation model

APSIM (the Agricultural Production Systems sIMulator) crop model version 7.10 (Holzworth et al. 2014) was used to estimate the impacts of intensity and frequency of heat stress on maize grain yield. The model simulates growth, development, biomass, and grain yield in response to solar radiation, temperature, day length, and soil moisture and nitrogen in daily time steps from sowing to maturity (Holzworth et al. 2014). In the model, development and phenological stages are controlled by temperature and day length (photoperiod). Biomass production (dry matter) and growth are predicted based on radiation interception and radiation use efficiency (RUE). Partitioning of dry matter into different organs varies by stage and is allocated to different organs according to allocation coefficients. Water balance is measured based on soil evaporation, plant transpiration, drainage, and runoff on daily time-steps which are individually calculated according to the relationships and equations introduced in APSIM. For example, plant transpiration and runoff are calculated based on both transpiration efficiency and the USDA curve number (Archontoulis et al. 2014).

The APSIM crop model has already been evaluated under different management practices including sowing season, sowing date, cultivar, plant density, and irrigation regime under potential (Rahimi-Moghaddam et al. 2018) and water-limited (Rahimi-Moghaddam et al. 2019) conditions for both late-maturity (SC704) and early-maturity (SC260) cultivars. All the previous results associated with the model evaluation are presented in Fig. S1. Further details regarding the field experiments and methodologies applied for model evaluation could be found in the above-mentioned articles.

General circulation models, emission scenarios, and AgMIP methodology

To investigate the impacts of heat stress on maize under future global warming, a projection of the future climate was needed. Accordingly, future climate conditions of the Iranian maize agroecosystem were projected based upon two representative concentration pathways (RCP4.5 and RCP8.5) and five general circulation models (GCMs) from the CMIP5 (Coupled Model Intercomparison Project Phase 5) for the 2050s (mid-century) (Table S4). The five GCMs were chosen based on wet and dry time series and included models with relatively large and relatively small global sensitivity to the greenhouse gasses, and they were considered to be a perfect combination of dry and wet GCMs (Ruane and Mcdermid 2017; Asseng et al. 2019; E. Eyshi-Rezaei, pers. comm.). To downscale the monthly outputs of GCMs to daily form, daily long-term baseline observations (1980–2010) were used. To do this, the AgMIP (Agricultural Model Intercomparison and Improvement Project) methodology presented in AgMIP (2013) was applied. In this methodology, the future climate data is generated according to the absolute change in minimum and maximum air temperatures and relative change in rainfall in the climate model using the delta change technique (Ruane et al. 2013; Rahimi-Moghaddam et al. 2019, 2018). The properties of GCM and RCP scenarios are shown in Table S4. The projected changes in temperature and cumulative rainfalls for maize in five GCMs for two emission scenarios are drawn in Fig. 2. For each emission scenario and simulation treatment, the median of the multi-model ensemble (median of 5 GCMs) was subjected to analysis.

Long-term simulation experiments

To mitigate the effects of global warming and reduce the risk of heat stress on maize cultivation, two different adaptation strategies were applied. The first one was sowing date which included the common sowing date in each location (Table 1), early sowing date (20 days prior to the common sowing date), and late sowing date (20 days after the common sowing date). The second one was cultivar which

