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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Effects of climatic factors, drought risk and irrigation requirement on maize yield in the Northeast Farming Region of China

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SUMMARY

Drought risk is considered to be among the main limiting factors for maize (*Zea mays* L.) production in the Northeast Farming Region of China (NFR). Maize yield data from 44 stations over the period 1961–2010 were combined with data from weather stations to evaluate the effects of climatic factors, drought risk and irrigation requirement on rain-fed maize yield in specific maize growth phases. The maize growing season was divided into four growth phases comprising seeding, vegetative, flowering and maturity based on observations of phenological data from 1981 to 2010. The dual crop coefficient was used to calculate crop evapotranspiration and soil water balance during the maize growing season. The effects of mean temperature, solar radiation, effective rainfall, water deficit, drought stress days, actual crop evapotranspiration and irrigation requirement in different growth phases were included in the statistical model to predict maize yield. During the period 1961–2010, mean temperature increased significantly in all growth phases in NFR, while solar radiation decreased significantly in southern NFR in the seeding, vegetative and flowering phases. Effective rainfall increased in the seeding and vegetative phases, reducing water deficit over the period, whereas decreasing effective rainfall over time in the flowering and maturity phases enhanced water deficit. An increase in days with drought stress was concentrated in western NFR, with larger volumes of irrigation needed to compensate for increased dryness. The present results indicate that higher mean temperature in the seeding and maturity phases was beneficial for maize yield, whereas excessive rainfall would damage maize yield, in particular in the seeding and flowering phases. Drought stress in any growth stage was found to reduce maize yield and water deficit was slightly better than other indicators of drought stress for explaining yield variability. The effect of drought stress was particularly strong in the seeding and flowering phases, indicating that these periods should be given priority for irrigation. The yield-reducing effects of both drought and intense rainfall illustrate the importance of further development of irrigation and drainage systems for ensuring the stability of maize production in NFR.

INTRODUCTION

The Northeast Farming Region (NFR) is the most important and the largest rain-fed maize production region in China, accounting for 0·30 of China's maize production (Liu *et al*. 2012). Although maize yield has shown an increasing trend during recent decades in NFR, maize production has been highly affected by climate change in this region (Zhang 2004; Chen *et al*. 2011, 2012; Liu *et al*. 2013*c*; Tao *et al*. 2014). The increase in temperature has delayed autumn frosts and led to earlier sowing and later harvest, thus prolonging the potential growing season (Tao *et al*. 2006, 2014; Chen *et al*. 2012; Yuan *et al*. 2012). In addition, warmer conditions have shifted the maize planting boundary northwards (Liu *et al*. 2013*c*). Moreover, higher temperatures have also caused heat stress during the maize growing season over the last 50 years in NFR, which has severely affected maize yield (Yin *et al*. 2015). Rainfall has declined slightly and fluctuated greatly during the recent 50 years and the uneven distribution of rainfall has led to periods

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of drought that has affected maize production severely in NFR (Zhang 2004; Gao *et al.* 2012; Xu *et al.* 2013; Song *et al.* 2014; Yu *et al.* 2014).

The frequency of drought has increased in large parts of NFR because of the increased temperature and decreased rainfall (Zhang *et al.* 2011; Xu *et al.* 2013; Yu *et al.* 2014). With the expanding maize area, agriculture in NFR has become even more sensitive to drought (Xu *et al.* 2013). However, most reports on assessments of drought in NFR are based on general changes of precipitation conditions without considering crop evapotranspiration and without taking into account the relationship between drought risk and maize yield (Wu *et al.* 2010; Zhang *et al.* 2011; Song *et al.* 2014; Yu *et al.* 2014). It is estimated that temperature will continue to increase by 1·5–3 °C by the 2050s in NFR; as a result, droughts may become more severe in the region (Zhao & Luo 2007; Zhang *et al.* 2009; Piao *et al.* 2010; IPCC 2013; Harrison *et al.* 2014). Due to the importance of NFR in China's food security, it is crucial to understand how drought risk potentially affects maize yield in different growth phases under climate change and to explore appropriate adaptation measures to maintain or increase maize production.

Previous studies indicate that irrigation is the most efficient adaptation measure to mitigate the negative effects caused by drought in crop production (Li *et al.* 2005; Olesen *et al.* 2011; Ji *et al.* 2012). However, due to the uneven distribution of rainfall and limited water resources, irrigation systems in NFR are not well developed (Liu *et al.* 2006); only 0·15 of maize growing areas are irrigated (MWR 2012). In order to improve maize production in NFR, the Chinese government has been introducing some large agricultural irrigation system infrastructure projects in this region since 2012 (MWR 2012). However, famers in NFR have insufficient knowledge and skills in the use of irrigation in maize cropping systems (Li *et al.* 2005). In addition, irrigation also improves nitrogen use efficiency, as demonstrated for China by Michalczyk *et al.* (2014). Therefore, an irrigation management and scheduling scheme that accounts for effects of actual soil water content is necessary for both farmers and policy makers in NFR to better cope with the variable and changing climate.

