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The effect of adapting cultivars on the water use efficiency of dryland maize (*Zea mays* L.) in northwestern China

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ABSTRACT

Global warming is predicted to have adverse effects on crop productivity and will present an enormous challenge to sustainable development and food security, especially in dryland regions. Prior studies have identified that adapted crop cultivars could effectively act to offset the effects of climate warming; however, the water use of adapted cultivars subject to climate warming is much less understood. We analysed warming trends across the Loess Plateau in north-western China beginning in 1960. There has been significant warming, especially since 1980, with an increase in the growing degree days (GDD, from April to September) of 260–330 °C being observed over the past 30 years. If the maize cultivars had remained unchanged, the decreased yield potential would have been 0.39–1.83 t ha^{-1} over the last 30 years. Meanwhile, the use of historical maize varieties has resulted in significantly decreased water use efficiency (WUE) across the Loess Plateau. Based on the increase in the GDD in each decade, we suggest planting adapted later-maturing maize cultivars to improve productivity. Compared with historical cultivars, the adapted later-maturing varieties significantly prolonged the maize growing cycle by an average of 27 d, thereby increasing the yield potential by 24.2–64.8% and the WUE by 9.0–38.1% throughout the Loess Plateau. However, the adapted maturing varieties may increase the water consumption (ET), which is the disadvantage for sustainable dryland farming, especially in dry regions. Hence, continuing to develop water-harvesting techniques (e.g., plastic film mulching) will help to offset the decreasing rainfall and guarantee food security and sustainability in dry regions.

1. Introduction

The yields of several crops (e.g., rice, maize, and wheat) have declined as a result of global warming trends (Lobell and Asner, 2003; Liu et al., 2010; Peng et al., 2004). The negative impacts of global warming on crop yields will shape the future severity of food shortages and may pose a substantial threat to the global food supply (Schmidhuber and Tubiello, 2007; Brown and Funk, 2008). Global warming presents a greater threat for semi-arid regions (or drylands), which cover approximately 45% of the earth's land surface (Schimel, 2010) and in which food shortages are a major limiting factor for economic development. Prior simulation studies have identified that adapted later-maturing crop cultivars could be effective in offsetting the negative climate warming impacts on crop productivity (Liu et al., 2010, 2013) or improving crop yields in different regions (Trnka et al., 2004; Ortiz et al., 2008; Luo et al., 2009). However, few quantitative data are available on the effect of adaptation strategies on the water use of rain-fed crop production in arid regions. Hence, studying the potential impacts of adapted strategies on the water use of dryland cropping systems is imperative for sustainable agricultural development.

Arid regions account for more than 70% of China's total land area, mainly in the northwest, and are an essential component of its agricultural production (Wu et al., 2005). Dryland maize (*Zea mays* L.) is one of the most widely grown grain crops in this region (Liu et al., 2009). Previous studies have suggested that, if cultivar evolution were excluded, warming would reduce the length of the growing period for maize (Tao et al., 2006; Liu et al., 2010), generally leading to a negative impact on crop productivity. Although the autonomous adoption of new crop varieties was able to compensate for the negative impact of climatic warming,

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the prolonged crop-growing period may lead to greater vapour flow [evapotranspiration (ET)], which, in theory, would be harmful to the sustainable water use of dryland agriculture production (Rockström et al., 2007). However, the relationship between vapour flow and yield growth subject to climate warming is much less understood for semi-arid, rain-fed agricultural systems.

The Loess Plateau of northwestern China is a typical arid region dominated by dryland farming (Xu, 1997). Maize (*Zea mays* L.) represents 17.9% of the total agricultural area and 30.8% of the total grain yield (Zhang et al., 2006) in this semi-arid region. Previous studies suggest that increasing temperatures and decreasing precipitation in semi-arid regions are likely to reduce maize yields within the next several decades (Lobell et al., 2008). However, there is little evidence relating the effects of climate warming and changing later-maturing cultivars on the maize yield and water use on the Loess Plateau. The Hybrid-Maize model has proven to be an effective tool to investigate the potential impacts of the climate variability and changing cultivars on the yield and water use of maize production (Yang et al., 2004, 2006; Grassini et al., 2009; Timsina et al., 2010; Chen et al., 2011, 2013). Therefore, we used the Hybrid-Maize model to explore the potential impacts of climate trends on existing and adapted cultivars, which would help to increase maize yield sustainably on the Loess Plateau. The objectives of this study were to (1) assess the climate trends of both temperature and precipitation across the Loess Plateau over the last 50 years, (2) characterise the yield potential response to the adapted later-maturing cultivars of maize, (3) and study the potential impacts of adapted varieties on the water use of dryland maize production.

2. Materials and methods

2.1. The Loess Plateau of China

The Loess Plateau in northwestern China extends from 101°01′ E to 115°10′ E and from 34°02′ N to 40°40′ N and covers the middle reaches of the Yellow River Basin (Fig. 1). The region extends across 287 counties, has an area of 0.62 million km^2 and supports a population of 90 million. The average annual temperature is 9.3 °C. Most of the Loess Plateau has an arid or semi-arid climate, with an average annual precipitation of 150–700 mm (Li and Xiao, 1992) and an average annual evaporation of over 1500 mm (Zhang et al., 2008). Dryland farming predominates in this region, and water supply is the major limiting factor in rain-fed crop production.

2.2. Study sites

Fifty sites were selected across the Loess Plateau (Fig. 1), each at an observation station of the National Meteorological Network of the Central Meteorological Agency. These sites were chosen because they provide representative coverage across the Loess Plateau region. We grouped the 50 sites into five regions based on temperature and elevation relative to other regions in the study: the southern region, with high temperatures and low elevations; the eastern region, with high temperatures and high elevations; the central region, with intermediate temperatures and moderate elevations; the northern region, with low temperatures and moderate elevations; and the western region, with low temperatures and high elevations.