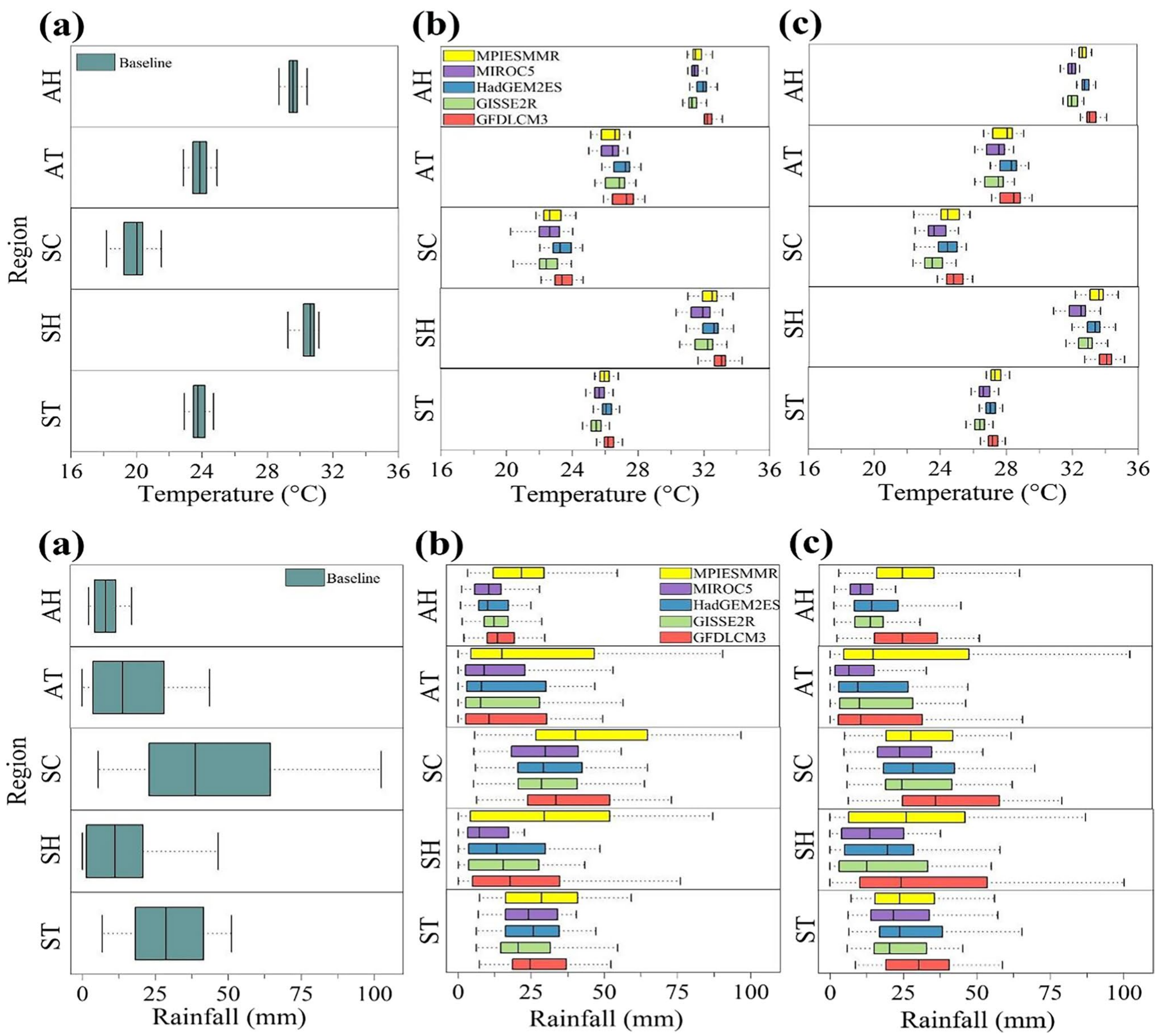

Fig. 2 Long-term seasonal mean temperature and cumulative rainfalls in the study regions (AH: arid and hot; AT: arid and temperate; SH: semi-arid and hot; ST: semi-arid and temperate; SC: semi-arid and cold) in baseline and five GCMs for two future emission scenarios. All the box plots are drawn based on common sowing dates (refer to Table 1 for the common sowing dates for each region). **a** Baseline; **b** RCP4.5; **c** RCP8.5

comprised early- (SC260) and late-maturity (SC704) cultivars. An attempt was made to investigate two cultivars with contrasting maturity to see which one is better adapted to each environment in terms of avoiding heat stress. Overall, considering five GCMs, two cultivars, three sowing dates, 24 locations, and two emission scenarios (RCP4.5 and RCP8.5) over a span of 31 years, there were ~ 45,000 simulation experiments for the future (24 locations × 5 GCMs × 3 sowing dates × 2 cultivars × 2 emission scenarios × 31 years) and ~ 5000 for baseline (24 locations × 3 sowing dates × 2 cultivars × 31 years).

All simulations were performed under no abiotic and biotic stresses. As described in Table 1, however, the number of irrigations differed among locations and regions. Most farmers apply 7 to 16 times irrigation over growing season. In other words, most farmers perform dry sowing and then start to irrigate immediately. The amount of each irrigation was 50 mm (Table S3) and the initial soil water is assumed to be equal to PAWC in a given location as reported by the farmers. It is worth noting that plant densities (7 plants m^{-2}), row spacing (750 mm), sowing depth (50 mm), and tillage (conventional) were considered constants throughout all simulations. Also, water, nitrogen, and surface organic matter were all reset at sowing in each year throughout all simulations at baseline and future.

Determination of heat stress risk for maize, high-risk window, and statistical analyses

Three dimensions (Teixeira et al. 2013) were considered in assessing heat stress risk for maize: (i) the most sensitive phenological phases in maize, (ii) the frequency of occurrence of extreme temperatures during the sensitive periods, and (iii) the intensity of extreme temperatures. In the APSIM-maize model, the most sensitive phenological phases in maize to heat stress, which result in yield reductions, occur during the 10 days before flowering (pre-flowering) and at flowering (Rahimi-Moghaddam et al. 2018; G.L. Hammer, pers. comm.). Accordingly, in the model, a maximum temperature of over 36 °C was assumed as the critical temperature for seed set and flowering (Fig. S2) (Holzworth et al. 2014). Hence, to estimate the intensity of heat stress, the mean of maximum temperatures during pre-flowering and flowering was computed. The number of days having a maximum temperature of over 36 °C ($T_{max} > 36$ °C) during pre-flowering and flowering was summed as frequency of heat stress events. The high-risk window for heat stress in each year was defined as the number of consecutive days having a maximum temperature of > 36 °C.

The outputs of the APSIM-model were analyzed in R (R Core Team 2017), graphed in OriginPro 9.1 (Seifert 2014), and mapped in ArcGIS 10.1 (ESRI 2012).

Results

A sharp increase projected in the intensity of heat stress during flowering for 2050

Figure 3a shows the intensity of heat stress at baseline and in future emission scenarios. As shown, the intensity of heat stress was extremely affected by region. For example, during the flowering time at baseline, maize stands experienced maximum temperatures ranging from 32.3 °C in semi-arid and cold regions to 39.8 °C in semi-arid and hot regions (Figs. 3a and 1). This huge variability became even larger when the different combinations of sowing date × cultivar were investigated.

When averaged across all regions and RCPs in the mid-future (2050), the maximum temperature increased 2.37 °C during maize flowering time compared to the baseline under current management practices (Fig. 3b and c). However, the increases differed considerably by region so that the greatest increase was simulated for the semi-arid and cold region at 2.5 °C and 3.6 °C for RCP4.5 and RCP8.5, respectively, and the lowest was simulated for the arid and hot region at 0.99 °C and 1.27 °C for RCP4.5 and RCP8.5, respectively. As can be seen from Fig. 3b and c, any changes in sowing date made a difference of ± 1.5 °C in maximum temperature, while changing cultivars resulted in a much lower difference (± 0.27 °C) in 2050. However, in arid and hot, semi-arid, and hot regions where the farmers used to sow maize in the summer season, on average, maximum temperature during flowering time exceeded 38.2 °C under the best combination of G × M (SC704 × late sowing dates) and increased even further to 43.6 °C under the worst management practices (SC260 × early sowing dates). This indicates that the summer-season maize did not show a good performance in either RCPs, even by applying the best option of sowing date × cultivar, so that in 97% of simulation years, maize crops experienced maximum temperatures above the critical point (Fig. S2 and Fig. 3b, and c). In contrast, in arid and temperate, semi-arid and temperate, and semi-arid and cold regions, farmers cultivate maize in spring. Under these circumstances, the average maximum temperature for maize flowering would be 36.3 °C for the best interaction (SC260 × early sowing dates) and 37.1 °C for common sowing dates (Fig. 3b and c).