Crop coefficients that are used in calculating evapotranspiration can help develop an efficient irrigation schedule, which varies during the growing season and with the wetness of the soil surface (Allen *et al.* 1998). There are two primary approaches for calculating crop evapotranspiration: the single crop coefficient and the dual crop coefficient. The single crop coefficient is widely used because of its simplicity and it combines evaporation and transpiration when computing crop evapotranspiration. The advantage of the dual crop coefficient is that it estimates the soil water balance using a daily time step, which calculates crop transpiration and soil evaporation separately, as well as water dynamics, to devise the irrigation scheme (Sahli & Jabloun 2009; Allani *et al.* 2012). This allows for a more precise analysis of how water from rainfall and irrigation is used by the crop (Allen *et al.* 1998; Allen 2011; Rosa *et al.* 2012; Pereira *et al.* 2015). The dual crop coefficient has been widely used in calculating crop evapotranspiration and soil water balance for various crops, including maize (Allen *et al.* 1998, 2005*a*, *b*; Li *et al.* 2005; Zhao & Nan 2007; Rosa *et al.* 2012; Pereira *et al.* 2015). However, it has rarely been used in computing crop evapotranspiration for maize production in NFR, except by Li *et al.* (2005) in Western Songliao. Hence, the dual crop coefficient was used in the present study to calculate crop evapotranspiration and soil water balance.

Most studies on the effects of climate change and climatic variability on maize yield in NFR have considered responses for the whole growing season (Chen *et al.* 2012; Liu *et al.* 2012, 2013*b*). However, maize growth is affected differently by the weather in different growth phases (Hu & Buyanovsky 2003; Trnka *et al.* 2011). Therefore, assessing yield effects of climatic variables in specific growth phases may provide a better understanding of how drought and rainfall impact maize yield under climate change, and how much irrigation is needed in each growth phase to mitigate the negative effects of drought on maize yield. Therefore, the aims of the present study are: (1) to analyse the spatial variation of climatic factors in different maize growth phases and their influences on maize yield; (2) to investigate the spatial variation of drought risk in specific growth phases and its impacts on maize yield; and (3) to estimate the spatial variation of irrigation water requirement in each growth phase.

MATERIALS AND METHODS

Area description

The study area is located in Northeast China, comprising the North-eastern Inner Mongolia, Heilongjiang,

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Jilin and most parts of Liaoning provinces (Fig. 1). The area includes 304 counties, with 14·2 million ha farmland. The NFR consists of five sub-regions: Xinganling, Sanjiang, Songliao, Changbaishan and Liaodong (Liu & Chen 2005). The region is located between 40° and 54°N and is a temperate semi-humid zone, where annual accumulated temperature above 10 °C ranges from 1700 to 3600 °C day and the frost-free period normally starts around 28 March and ends around 2 October. The annual mean sunshine duration is 2400–2900 h. Annual precipitation is 500–800 mm, 0·80 of which falls during May–September, which corresponds to the maize growing season (Li *et al*. 2008; Chen *et al*. 2011).

Data sources

Observed records of dates of sowing (BBCH growth stage (GS) 01), emergence (GS 10), flowering (GS 61), milk (GS 79) and maturity (GS 99) for maize at 40 stations during 1981–2010 were collected from the agro-meteorological experimental stations through the Chinese Meteorological Administration (BBCH 1997; CMA Archives 2011; Fig. 1). Maize was planted using the current local management practices at each station from 1981 to 2010 and maize phenology was recorded. Historical climate data (daily data on the minimum, mean and maximum temperature, precipitation, sunshine hours, wind speed and relative humidity) of this region from 1961 to 2010 were collected from 54 sites with complete records under the supervision of the National Meteorological Network of China Meteorological Administration (CMA Archives 2011; Fig. 1). Yield data from 44 maize yield stations with no missing values during 1961–2010 were obtained from the Planting Information Network of China (PINC Archives 2011; Fig. 1).

Data analyses

The MABIA model (Sahli & Jabloun 2009) was used for calculating the maize water balance at each station under rain-fed conditions. MABIA is an irrigation scheduling simulation model based on the computation of a daily soil water balance at field scale using the dual crop coefficient approach to compute crop evapotranspiration (Allen *et al*. 1998, 2005*a*). Calculations of crop evapotranspiration, effective rainfall and soil water balance are shown in the supporting information (available from http://journals.cambridge.org/AGS).

Water deficit (W_d) was calculated as follows:

$$W_d = 1 - \frac{\mathrm{ETa}}{\mathrm{ETc}} \quad (1)$$

where W_d is the water deficit, ETa is the actual crop evapotranspiration and ETc is the crop evapotranspiration. Water deficit increases with W_d. The days with water deficit were defined as the number of days with ETa/ETc < 0·4, equivalent to drought stress days (Trnka *et al*. 2011, 2014). The drought stress days in each phase were the total number of days with water deficit.

In order to investigate effects of climatic factors, drought risks and irrigation requirement on maize yield in specific growth phases, the maize growing season was divided into four phases; seeding (from sowing to emergence), vegetative (from emergence to flowering), flowering (from flowering to milk) and maturity (from milk to maturity). The average values of sowing, emergence, flowering, milk and maturity dates for the last 30 years (1981–2010) were used as the standard dates representing the last 50 years for each station (Fig. 2). Figure 2 shows that there were significant differences in days of year for sowing, emergence, flowering, milk and maturity in NFR, with earlier sowing and emergence in the south and later sowing and emergence in the north; however, the flowering, milk and maturity dates vary less because of the effects of maize varieties and management. For the weather stations without recorded crop phenology, the phenological dates of a nearby agro-meteorological experimental station were used. The years affected by drought stress and the years with need of irrigation were calculated. Zero values of drought stress and irrigation requirement were excluded when calculating the average of drought stress days and irrigation requirement during the last 50 years as shown in the result section.