2.3. Model validation

A maize simulation model, Hybrid-Maize (Yang et al., 2004, 2006), was used to estimate the maize yield potential on a daily basis. This model was developed by the University of Nebraska–Lincoln, US, and has been tested and widely applied to estimate the maize yield potential for rain-fed maize cultivation in the Corn Belt in the US (Grassini et al., 2009), South Asia (Timsina et al., 2010), and China (Liu et al., 2008; Bai, 2010; Chen et al., 2011, 2013).

All analysis in this study is based entirely on a modelling exercise, which required that the effectiveness and accuracy of the Hybrid Maize model be tested on the Loess Plateau. The model was tested using data from a four-year (2007–2010) experiment conducted at the *Changwu* experimental station (35.28° N, 107.88° E, approximately 1200 m above sea level), which is in a typical dryland farming area on the Loess Plateau.

We used the Hybrid-Maize model together with daily weather data (collected from a local standard weather station) to simulate the total biomass and grain yield of the three hybrids under the three density. The normalised root mean square error (NRMSE) was calculated as described by Sepaskhah et al. (2011):

$$\mathrm{NRMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{nO_{\mathrm{avg}}^2}} \quad (1)$$

where S_i is the simulated data, O_i is the observed data, O_{avg} is the mean of the measurement values and n is the number of pairs of simulated and observed data. NRMSE was calculated as the dry matter of both the total biomass ($NRMSE_{Total}$) and the grain ($NRMSE_{Grain}$).

2.4. Data preparation for simulation

We simulate the yield potential under water-limited (rain-fed) and no-frost conditions throughout the Loess Plateau. The Hybrid-Maize model requires the following daily weather variables: total solar radiation (in $MJ\,m^{-2}$), minimum and maximum air temperatures (in °C), rainfall (in mm), potential evapotranspiration (ET, in mm), relative air humidity (in %), and mean wind speed (in $m\,s^{-1}$). The daily climatic data had been collected by the Chinese Meteorological Agency. The daily total solar radiation and ET were estimated from the aforesaid climatic data using *WeatherAid*, a companion program of the Hybrid-Maize model.

The Hybrid-Maize model requires the date of planting, plant population, and hybrid maturity (in total growing degree days or relative maturity). In our simulation, the planting date and plant population of maize across the Loess Plateau were set as 25 April and 60,000 plants ha^{-1}, respectively. For each site, the potential growing degree days (GDD) from April to September (the spring-maize growing season) during the last 50 years since 1960 was estimated as follows:

$$\mathrm{GDD} = \sum \frac{T_{\max} + T_{\min}}{2} - T_{\mathrm{base}} \quad (2)$$

where T_{max} and T_{min} are the daily maximum and minimum temperatures, respectively, and T_{base} is the base temperature for maize (10 °C) (McMaster and Wilhelm, 1997). All of the GDD (in each day) values <0 were considered effectively equal to 0 °C (Arnold, 1974). The final results in GDD, growth duration, and yield potential comprised the average for all of the study sites in each region. The adapted varieties, based on the GDD, are used in all five study regions. In each year for each study site, the water use efficiency (WUE, $kg\,ha^{-1}\,mm^{-1}$) was calculated as the grain yield potential (in $kg\,ha^{-1}$) divided by the potential evapotranspiration during the crop growing season (ET, in mm).

2.5. Data analysis

Linear regression was used to detect trends in climate warming, maize grain yields, growing stage duration, and maize water use

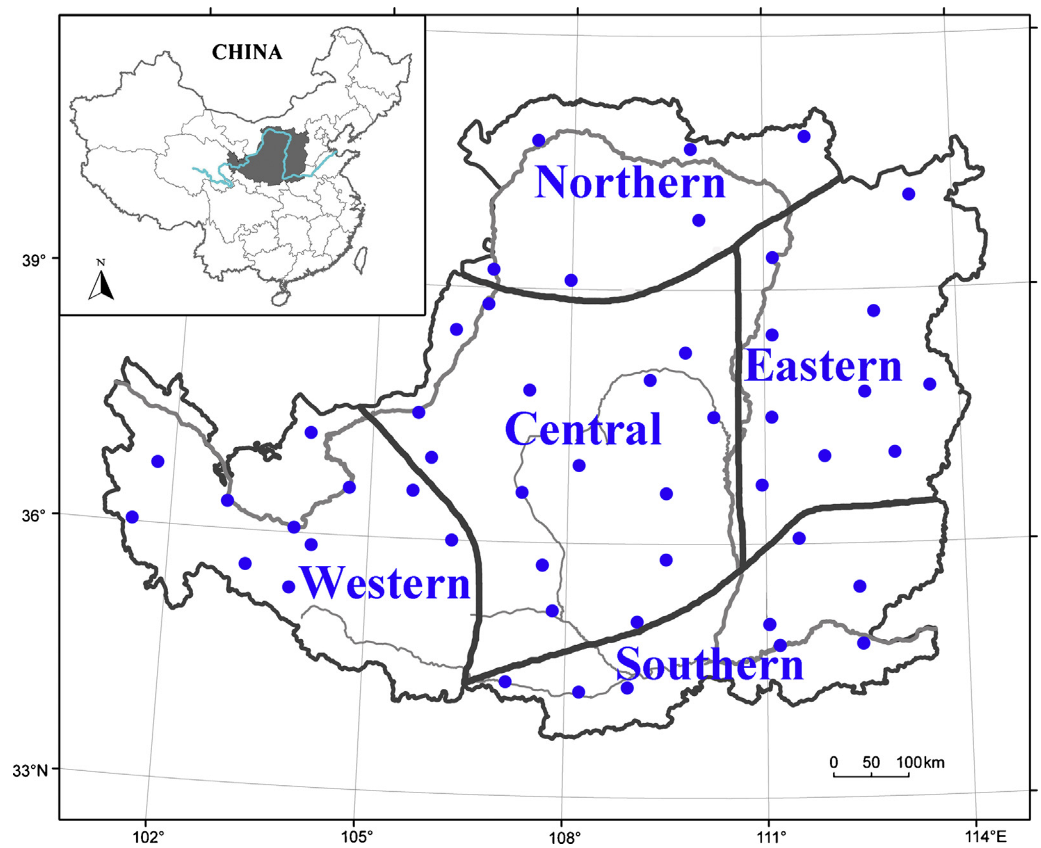

Fig. 1. Location of the Loess Plateau (light grey shading) in the middle reaches of the Yellow River Basin in China. The boundaries of the five study regions are indicated by thin grey lines. Dots indicate the locations of the 50 study sites included in this study. The thick blue line is the Yellow River. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