The occurrence of heat stress during flowering declined by choosing an optimal G × M

At baseline, simulation results indicated that heat stress is already occurring in all regions under common

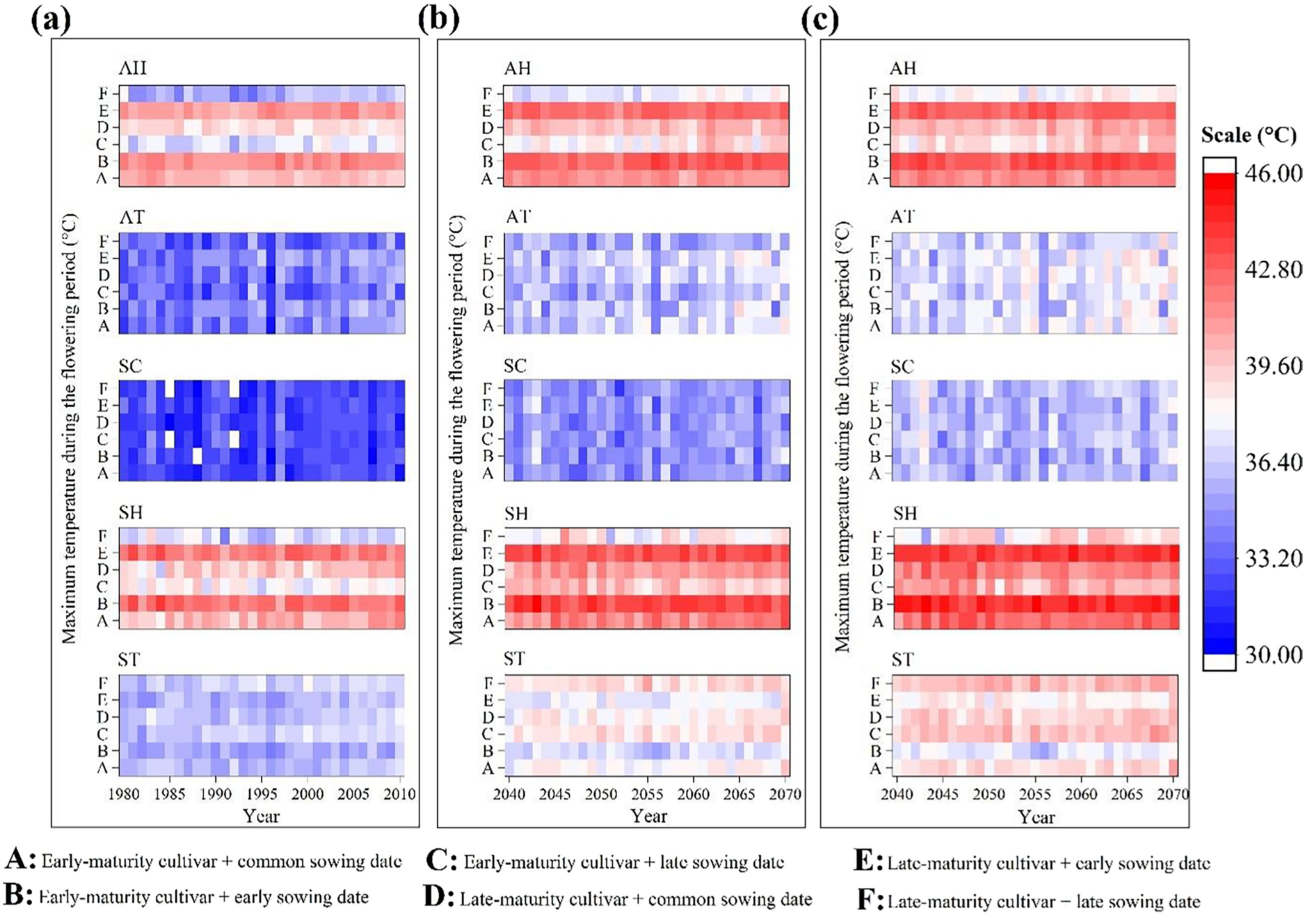

Fig. 3 Median of maximum temperature (over the five GCMs) during flowering period of maize for different regions (AH: arid and hot; AT: arid and temperate; SH: semi-arid and hot; ST: semi-arid and temperate; SC: semi-arid and cold) and cultivars × sowing dates at baseline and future emission scenarios. Refer to Table 1 for full name of the regions. **a** Baseline; **b** RCP4.5; **c** RCP8.5. The current management practice by farmers is shown as D

management practices, such that around 58% of simulation years are currently under heat stress (Fig. 4a). However, the frequency of heat stress events was much higher in hot regions (97.2% of simulation years) compared with cold and temperate zones (28.3% of simulation years). Results also showed that applying SC704 along with a late sowing date reduced the frequency by 24.9% compared to the current cultivar and sowing date in all regions at baseline (Fig. 4a).