A linear regression was used to estimate the trends in mean temperature, solar radiation, effective rainfall, ETa, water deficit and maize yield over time. Maize yield was influenced by many technological and environmental factors and responded to improvements in genetics, fertilizer application and management (Hu & Buyanovsky 2003). In order to separate the contributions of climate and agronomic management, the crop yield time series should be de-trended. A broken linear method was used to de-trend maize yield, where the yield trend is allowed to change a point during the last 50 years (Olesen *et al*. 2000), which

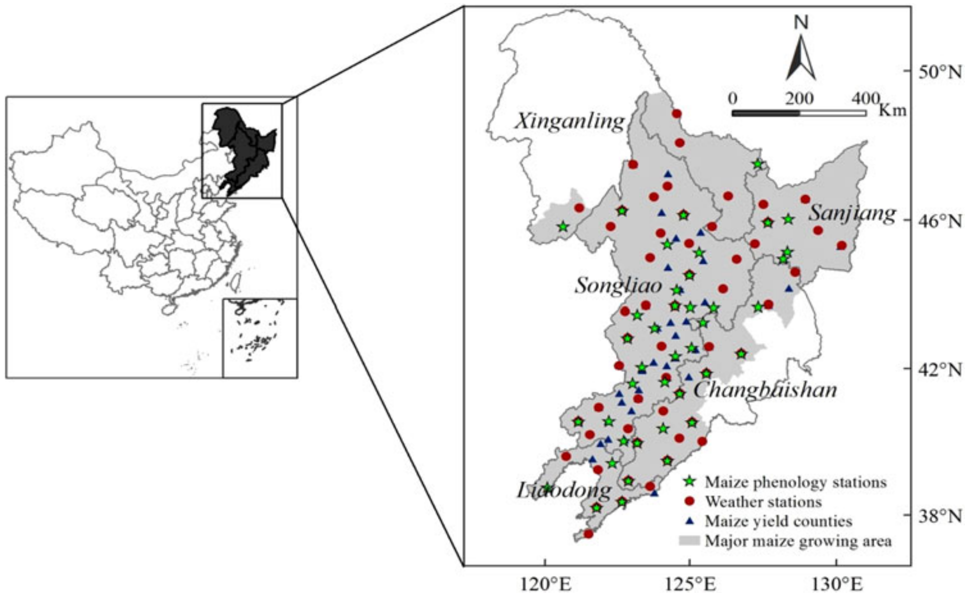

Fig. 1. Locations of weather stations, maize yield counties and agro-meteorological experimental stations in the Northeast Farming Region of China (NFR). Colour online.

can be described as:

$$\begin{cases} Y_n = a + b1x, & x \leq xb \\ Y_n = a + b1xb + b2(x - xb), & x > xb \end{cases} \quad (2)$$

$$Y_{cn} = Y_{an} - Y_n \quad (3)$$

where Y_n is the predicted crop yield, x is the year, xb is constrained to $1965 < xb < 2005$ to reduce risk of spurious results in the study, a is the model intercept, xb is the end of the first period, $b1$ is the slop of the regress line in the first period, $b2$ is the slop of the regress line in the second period. Y_{cn} and Y_{an} are the de-trended yield and the actual yield of the year n. The parameters of Eqn (2) were estimated using the NLIN procedure of SAS 9·3 software (SAS Institute Inc., Cary, USA). The de-trended yield can be assumed to reflect the impacts of inter-annual climatic variability (Fig. S1, available from http://journals.cambridge.org/AGS). Pearson correlation coefficients were subsequently used to explore the relationship between de-trended yield and separate climatic factors for specific growth phases.

Finally, a linear mixed model was used to estimate the effects of climatic variables on crop yield. For crop yield counties without weather stations, the best-fitted nearby weather stations were used in the analysis. To investigate the effect of drought stress, four configurations of the mixed model were considered. Mean temperature, solar radiation and effective rainfall were the three basic climatic factors included, while water deficit, drought stress days, ETa and irrigation requirement calculated by MABIA were used separately each time with the three basic climatic factors. As there was no information about maize varieties and agricultural technology, year was included in the model to represent the development of varieties and technology and the stations were used as the random effect for different models. The variance inflation factor (VIF) test was performed for each mixed model including all variables to test the multicollinearity and the results showed that multicollinearity is not a problem in any of the mixed models (Montgomery *et al.* 2012; Table S1, available from http://journals.cambridge.org/AGS). Therefore, the mixed model reflects well the effects of climatic factors on maize yield in different phases.