under rain-fed conditions. The slopes of the linear regression lines were evaluated using *t*-tests at 95% or 99% significance levels.

3. Results

3.1. The credibility of Hybrid-Maize model

The results of model testing indicated that the values that were estimated for the three maize varieties were close to the measured values of the final biomass (Fig. 2). The grain yields were also estimated with a high degree of accuracy for both years. The simulation results for both the shoot biomass and the grain dry matter agreed with the observed data (Fig. 2). The correlation analysis showed that the estimated values predicted both the shoot biomass (Fig. 3a, $NRMSE_{Total} = 0.167$) and the grain dry matter dynamics (Fig. 3b, $NRMSE_{Grain} = 0.188$) extremely accurately. These results indicated that the Hybrid-Maize model could accurately estimate the biomass and grain yield in the Loess Plateau.

3.2. Climate warming on the Loess Plateau

Climate warming was not obvious before the 1980s (Fig. 4); however, beginning in the 1980s, significant warming trends ($p < 0.01$) have been apparent across the Loess Plateau. As a result, the average growing season temperature has increased significantly by 0.51 °C per decade (Fig. 4). In addition, the maize season precipitation has decreased by 8.8 mm per decade since 1960, but this change is not significant at the 95% level.

Based on the warming trends, we calculated the available GDD (>10 °C) during April–September for all study regions beginning in the 1960s (Fig. 5). The GDD trends in each region over the last 50 years can be divided into two stages: essentially no change since the 1980s and a significant increase thereafter. The warming rate has increased from south to north since the 1980s: the average increase in GDD per decade ranged from 90.1 °C in the southern region to 94.1 °C in the central region and 109.8 °C in the northern region. Meanwhile, the GDD increased by 88.3 °C per decade in the western region and 87.8 °C per decade in the eastern region.

3.3. Adaptation strategies

3.3.1. Adapted maize varieties in each region

We use the adapted varieties selected based our estimated GDD for all of the study regions for April–September in each decade (Table 1). Notably, if farmers have not changed the varieties grown since 1960, it can be ascertained that the varieties currently in use do not optimally utilise the available heat. Indeed because 1980, the gap between the yield performances of the commonly used varieties has not changed, and the potential yield performance of the adapted varieties has increased significantly (Figs. 6 and 7).

Table 1
The average growing degree days (GDD, >10 °C) from April to September in each decade since the 1960s in the five study regions across the Loess Plateau.

Region	1960s	1970s	1980s	1990s	2000s
Southern	1600	1600	1650	1750	1800
Eastern	1500	1500	1500	1600	1680
Central	1400	1400	1450	1530	1600
Northern	1300	1300	1350	1440	1560
Western*	1250	1250	1300	1400	1500

Frequent frosts in the western region rendered most areas unsuitable for maize growth; thus, these data refer to only three sites (Lanzhou, Jingtai, and Jingyuan).

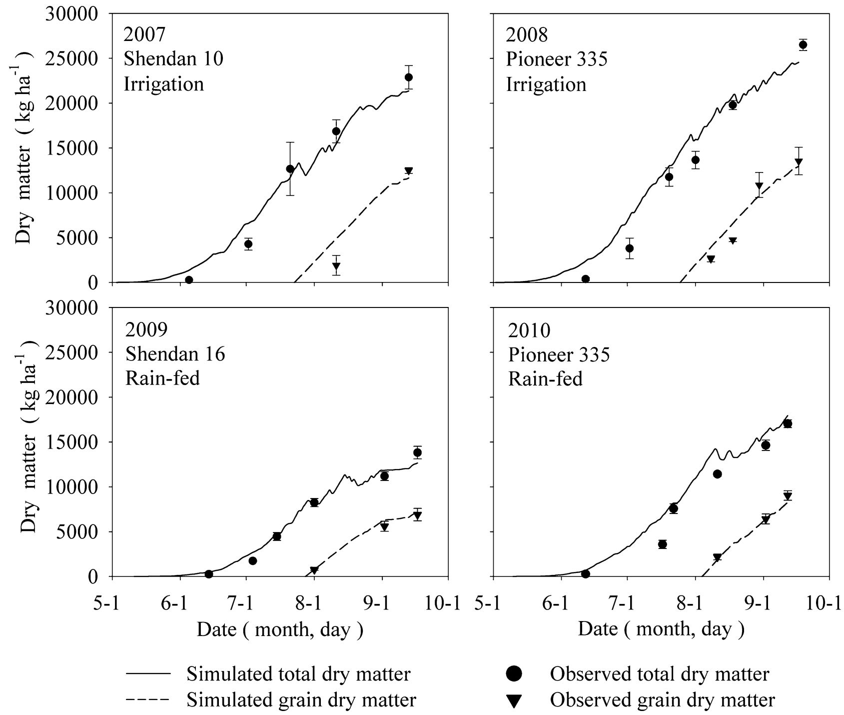

Fig. 2. Hybrid-Maize-simulated and observed growth dynamics from emergence to maturity under full irrigation (a in 2007, b in 2008) and rain-fed (c in 2009, d in 2010) conditions at Changwu experimental station.