As expected, the predicted global warming increased the occurrence of heat stress events around flowering, with 75.6% and 83.9% in the frequency of heat stress events in the period 2040–2070 for RCP4.5 and RCP8.5, respectively (Fig. 4b and c). However, the occurrence of heat stress events was quite different among regions. For example, when averaged across both RCPs, the values simulated from 71.9 to 100% in the arid and temperate and arid and hot regions, respectively. These results changed substantially when a different G × M was applied for different regions. In regions with spring-dominant sowing seasons (i.e., arid and temperate, semi-arid and temperate, and semi-arid and cold, Fig. 1), SC260 × early sowing dates (10 March to 5 May) resulted in 57% years with a maximum temperature > 36 °C during flowering. In contrast, regions with a summer-dominant sowing season (i.e., arid and hot and semi-arid and hot, Fig. 1), SC704 × late sowing dates (from 11 July to 22 August) led to 87% years with a maximum temperature > 36 °C during flowering (Fig. 4b and c). These results indicate that there would still be a huge amount of risk in terms of the frequency of occurrence of heat stress across maize agro-ecosystems in the study areas, despite applying the best G × M in the future.

The high-risk windows for heat stress expanded under future emission scenarios

Figure 5 displays the duration of high-risk windows for heat stress (T_{max} > 36 °C) in the study regions. At baseline, the

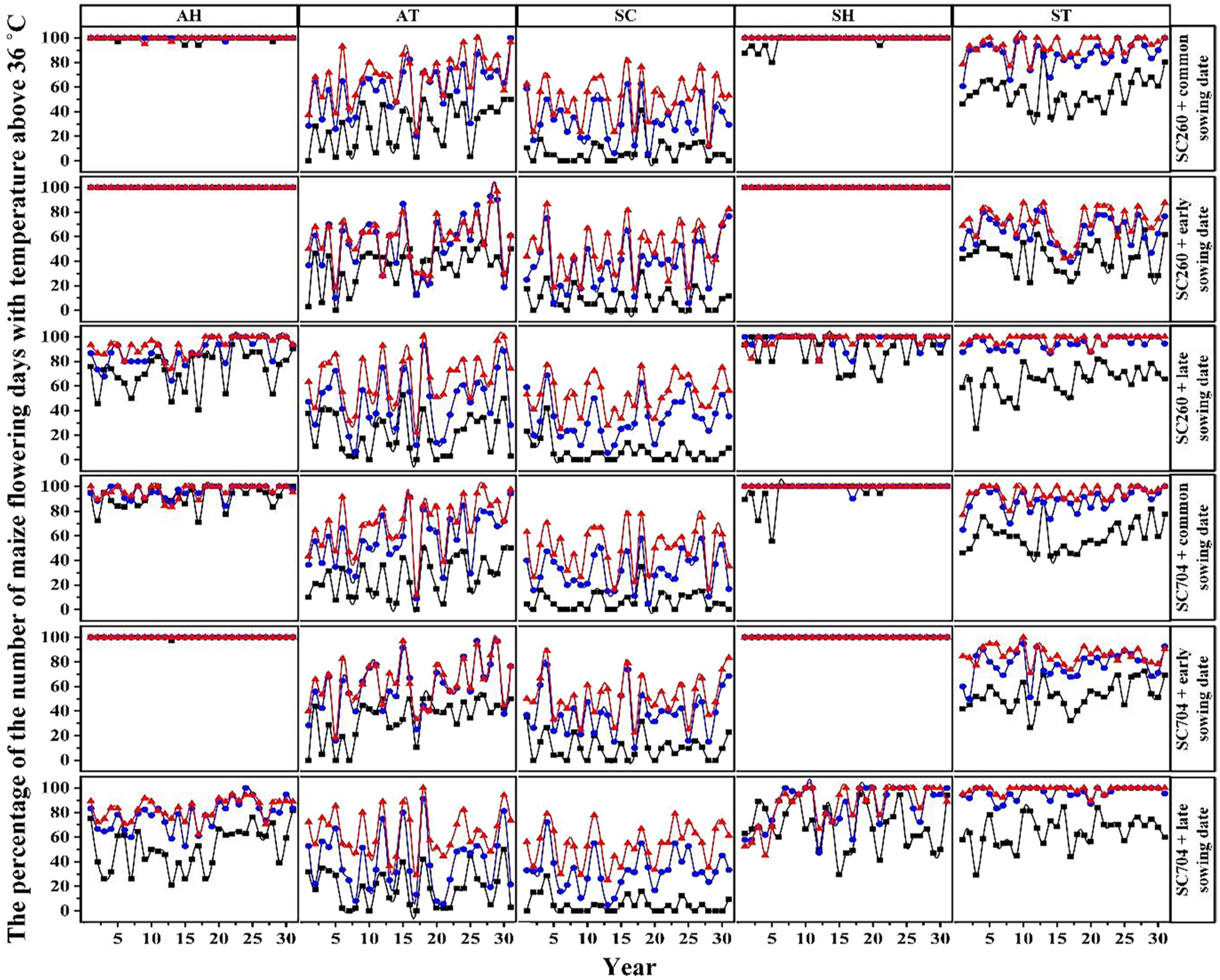

Fig. 4 Percentage of the number of maize flowering days with temperature above 36 °C (median of the five GCMs) for different regions (AH: arid and hot; AT: arid and temperate; SH: semi-arid and hot; ST: semi-arid and temperate; SC: semi-arid and cold) and cultivars × sowing dates at baseline and future emission scenarios. Baseline: line and square in black; RCP4.5: line and circle in blue; RCP8.5: line and triangle in red. The horizontal scale shows simulation year (31 years from 1980 to 2010 for baseline and 2040 to 2070 for both RCP4.5 and RCP8.5). SC260: an early-maturity cultivar; SC704: a late-maturity cultivar

longest window was simulated for arid and hot regions (1 April–29 September; 164 days) and the shortest for semi-arid and cold regions (15 July–7 August; 23 days) (Fig. 5a). Choosing the late-maturity cultivar (SC704) × late sowing date in hot and arid regions resulted in moving the flowering period (14 September–15 October) to almost out of the high-risk window (from April to 29 September) (Fig. 5a). In contrast, in semi-arid and cold regions, any change in cultivars and sowing dates had no impact on moving the flowering time.