There are 2200 observations in each mixed model and the model can be written as follows:

$$\begin{aligned} Y = {} & Y_0 + \alpha_{st} Y_r + \beta_s T_s + \beta_v T_v + \beta_f T_f + \beta_m T_m \\ & + \chi_s R_s + \chi_v R_v + \chi_f R_f + \chi_m R_m + \delta_s P_s + \delta_v P_v \\ & + \delta_f P_f + \delta_m P_m + \gamma_s A_s + \gamma_v A_v + \gamma_f A_f \\ & + \gamma_m A_m + X_s + \varepsilon \end{aligned} \quad (4)$$

where Y represents actual crop yield, Y_0 is the model intercept, Y_r is year, α_{st} is the coefficient for year at station s, β, χ, δ and γ are the coefficients for each climate variable in specific phase, respectively, X_s is

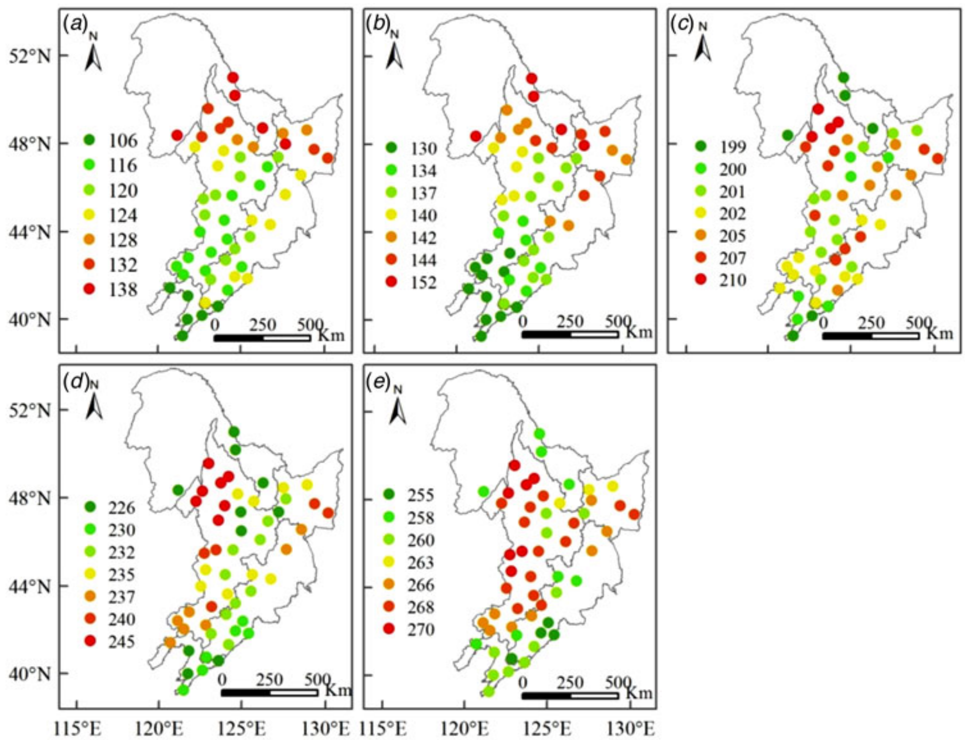

Fig. 2. Spatial distributions of DOY (day of year) for (*a*) sowing, (*b*) emergence, (*c*) flowering, (*d*) milk and (*e*) maturity. Colour online.

a random error associated with station, and ε is the model error. The subscripts 's', 'v', 'f' and 'm', respectively, represent the seeding, vegetative, flowering and maturity phases. *T, R* and *P* represent the mean temperature, solar radiation and effective rainfall, respectively; and *A* represents either ETa, water deficit, drought stress days or irrigation requirement in different scenarios. SAS 9·3 software (SAS Institute Inc., Cary, USA) and R software were used in the study. The spatial and temporal characteristics of climatic factors, drought risks and irrigation requirement were displayed using ArcMap 10·2 software (ESRI, Redlands, CA, USA).

RESULTS

Spatial and temporal variation in climatic factors

During 1961 to 2010, the average mean temperature was higher in the south compared with the north through all growth phases. It was highest in the flowering phase, which varied between 17·1 and 25·6 °C, and lowest in the seeding phase, which varied between 11·0 and 17·0 °C (Figs 3(*a*)–(*d*)). The mean temperature increased by 0–0·07 °C/year in most parts of NFR in all growth phases from 1961 to 2010, except in Sangjiang and southern NFR in the flowering phase (Figs 3(*e*)–(*l*)). The increase was highest in the seeding phase and lowest in the flowering phase. The mean temperature increased more in the north than in the south in all growth phases (Figs 3(*e*)–(*h*)).

Average solar radiation varied between 14·5 and 22·4 MJ/m^2/day through all growth phases across NFR. It was highest in the vegetative phase, but lowest in the maturity phase. Solar radiation increased from east to west across NFR in all growth phases (Figs 4(*a*)–(*d*)). During the last 50 years, solar radiation decreased significantly in most parts of NFR at a rate of 0·03–0·10 MJ/m^2/day/year in the seeding, vegetative and flowering phases, while it increased in most parts of NFR, excluding western Songliao, in the maturity phase (Figs 4(*e*)–(*h*)).