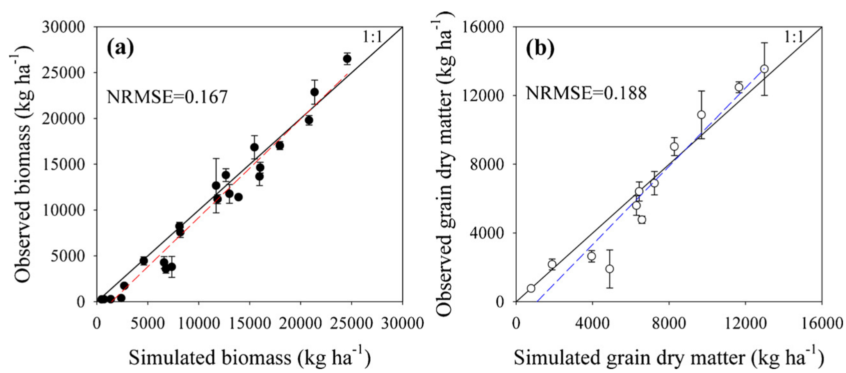

Fig. 3. Correlation analysis between simulated and observed values of total biomass and grain dry matter.

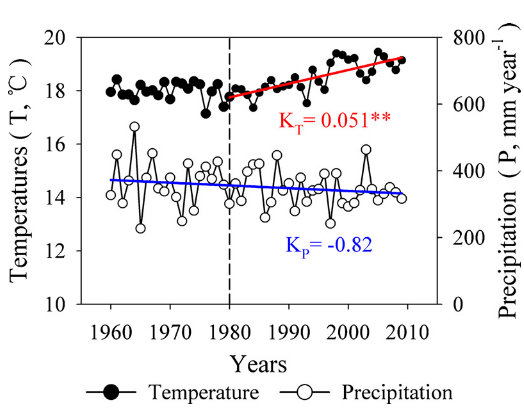

Fig. 4. Trends of both average temperature and precipitation during April–September from 1960 to 2009 across the Loess Plateau. Straight lines represent the regressions of each variable against year (*k*, the rate at which the climatic conditions changed). *Significant at 95%; **significant at 99%.

3.3.2. Growth duration of maize in each region

An increase in the growing season GDD would have resulted in an overall reduction in the length of the maize growing season if the maize varieties remained unchanged from 1980 to 2000 (Fig. 6a–e). The maize total growth duration (the crop days to maturity) declined significantly (from 9 to 19 d) in all regions. The decline was greatest in the eastern region (Fig. 6b) and greater in the western and northern regions (Fig. 6e) than in the southern and central regions. On average, across the five regions, comparing the 2000s with the 1980s, the pre-flowering stage has decreased by 4 d and the post-flowering stage by 5 d.

The adapted later-maturing variety has effectively adapted to higher temperatures, given that its growing cycle has lengthened since the 1980s (Fig. 6f–j). The pre-flowering stage (vDays) of a later-maturing cultivar was found lengthen with increasing latitude relative to the historical varieties, being prolonged by 6 d in the southern region and 10 d in the northern region. When viewed east to west, minimising latitude differences, the pre-flowering stage was prolonged by 7 d in the eastern region and 9 d in the western region (Table 2). In a similar comparison, the post-flowering stages

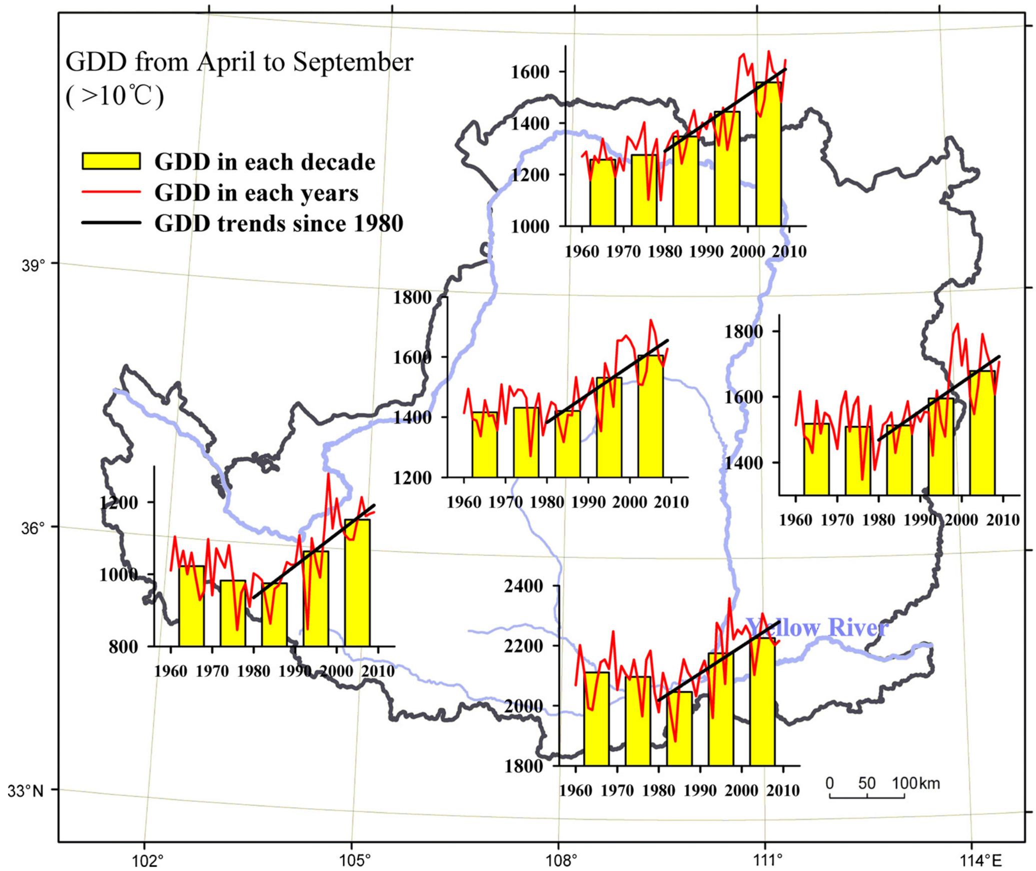

Fig. 5. Growing degree days (GDD, >10 °C) during the period from April to September in the five study regions since 1960. Straight lines represent the regressions of each variable against year. Bars show the average accumulated temperature in each decade since the 1960s.