Under future global warming, the high-risk windows were lengthened up to 16 and 26.6 days for RCP4.5 and RCP8.5, respectively, relative to baseline (Fig. 5). The longest and shortest high-risk windows were almost identical to baseline; the longest was simulated in arid and hot regions (184 and 195 days in RCP4.5 and RCP8.5, respectively), and the shortest was obtained in semi-arid and cold regions (35 and 43 days in RCP4.5 and RCP8.5, respectively) (Fig. 5b and c). Expansion of the high-risk windows in the future made maize cultivation much more vulnerable to heat stress such that under RCP8.5, most G × M interactions flowered during the high-risk window. However, a suitable combination of G × M could improve the situation. In hot regions with summer season cultivation, under RCP4.5, SC704 and late sowing date were the only successful interaction for maize to escape the high-risk windows. However, under RCP8.5, this combination completely flowered (5 September–13 October) during the high-risk window (11 April–13

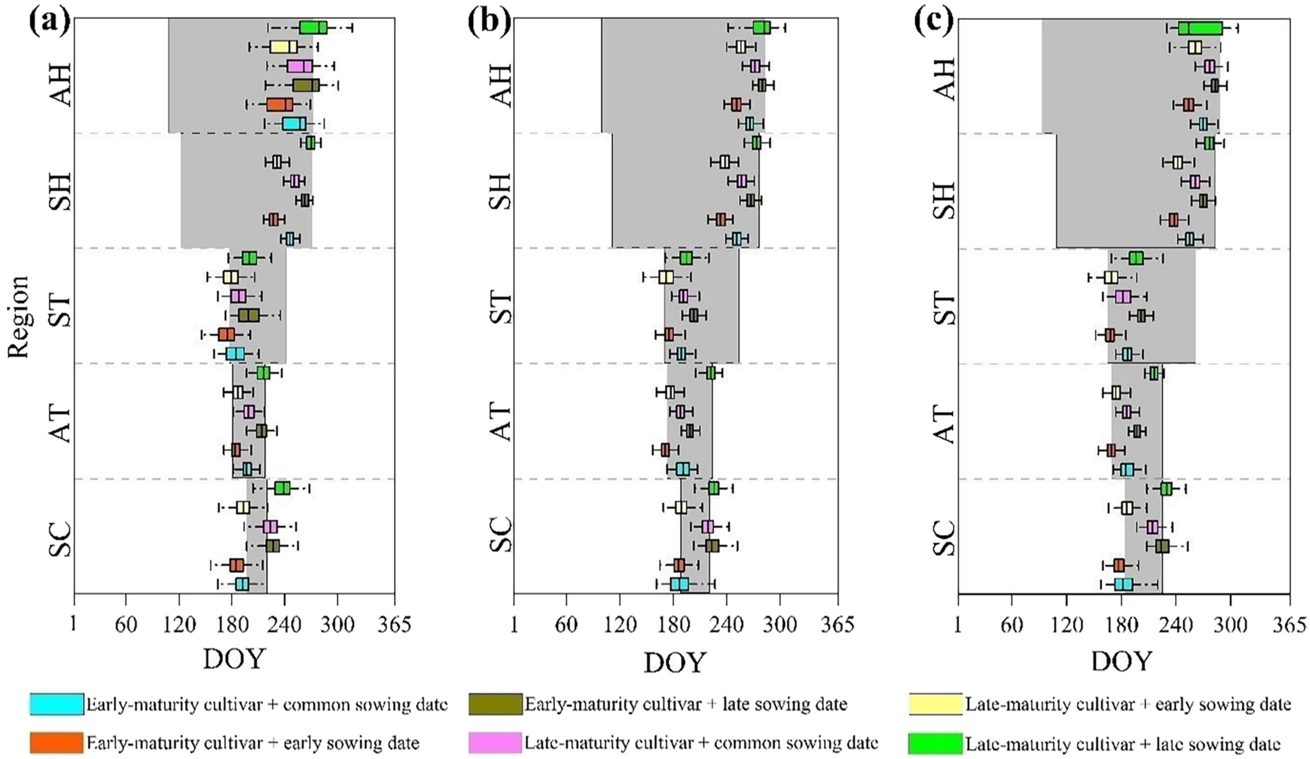

Fig. 5 High-risk windows for heat stress in maize (backgrounds in gray) and the period of maize flowering (box plots) in different regions (AH: arid and hot; AT: arid and temperate; SH: semi-arid and hot; ST: semi-arid and temperate; SC: semi-arid and cold), cultivars × sowing dates at baseline and future emission scenarios (median of the five GCMs). The high-risk window for heat stress was defined as the number of days having a maximum temperature of > 36 °C for each year. Refer to Table 1 for full name of the regions. **a** Baseline; **b** RCP4.5; **c** RCP8.5. The box plots in pink are those under current management practice by farmers

October) (Fig. 5c). Conversely, in temperate regions with spring season cultivation, under both optimistic and pessimistic emission scenarios, SC260 and early sowing date almost flowered (15 June–24 June) out of the high-risk window (20 June–30 August). The results in the cold regions were completely promising, such that the flowering time of both SC260 × early sowing date (25 June–7 July) and SC704 × late sowing date (11 August–23 August) did not coincide with the high-risk window (5 July–13 August) across two RCPs (Fig. 5b and c).