Effective rainfall was concentrated in the vegetative and flowering phases, while it was very low in the seeding phase (Figs 5(*a*)–(*d*)). Effective rainfall increased from west to east in NFR, with lowest rainfall in West Songliao and the highest in Southern Changbai through all growth phases. During the last 50 years, effective rainfall in the seeding phase has

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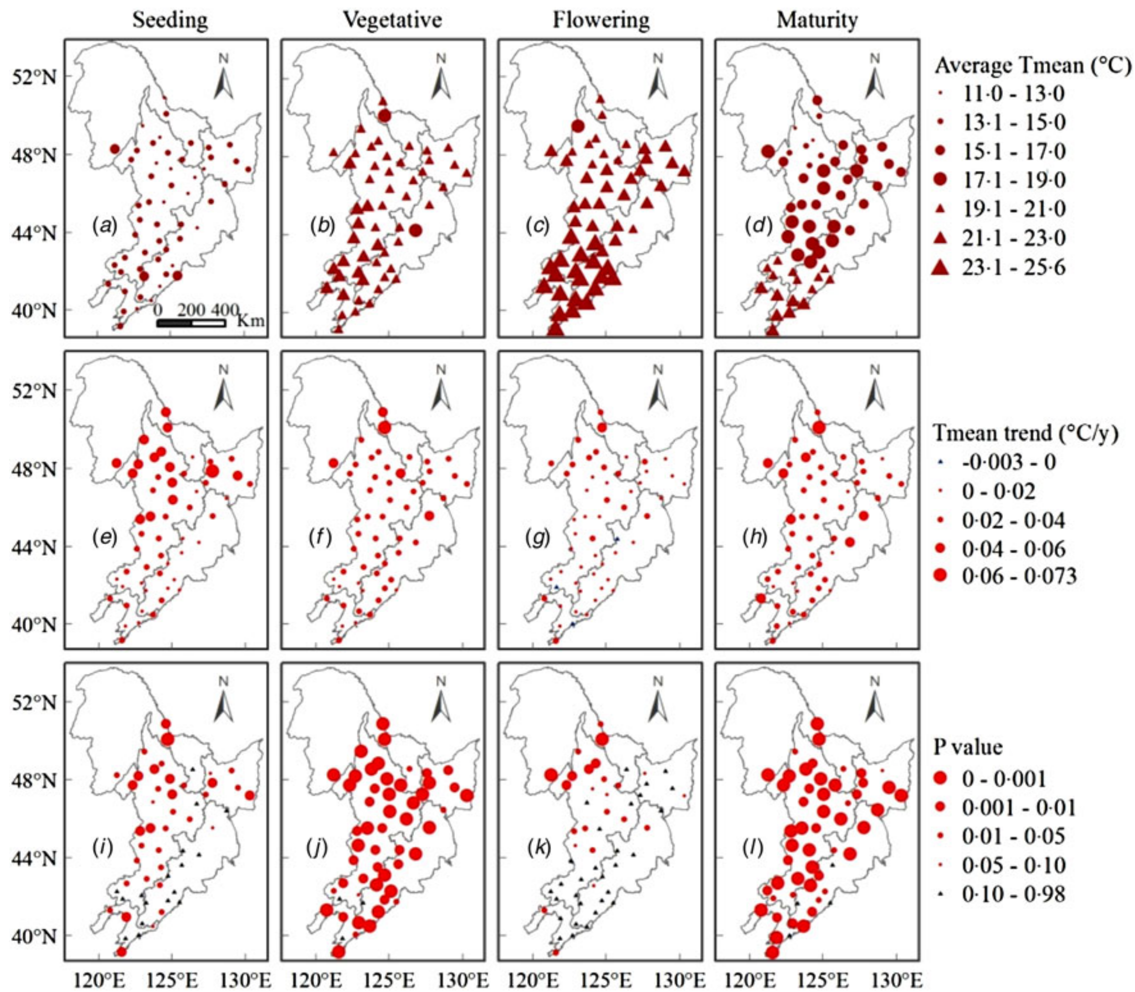

Fig. 3. Spatial variation of (*a*–*d*) average mean temperature, (*e*–*h*) mean temperature trends and (*i*–*l*) the correlations between mean temperature and year in different maize growth phases during 1961–2010 across NFR. The blue triangles show the decreasing trend and the red points show the increasing trend (*e*–*h*). The black triangles show that the correlation between mean temperature and year is not significant, while different size of red points indicates the level of significance (*i*–*l*). Colour online.

increased at a rate of 0·01–0·80 mm/year across NFR, except for the northern part. It also increased in the vegetative phase in most parts of Songliao and Southern Sangjiang at the rate of 0·01–1·17 mm/year. However, it decreased in most parts of NFR in the flowering and maturity phases (Figs 5(*e*)–(*h*)).

Drought risk

Average water deficit was highest in the maturity phase, especially in the western parts of Songliao where the mean water deficit reached 0·31–0·34, while the lowest water deficit was found in the vegetative phase. Average water deficit was higher in the west and lower in the east in all growth phases (Figs 6(*a*)–(*d*)). Water deficit decreased significantly over time in most parts of NFR in the seeding phase, and it also decreased in most parts of Songliao in the vegetative phase. However, it increased in most parts of NFR in the flowering and maturity phases (Figs 6(*e*)–(*h*)).