Table 2
Growth durations of the total growing cycle, pre-flowering stage (vDays), and post-flowering stages (rDays). Yield potential of spring maize in each decade since the 1980s with historical and adapted varieties in the five study regions across the Loess Plateau.

Region	Decade	Growth duration (d)						Yield potential ($t\,ha^{-1}$)	
		Historical			Adapted			Historical	Adapted
		Total	vDays	rDays	Total	vDays	rDays		
Southern	1980s	109 ± 5	60 ± 3	50 ± 3	116 ± 6	62 ± 3	54 ± 4	9.5 ± 1.1	10.6 ± 1.4
	1990s	104 ± 6	58 ± 3	46 ± 3	118 ± 8	63 ± 3	55 ± 5	8.8 ± 1.5	10.7 ± 2.0
	2000s	101 ± 4	55 ± 2	46 ± 3	118 ± 4	61 ± 2	57 ± 3	8.4 ± 1.2	10.5 ± 1.5
Eastern	1980s	126 ± 5	66 ± 2	60 ± 4	126 ± 5	66 ± 2	60 ± 4	12.2 ± 0.7	12.2 ± 0.7
	1990s	118 ± 8	64 ± 3	54 ± 6	140 ± 16	68 ± 3	71 ± 14	10.8 ± 1.8	13.3 ± 2.6
	2000s	113 ± 6	62 ± 3	51 ± 4	141 ± 13	68 ± 4	73 ± 10	9.3 ± 1.0	12.8 ± 1.8
Central	1980s	122 ± 4	68 ± 2	55 ± 3	122 ± 4	67 ± 2	55 ± 3	8.7 ± 0.9	9.4 ± 0.9
	1990s	119 ± 8	67 ± 3	52 ± 5	132 ± 13	68 ± 3	64 ± 11	8.6 ± 1.5	9.9 ± 2.1
	2000s	111 ± 5	63 ± 3	48 ± 3	132 ± 8	67 ± 3	65 ± 7	7.3 ± 1.0	9.7 ± 1.5
Northern	1980s	107 ± 5	62 ± 3	46 ± 3	129 ± 10	66 ± 3	63 ± 9	6.9 ± 1.3	9.1 ± 1.6
	1990s	105 ± 4	61 ± 2	44 ± 3	135 ± 12	68 ± 3	67 ± 11	7.2 ± 1.3	10.2 ± 2.8
	2000s	100 ± 4	59 ± 2	41 ± 2	141 ± 12	69 ± 4	72 ± 9	6.2 ± 1.2	10.2 ± 2.3
Western	1980s	111 ± 4	66 ± 3	46 ± 3	124 ± 6	69 ± 3	55 ± 4	7.1 ± 1.1	8.4 ± 1.3
	1990s	108 ± 8	62 ± 4	45 ± 5	130 ± 14	69 ± 4	61 ± 11	7.8 ± 1.2	10.4 ± 2.2
	2000s	101 ± 4	59 ± 1	42 ± 3	132 ± 7	69 ± 2	63 ± 6	5.7 ± 1.2	8.4 ± 1.4

Values are given as the mean ± standard error of each region.

(rDays) were found to be extended by 11 d in the southern region, 30 d in the northern region, 20 d in the eastern region, and 21 d in the western region. Compared with the historical varieties, the average vDays across all five regions of later-maturing cultivars was significantly extended by 7 d, while the corresponding rDays value was extended by 20 d. In essence, the selection of later-maturing cultivars ensures the effective capture and utilisation of light, heat, and rainwater resources and extends the duration of grain filling.

3.3.3. Yield potential

When assessing historical maize varieties, the decrease in yield potential averaged 0.067 $t\,ha^{-1}$ per year ($p < 0.01$) due to the warming trends across the Loess Plateau since the 1980s (Fig. 6f–j).