Large variability in grain yield depending upon region, cultivar, sowing date, and emission scenarios

Across all regions at baseline, the response of maize grain yield to sowing date and cultivar ranged from 5.5 to 9.3 t ha^{-1}. However, the variability in grain yield was considerable region by region. In hot regions, grain yield varied from 0 (under severe heat stress) to 8.3 t ha^{-1} under optimum conditions (Fig. 6a). The lowest response to sowing date and cultivar was simulated for temperate regions (from 9.5 to 11.4 t ha^{-1}). Under current climate situations, SC704 in combination with the late sowing date was the best in terms of grain yield (9.3 t ha^{-1}) when averaged across all climate types and seasons at baseline (Fig. 6a).

By 2050, the intensity and frequency of heat stress affected maize grain yield considerably so that grain yield was reduced by 39% and 58.3% for RCP4.5 and RCP8.5, respectively, compared with baseline (Fig. 6b and c). However, the grain yield reduction was strongly affected by cultivar, sowing date, emission scenario, climate type, and sowing season. For example, under the optimistic emission scenario (RCP4.5), in semi-arid and temperate regions with a spring-dominant sowing season, the combination of SC704 × early sowing date produced higher grain yield (6.9 t ha^{-1}) than other interactions, while under the pessimistic emission scenario (RCP8.5), SC260 along with early sowing date became the superior combination (5.3 t ha^{-1}, Fig. 6b and c). In other regions, the simulated maize grain yields were much higher under the best combination of G × M compared to semi-arid and temperate regions (Fig. 6b and c).

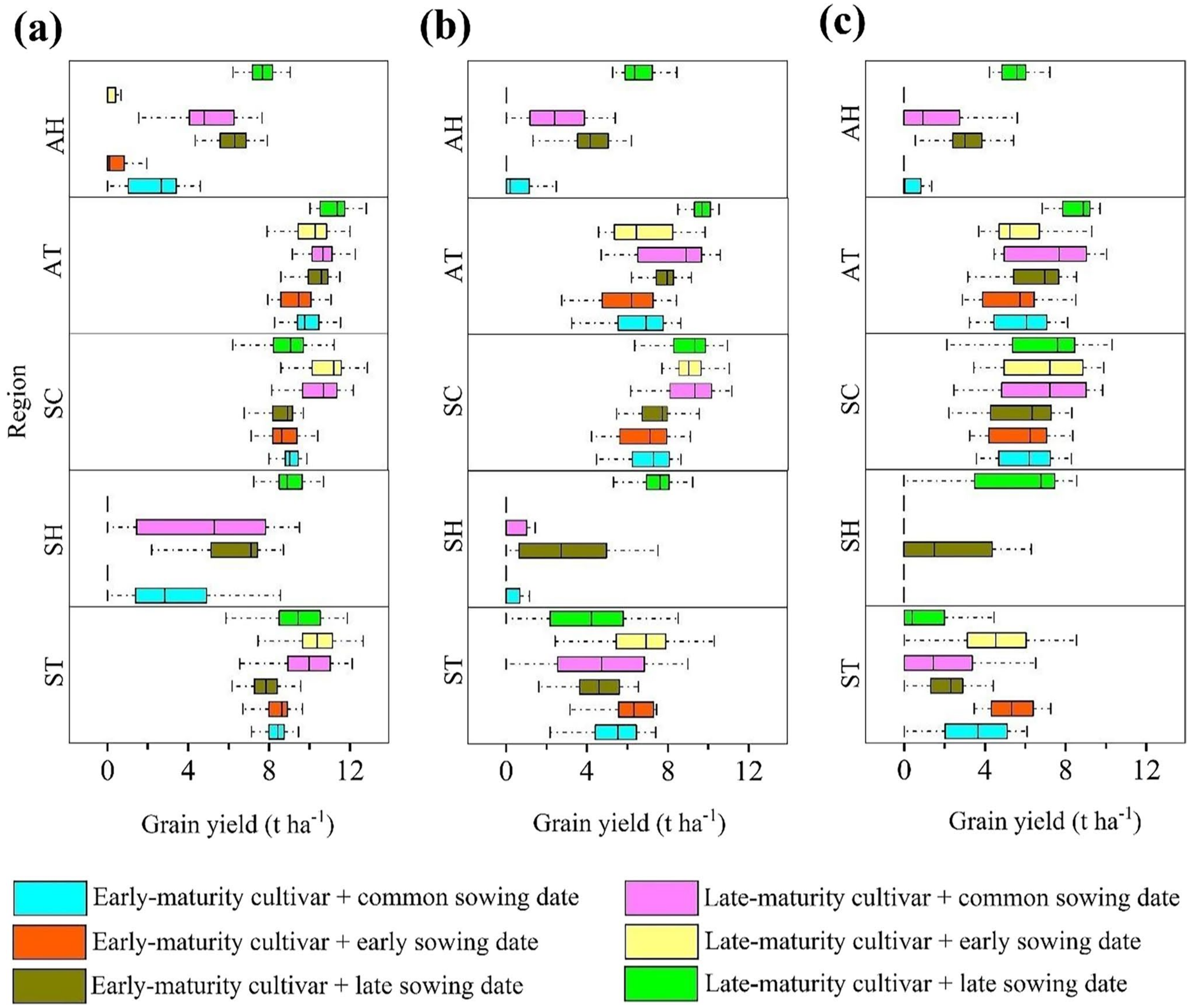

Fig. 6 Grain yield (box plots) in different regions (AH: arid and hot; AT: arid and temperate; SH: semi-arid and hot; ST: semi-arid and temperate; SC: semi-arid and cold), cultivars, and sowing dates at baseline and future emission scenarios (median of the five GCMs). Refer to Table 1 for full name of the regions. **a** Baseline; **b** RCP4.5; **c** RCP8.5. The box plots in pink are those under current management practice by farmers