Over the last 50 years, the number of days affected by drought stress in a year was greatest in the vegetative phase, which varied between 21 and 50, but smallest in the flowering phase across NFR. The western part of NFR suffered more years with drought stress compared with other parts of NFR in all growth phases (Figs 7(*a*)–(*d*)). The number of average drought stress days was very large in the vegetative phase across the whole NFR and highest in the maturity phase, especially in western NFR, with the average drought stress days varying between 8·1 and

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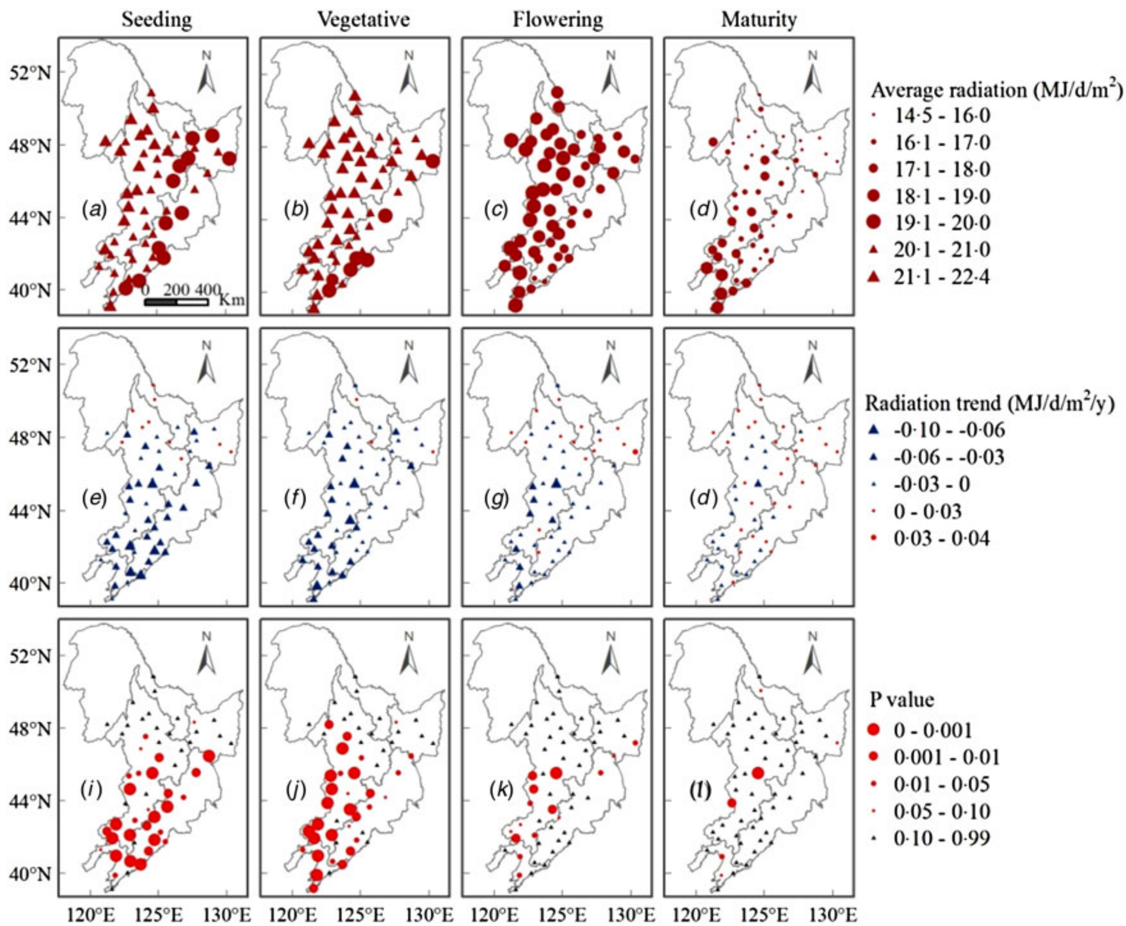

Fig. 4. Spatial variation of (*a–d*) average solar radiation, (*e–h*) solar radiation trends and (*i–l*) the correlations between solar radiation and year in different maize growth phases during 1961–2010 across NFR. The descriptions of symbols for the figure are similar to Fig. 3. Colour online.

20·0 over the last 50 years. The seeding phase suffered the least drought stress days and there were no drought days in most parts of Changbai in the flowering and maturity phases (Figs 7(*e*)–(*h*)).

Actual crop evapotranspiration and irrigation requirement

Average ETa was highest in the vegetative phase, with values ranging from 150·1 to 229·3 mm across NFR and lowest in the seeding phase, varying between 37·3 and 60·0 mm (Figs 8(*a*)–(*d*)). During the last 50 years, ETa showed a tendency to increase in the seeding phase in southern NFR, and in the vegetative and flowering phases in northern NFR, but neither of these increases were significant (Fig. 8). However, ETa decreased in Southern Songliao in the vegetative and flowering phases and in most parts of NFR in the maturity phase.

Estimated irrigation demand was very high during the seeding and vegetative phases across NFR, where the frequency of years requiring irrigation reached 41–50 out of the 50 years considered (Figs 9(*a*) and (*b*)). Irrigation was also needed in Sanjiang and Songliao in the flowering and maturity phases (Figs 9(*c*) and (*d*)). Despite the high frequency of irrigation needed in the seeding phase the actual amount of water required was small, ranging from 36 to 90 mm across NFR (Fig. 9(*e*)). The largest irrigation need was in the vegetative phase with values of 120–195 mm, in particular in Songliao. The average irrigation demand in the flowering and maturity phases was also very large (Fig. 9).