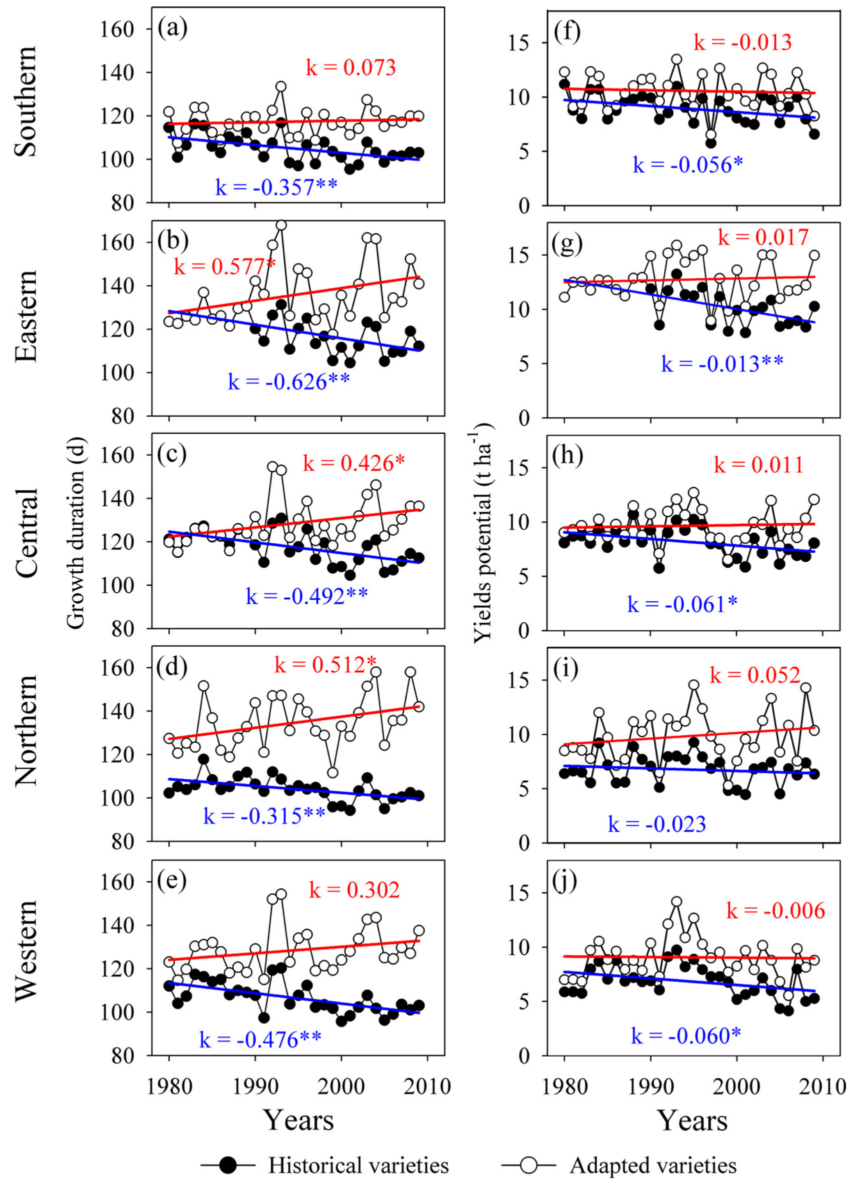

Fig. 6. Simulated growth duration (a–e) and yield potential (f–j) of spring maize with no change in the historical or adapted varieties since the 1980s. Straight lines represent the regressions of each variable against year (*k*, the rate at which dependent variables changed). *Significant at 95%; **significant at 99%.

However, compared with the historical maize varieties, the adapted varieties exhibited a significantly increased crop yield potential.

Assuming there was no change relative to the historical varieties, the yield potential decreased with decreasing latitude for the 1980–2010 period, with yield reductions of 0.69 t ha^{-1} in the northern region (Fig. 6i), 1.83 t ha^{-1} in the central region (Fig. 6h), and 1.68 t ha^{-1} in the southern region (Fig. 6f). When considered in the east to west direction, relative to historical varieties, the yield potentials decreased by 0.39 t ha^{-1} in the eastern region (Fig. 6g) and 1.80 t ha^{-1} in the western region (Fig. 6j). The yield potentials of the adapted varieties were significantly higher than those for the historical varieties. The yield potentials of the adapted varieties were significantly higher for the 1980–2010 periods, increasing by 0.39 t ha^{-1} in the southern region, 0.51 t ha^{-1} in the eastern region, 1.26 t ha^{-1} in the central region, and 1.56 t ha^{-1} in the northern region. However, the potential yields of the adapted varieties slightly decreased (by 0.18 t ha^{-1}) in the western region. Thus, in the 2000s (Table 2), the yield potentials of adapted varieties were greater than those of the historical varieties by 2.1 t ha^{-1} in the southern region, 1.5 t ha^{-1} in the eastern region, 2.4 t ha^{-1} in the central region, 4.0 t ha^{-1} in the northern region, and 2.7 t ha^{-1} in the western region.

3.3.4. *Water consumption during maize season*

The potential evapotranspiration (ET) decreased slightly for the unchanged maize varieties across the Loess Plateau since the 1980s (Fig. 7a–e). The extent of this decrease varies by region: 9.10 mm per decade in the warm southern region (Fig. 7a), 12.0–16.8 mm per decade ($p < 0.05$) in the intermediate-temperature central and eastern regions (Fig. 7b and c), and 6.41–7.97 mm per decade in the cold, dry northern and western regions (Fig. 7d and e).

Compared with the unchanged varieties, the adapted varieties exhibited increased ET in each study region since the 1980s. On average, the ET of the adapted varieties increased by 35 mm in the warm southern region, 40–70 mm in the intermediate-temperature central and eastern regions, and 50–70 mm in the cold northern and western regions relative to the unchanged varieties over the last 30 years. In the 2000s (Table 3), the ET of the adapted varieties was greater by 50 mm, and 70–80 mm, and 70–90 mm in the warm, intermediate-temperature, and cold regions,