Discussion

Large variability in heat stress risk simulated across the maize agro-ecosystems under global warming depending upon various climates

Iranian grain maize agro-ecosystems are currently subjected to heat and drought stresses during the flowering period with high frequency and intensity which varies greatly among seasons and regions (Figs. 3a, 4a, and 5a). This high frequency and intensity of heat and drought stresses during the maize flowering time resulted in a low average grain yield of 7 t ha^{-1} at baseline (Fig. 6a). It should also be noted that although the current study emphasized the effects of heat stress on maize grain yield, drought stress could also exacerbate the effects of heat stress on maize grain yield, given that the simulations were performed under water-limited conditions based on the farmers' number of irrigations (Table 1). For example, Li et al. (2022) assessed the compound and separate effects of drought and high temperature on maize yield under 9 climate-year types with different combinations of precipitation and temperature in Northeast China and reported that the magnitude of maize grain yield loss caused by the compound of high temperature and drought (18.75%) was higher than the individual ones (drought 17.32% and high temperature 1.27%).

In future climate changes across five GCMs and two RCPs, an increase of 2.5 °C in seasonal mean temperatures (Fig. 2b and c) was simulated for summer-dominant sowing seasons (i.e. arid and hot, semi-arid and hot regions). In these regions, the maize flowering period completely (100%) coincided with the high-risk window (AH and SH regions in Fig. 5b and c), characterized by maximum temperatures with high intensity (41 °C) (Fig. 3b and c), which resulted in a yield reduction (83.4%) of 0.83 t ha^{-1} (Fig. 6b and c) in all simulation years under current local management practices (Table 1). The issue was clearly illustrated by the negative coefficients of regression between grain yield versus average maximum temperature during the flowering period (intensity of heat stress) and number of flowering days with temperatures above 36 °C (frequency of heat stress) (Fig. 7a and b). The regression slopes show the greater importance of the intensity of extreme temperatures (b = − 1.07; R^2 = 0.73**) than the frequency of occurrence of critical temperatures (b = − 0.98; R^2 = 0.57**) (Fig. 7a and b). The negative effect of extreme temperatures on grain yield for different crops has been reported worldwide. For example, in a risk assessment study on investigating the effects of direct heat stress on summer maize in the Haihe Plain (the northern part of the North China Plain), it was reported that summer maize was more vulnerable to extreme heat direct stress at reproductive stage. At this stage, the number of extreme heat days over 1.6 days could result in yield losses, and yield losses increased rapidly with the number of extreme heat days. At vegetative stage, however, the extreme heat days over 9.1 may result in yield losses, and yield losses increased slowly with the number of extreme heat days (Zhang et al., 2021). In a 2-year field experiment within the North West Province of South Africa with semi-arid climate, heat stress effects were assessed on grain yield of drought-tolerant maize varieties and it was reported that rising temperatures (33 to 38 °C) during the reproductive phase reduced grain weight and grain number by 73% and 69%, respectively. Grain number and grain weight were recognized as the most sensitive yield components to rising temperature in this study (Chukwudi et al., 2021).

In temperate regions with spring-dominant sowing seasons under global warming, a considerable reduction in grain yield was also simulated. However, the reduction was much lower compared with hot regions (45.7% and 82.6%, respectively) (Fig. 6). Simulation results of the current study also showed that under future climate changes, heat stress risk could be substantially alleviated in terms of both intensity (Fig. 3b and c) and frequency (Fig. 4b and c) by adopting an early-maturity cultivar (SC260) in combination with an early sowing date in these regions. SC260 flowered 5 to 15 days earlier than the late-maturity cultivar (SC704) owing to its genetic characteristics (Table S2). Accordingly, its flowering occurred before the onset of the high-risk window, particularly when combined with an early sowing date (Fig. 5b and c). Deryng et al. (2011) also obtained similar results. In their simulation study, they concluded that choosing the optimal sowing date and cultivar could reduce the negative impact of climate change on global maize (18%), spring wheat (12%),