Effects of climatic factors, drought risk and irrigation requirement on maize yield

Mean maize yield was 2898–6907 kg/ha across NFR during 1961–2010 (Fig. 10). The counties with the

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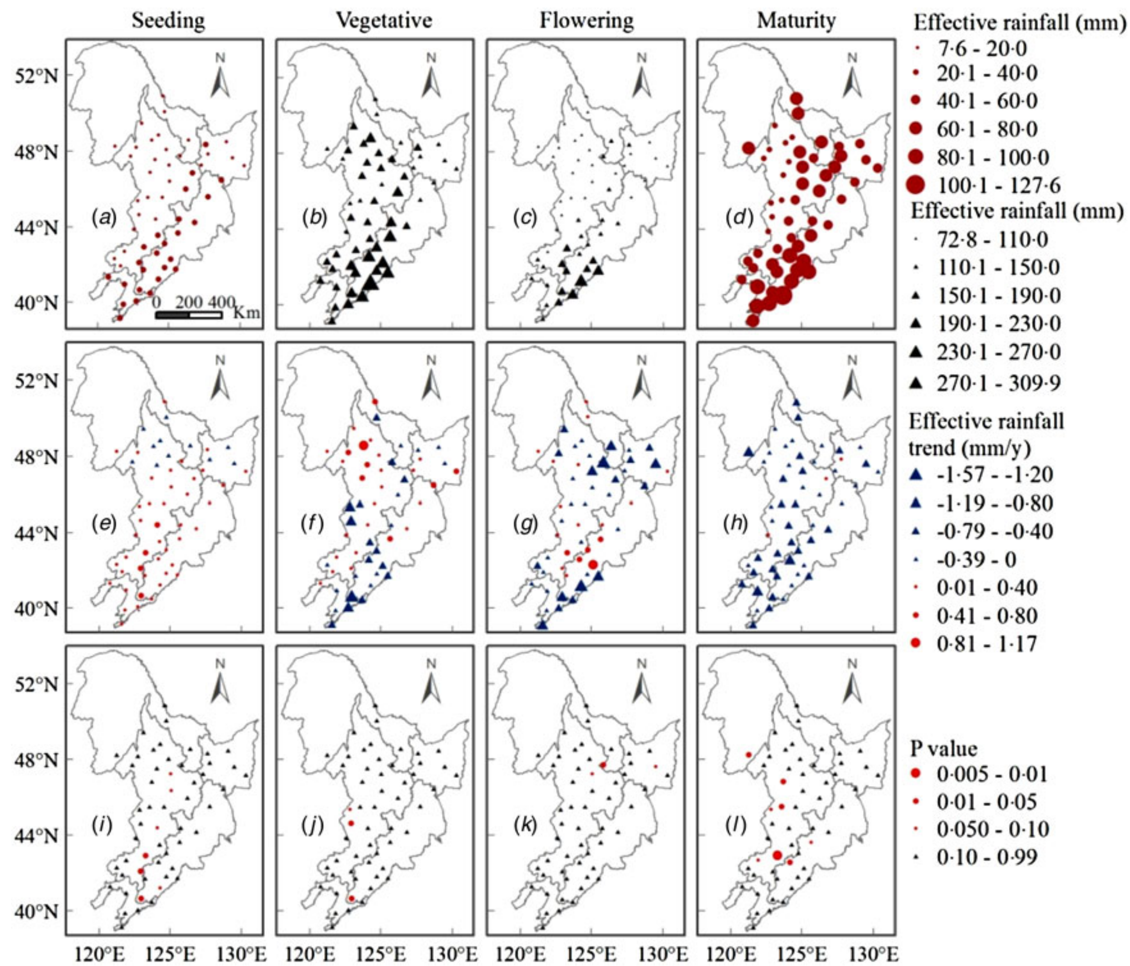

Fig. 5. Spatial variation of (*a*–*d*) average effective rainfall, (*e*–*h*) effective rainfall trends and (*i*–*l*) the correlations between effective rainfall and year in different maize phases during 1961–2010 across NFR. The descriptions of symbols for the figure are similar to Fig. 3. Colour online.

highest maize yield were concentrated in Central Songliao. Maize yield increased by 66 to 283 kg/ha/year over all counties during the last 50 years, with the highest increase in Central Songliao.

The correlation between mean temperature and de-trended maize yield was positive in the seeding and maturity phases, while it was negative in the vegetative and flowering phases (Table 1). Analysis indicated that when mean temperature was considered with other factors as shown in Table 2, mean temperature had significantly ($P < 0{\cdot}01$) positive effects on maize yield in the seeding and maturity phases in most cases.

There were significant ($P < 0{\cdot}05$) negative correlations between the average solar radiation and mean de-trended yield in the vegetative and flowering phases and there were three and seven counties with significant ($P < 0{\cdot}05$) negative correlations in the vegetative and flowering phases, respectively (Table 1). When solar radiation was combined with other factors in analysis, solar radiation mainly had significantly ($P < 0{\cdot}05$) positive effects on maize yield in the vegetative and maturity phases, while it had significant ($P < 0{\cdot}001$) negative effects on maize yield in the flowering phase across all four groups of statistical models (Table 2).

There were five counties with significant ($P < 0{\cdot}05$) positive correlations between effective rainfall in the vegetative phase and de-trended yield (Table 1). In contrast, when combining effective rainfall with other factors in mixed models (Table 2), effective rainfall mainly had significantly ($P < 0{\cdot}05$) negative effects on maize yield, in particular in the seeding and flowering phases.

There were significant ($P < 0{\cdot}05$) negative correlations between average water deficit and mean de-trended yield in the vegetative and flowering phases.