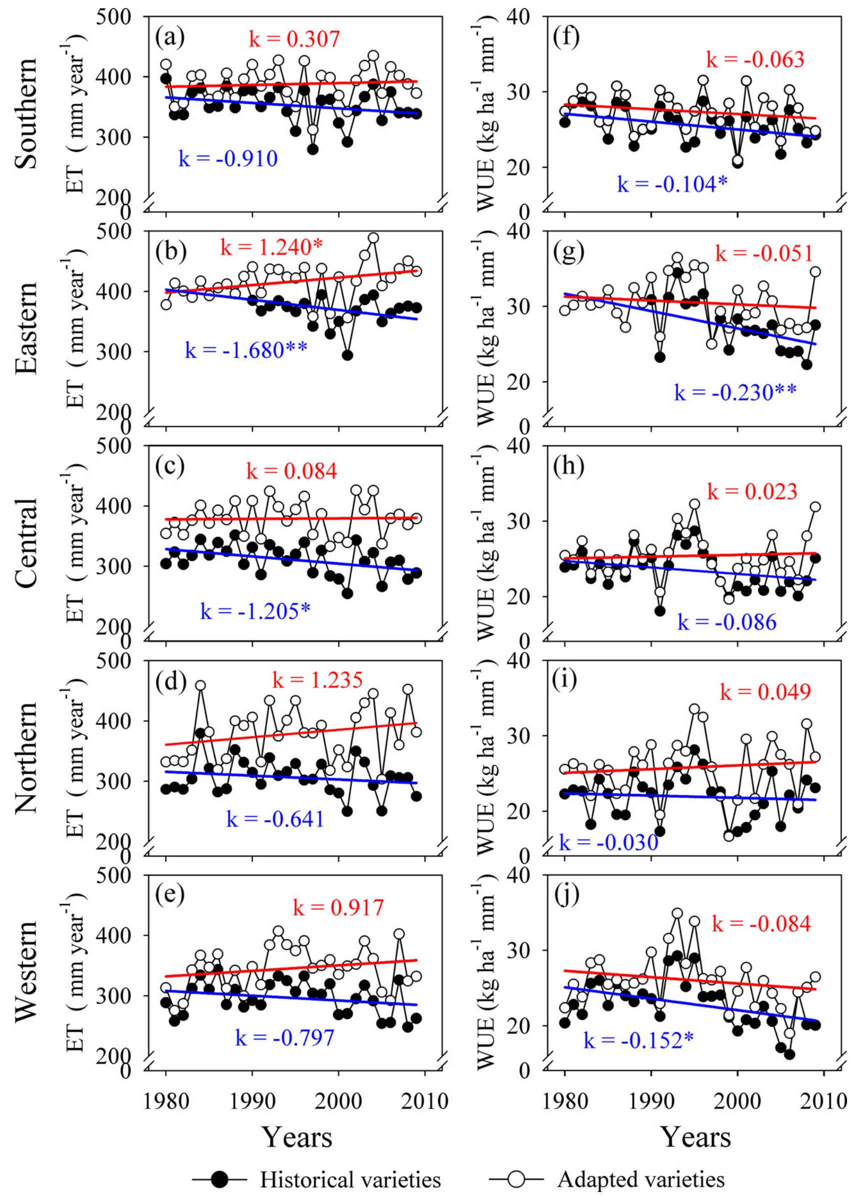

Fig. 7. Simulated total evapotranspiration (ET, a–e) and water use efficiency (WUE, f–j) during the maize growing-season since the 1980s with no change in the historical and adapted varieties in the five study regions across the Loess Plateau. Straight lines represent the regressions of each variable against year (*k*, the rate at which the dependent variables changed). *Significant at 95%; **significant at 99%.

respectively. Hence, the water deficit is more serious during the growing season in these regions (Table 3).

3.3.5. *Water use efficiency during the maize season*

The water use efficiency (WUE) has increased to varying degrees as adapted varieties of maize were grown in rain-fed systems across the Loess Plateau (Fig. 7f–j). Since 1980, higher temperatures resulted in decreased WUE for historical maize varieties across the Loess Plateau. There were greater WUE reductions from north to south for the 1980–2010 period when using the historical varieties, with decreases in WUE of 0.90 kg ha^{-1} mm^{-1} in the northern region (Fig. 7i), 2.58 kg ha^{-1} mm^{-1} in the central region (Fig. 7h), and 3.12 kg ha^{-1} mm^{-1} in the southern region (Fig. 7f). Unsurprisingly, in the eastern region, the WUE decline amounted to 6.90 kg ha^{-1} mm^{-1} (Fig. 7g) and was somewhat higher than the yield reduction in the western region, where the predicted reduction was 4.54 kg ha^{-1} mm^{-1} (Fig. 7j).

Compared with the historical varieties, the adapted varieties had higher WUE values when considered across the five regions for the 1980–2010 period. In the 2000s (Table 3), the WUE of the adapted varieties increased with increasing latitude: by 2.21 kg ha^{-1} mm^{-1} in the southern region, 7.14 kg ha^{-1} mm^{-1} in the central region, and 5.36 kg ha^{-1} mm^{-1} in the northern region relative to the unchanged varieties. Similarly, the WUE increased by 3.92 kg ha^{-1} mm^{-1} in the eastern region and 4.09 kg ha^{-1} mm^{-1} in the western region. On average, across the five regions, the WUE of the adapted varieties increased by 4.44 kg ha^{-1} mm^{-1} relative to the historical maize varieties.

4. Discussion

The temperature in China has increased by 1.2 °C since 1960 (Piao et al., 2010), and the temperature rises are likely to affect the phenology (Walther et al., 2002; Estrella et al., 2007) and decrease the yields of several crops (Peng et al., 2004; Asseng et al.,

Table 3
WU, WUE and water balance of spring maize in each decade since the 1980s with historical and adapted varieties in the five study regions across the Loess Plateau. Precipitation (annual and April–September) for each decade since the 1980s.