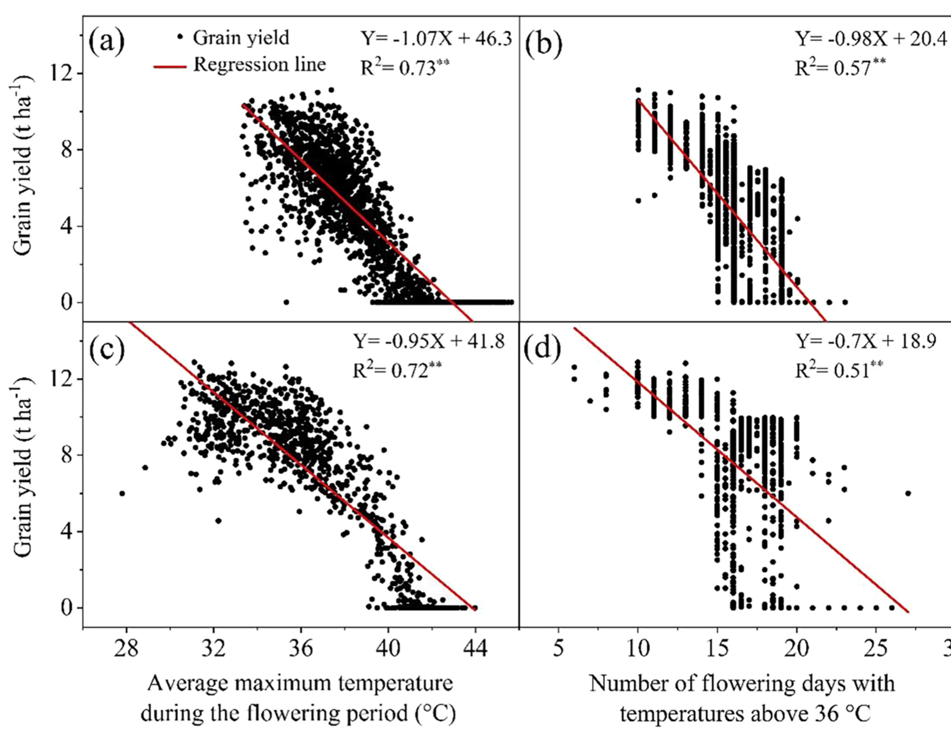

Fig. 7 Regression analysis between simulated grain yield and average maximum temperature during flowering period (heat stress intensity) for future (**a**) and baseline (**c**); and between the simulated grain yield and number of maize flowering days with temperature above 36 °C (frequency of heat stress) for future (**b**) and baseline (**d**). ** indicates significant at 1% probability level

and soybean production (7%). Yang et al. (2019) also examined adaptation options, including earlier flowering cultivars and early sowings on rainfed wheat, and reported that earlier flowering cultivars obtained higher yield gains (26–38%) than that of early sowings (6–10%) and were able to reverse the grain yield reductions under climate conditions in southern Portugal. They also indicated that the adopted early flowering cultivars reduced the risks of exposure to drought and heat stresses in late spring by accelerating the anthesis and grain filling stages.

Expansion of maize cropping systems to cooler zones as an opportunity to tackle the negative impacts of global warming on maize productivity

According to the previous discussions, although maize cultivation should be reduced in hot regions under the changing climate, global warming will open up opportunities to cultivate maize in cold zones which currently have lower areas under cultivation compared with hot regions (Table 1). Under the optimistic emission scenario and optimal management practices, farmers will be able to boost grain yield up to 9.2 t ha^{-1} in cold regions, while under the same situations in hot regions, farmers must accept a huge heat stress risk and much lower grain yield, up to 6.5 t ha^{-1} (Fig. 6b and c). In fact, rising temperatures in cold regions as a result of global warming will provide better climate conditions for maize growth and, consequently, reduce heat risk during flowering through choosing the optimal sowing date and cultivar (i.e., SC260 × early sowing date). In a study on a global scale, Mueller et al. (2015) concluded that expansion of areas with more than 150 days of growing season into the northern latitudes could make more lands potentially available for planting wheat and maize. Accordingly, they reported that some locations that are currently too cold for growing wheat and maize might be benefitted from higher temperatures and longer growing seasons due to global warming. Meng et al. (2014) in their study in Heilongjiang, China, also indicated that farmers rapidly expanded maize areas by more than 290 km from ~ 50.8°N to ~ 53.4°N benefitting from global warming by 35% in yield gains in this region over 1980 to 2000.

In cold regions in northwestern maize agro-ecosystems with spring-dominant sowing seasons under global warming, despite the increase in the maximum temperature during maize flowering time, the frequency and intensity of heat stress were still much lower than in temperate and hot regions. In fact, maize crops could adopt "escape" strategy by avoiding from heat stress risk in these regions. Some researchers have been reported that the escape strategy could be considered as a suitable way in some areas to tackle global warming (Rodríguez et al. 2005; Zheng et al. 2012). For example, in a similar study in southwestern of Iran, it was reported that applying early sowing date along with an early-maturity cultivar caused maize flowered before high risk window at $T_{max} > 36$ °C and escaped from extreme temperatures in winter sowing season and consequently, resulted in the decreasing number of seasons with uneconomical (i.e., grain yields < 4.5 t ha^{-1}) and null grain yields by 42% in 2050 (Rahimi-Moghaddam et al. 2018). Semenov et al. (2014) reviewed that under European climates with hotter and drier summers, using a quicker maturation cultivar could help wheat crops to escape from excessive heat stress. In contrast, some other researchers focused only on "tolerance" strategy when dealing with heat stress. For instance, Tesfaye et al. (2017) in South Asia, reported that under global warming, heat-tolerant maize cultivars could minimize yield loss by up to 36 and 93% in 2030 and 33 and 86% in 2050 under rainfed and irrigated conditions, respectively, compared to non-tolerant maize cultivars. Therefore, heat-tolerant cultivars might have the potential to shield maize from severe yield loss due to heat stress helping them adapt to climate change. The current study did not aim at examining tolerance as a resistance strategy.

Conclusions

Global warming in the period of 2040–2070 can threaten maize production in arid-based climates by sharply exacerbating heat stress events during maize flowering in terms of both its intensity and frequency. The risk of heat stress would be almost 100% in arid hot regions in the future climate under current management practices (sowing dates, cultivars, and number of irrigation), mostly because of the increasing high-risk window for heat stress which will be resulted in a yield reduction of 0.83 t ha^{-1}. In the cold regions, however, rising temperatures would provide better climate situations for maize growth so that under the optimistic emission scenario and optimal management practices, farmers will be able to boost grain yields up to 9.2 t ha^{-1} in those areas. Overall, flowering time could be adjusted by a suitable G × M to reduce heat stress risk, which is late-maturity cultivar × late sowing date for hot regions, and early-maturity cultivar × early sowing date for temperate and cold regions. These findings are important for the similar arid-based areas worldwide, where policymakers should invest in and apply policies to adapt and shift maize production to cold regions.

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Declarations

Ethics approval We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

Consent for publication We confirm that the manuscript has been read and approved by all named authors.

Conflict of interest The authors declare no competing interests.

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