Region	Decade	WU (mm)		WUE (kg ha^{-1} mm)		Precipitation (mm)		Water balance (mm)	
		Historical	Adapted	Historical	Adapted	Annual	April–September	Historical	Adapted
Southern	1980s	363 ± 21	383 ± 25	26.2 ± 2.0	27.6 ± 2.5	606	502	243	119
	1990s	351 ± 33	390 ± 36	24.9 ± 2.4	27.1 ± 3.1	527	410	176	20
	2000s	343 ± 28	391 ± 28	24.5 ± 2.9	26.7 ± 2.9	547	448	204	57
Eastern	1980s	403 ± 14	403 ± 14	30.3 ± 1.5	30.3 ± 1.5	449	399	49	−2
	1990s	370 ± 20	415 ± 32	29.0 ± 3.7	31.7 ± 4.4	426	362	63	−48
	2000s	362 ± 28	430 ± 35	25.8 ± 2.0	29.7 ± 2.7	446	386	85	−46
Central	1980s	323 ± 17	375 ± 20	24.1 ± 1.7	25.1 ± 1.7	313	277	58	−30
	1990s	314 ± 21	383 ± 31	24.4 ± 3.5	25.6 ± 4.1	303	258	56	−63
	2000s	296 ± 27	378 ± 32	22.0 ± 1.8	25.5 ± 3.0	305	266	83	−52
Northern	1980s	312 ± 33	364 ± 44	22.0 ± 2.2	25.0 ± 2.0	242	219	−51	−128
	1990s	312 ± 17	385 ± 38	23.0 ± 3.6	26.2 ± 5.4	269	237	−22	−129
	2000s	295 ± 32	387 ± 51	20.9 ± 2.8	26.2 ± 3.8	248	220	−31	−154
Western	1980s	299 ± 28	325 ± 33	23.6 ± 1.9	25.8 ± 1.9	226	197	39	−28
	1990s	312 ± 16	366 ± 26	25.0 ± 3.0	28.2 ± 4.4	249	225	45	−49
	2000s	279 ± 27	345 ± 35	20.2 ± 2.4	24.2 ± 2.5	212	182	71	−41

Values are given as the mean ± standard error of each region.

2011; Liu et al., 2010; Lobell and Field, 2007). It is widely understood that temperature has a strong influence on crop development due to its influence on the meristem (Warrington and Kanemasu, 1983). As a typical thermophilous crop, maize requires cumulative temperatures exceeding 10 °C (Miedema, 1982) to guide plant development (Warrington and Kanemasu, 1983) and for its related physiological processes. Our results show that the elevation in temperature increased the GDD from April to September (>10 °C) by 88 °C to 110 °C per decade during the spring-maize growth season across the Loess Plateau since the 1980s. Assuming no change in maize varieties during the study period, the crop growth duration declined by 9–19 d, thereby significantly ($p < 0.01$) decreasing the yield potential from 0.39 to 1.83 t ha^{-1} over the last 30 years.

Howden et al. (2007) suggest that the use of adaptation strategies will depend on the integration of climate change-related issues and other risk factors. The IPCC (2007) has shown that adapted varieties should be able to take advantage of the positive aspects of climate change. The autonomous adoption of new crop varieties in the NCP mitigated the adverse impact of climate warming (Tao and Zhang, 2010; Liu et al., 2010). Based on the accumulated temperature increase in each decade, we suggest planting later-maturing maize cultivars to adapt to the climate warming across the Loess Plateau. Compared with the unchanged varieties, the adapted later-maturing maize cultivars significantly extended the growth cycle and induced greater productivity, mainly due to the adjustment of the adapted varieties to the warming growth environment (Cirilo and Andrade, 1994) and their more effective capture and use of light, warmth and rainfall resources across the Loess Plateau.

Liu et al. (2010) showed that, on the North China Plain (NCP), higher temperatures before flowering have led to a reduction in the duration of vegetative growth for summer maize, generally leading to a reduction in grain yield. In this study, however, the yield decline was mainly due to the shorter duration of the post-flowering stages (the main period for grain filling) across the Loess Plateau, thereby reducing the heat energy available for grain production. On average across the five regions, the adapted later-maturing maize cultivars significantly extended the growth duration by 27 d (on average) than the no changed varieties, the vDays of adapted cultivar significant extended by 7 d, while the rDays by 20 d. The adapted later-maturing maize varieties allowed the prolonged grain-filling period to obtain greater dry matter for grain yield. Hence, the yield potential of adapted varieties significant increased by 24.2–64.8% over the last 30 years across the Loess Plateau.

Limited water resources are the major constraints on crop production in semi-arid areas (Rockström et al., 2007). Under water-limited conditions, crop yields appear to be most strongly related to water resource use; thus, grain yield can be dramatically reduced by water resource deficits (Liu et al., 2009). Our research indicated that the magnitude of warming may induce significant decreases in the WUE of spring maize if the varieties remained unchanged in this typical arid region since the 1980s. The adapted maize varieties exhibited a significantly delayed decrease of WUE, and their WUE remained high over last 30 years. Especially, the WUE of the adapted varieties is higher by 9.0–38.1% relative to the unchanged varieties in the 2000s. Finally, the adapted varieties result in higher grain yield, this may due to their longer growth cycle, allowing the crops to obtain more water resources for plant growth and grain production. Its means that the yield increase is not depend on the greater WUE, but on the more rain water from longer growing season.

For semi-arid regions, increasing temperatures and declining precipitation are likely to reduce the yields of several primary crops over the next two decades (Lobell et al., 2008). As a result of future climate warming, improved water productivity in rainfed crop production systems should reduce additional water needs in agriculture (Rockström et al., 2007). Our results showed that the unchanged varieties results in shorter growth duration, which may induce ET decreases. For adapted maize varieties, warming results in greater ET during longer growing season. Its mean that the higher yield depend only on the longer growth duration allowed the more rain water to improve maize plant growth and grain production. However, the greater ET is disadvantageous to the sustainability of dryland farming in long-term production, especially in dry Northern and Western regions. Hence, if we plant the adapted maize varieties in dry regions, we need to evaluate the relative potential of different adaptation strategies and develop effective water-harvesting strategies to offset the risk of the water losses by limited rainfall from climate change.

5. Conclusions

The magnitude of warming since the 1980s may have reduced maize growth duration, yield potential, and water use efficiency (WUE) if the maize varieties remained unchanged. We suggest the use of adapted later-maturing cultivars based on the increases in the cumulative temperatures for April–September in each of the decades in all study regions. The adapted varieties provided longer growth durations, increased yield potential, increased WUE and will be an effective approach to managing food production in the warming environment. Hence, adapted later-maturing cultivars allowed the substantial increases in maize production are possible in dry regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2014.09.010.

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