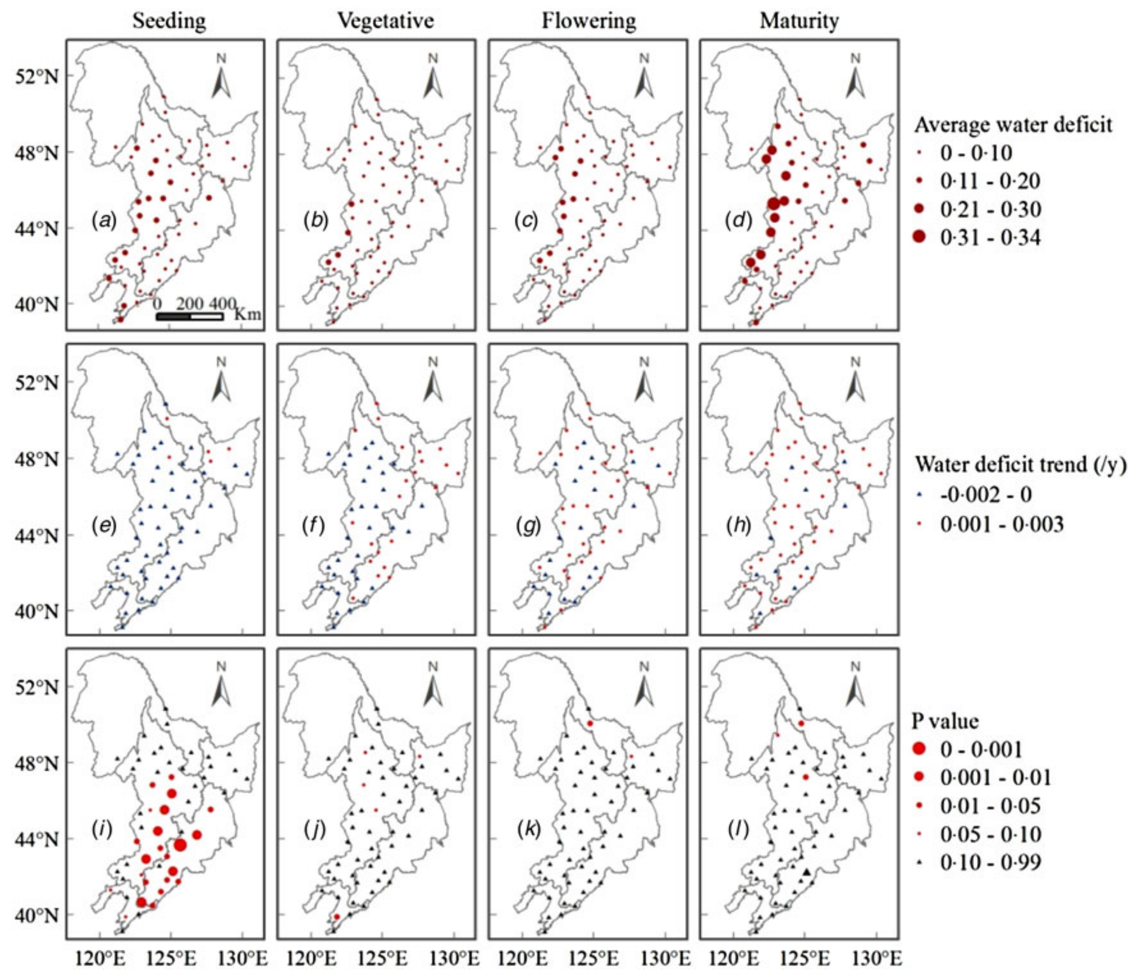

Fig. 6. Spatial variation of (*a*–*d*) average water deficit, (*e*–*h*) water deficit trends and (*i*–*l*) the correlations between water deficit and year in different maize growth phases during 1961–2010 across NFR. The descriptions of symbols for the figure are similar to Fig. 3. Colour online.

There were seven, 14 and seven counties with significant ($P < 0{\cdot}05$) negative correlations in the vegetative, flowering and maturity phases, respectively (Table 1). When water deficit was considered with the three other climatic factors in the analysis, the results showed that one unit increase of water deficit (i.e. from no to full deficit) in the seeding, vegetative, flowering and maturity phases would lead to decreases of 5287, 3978, 1453 and 784 kg/ha, respectively, in maize yield (Table 2).

Correlation between average drought stress days and mean de-trended yield was negative significant ($P \leqslant 0{\cdot}05$) in the seeding phase and the number of counties with significant ($P < 0{\cdot}05$) negative correlation in the flowering and maturity phases were three and five, respectively (Table 1). When considered together with mean temperature, solar radiation and effective rainfall in the analysis, a 1-day increase of stress days in the seeding, flowering and maturity phases would lead to decreases of 56·1, 58·7 and 21·2 kg/ha, respectively, in maize yield (Table 2).

Significant ($P < 0{\cdot}05$) positive correlations between the average ETa and mean de-trended yield were found in seven and six counties in the flowering and maturity phases, respectively (Table 1). When including the other three climatic factors in the analysis, the results indicated that a 1 mm increase in ETa would lead to increases of 12·7, 10·5 and 5·1 kg/ha in maize yield in the seeding, flowering and maturity phases, respectively (Table 2).

There was a significant ($P \leqslant 0{\cdot}05$) negative correlation between average irrigation requirement and mean de-trended yield in the vegetative phase. Additionally, there were six and six counties with significant ($P < 0{\cdot}05$) negative correlations in the vegetative and flowering phases, respectively (Table 1).

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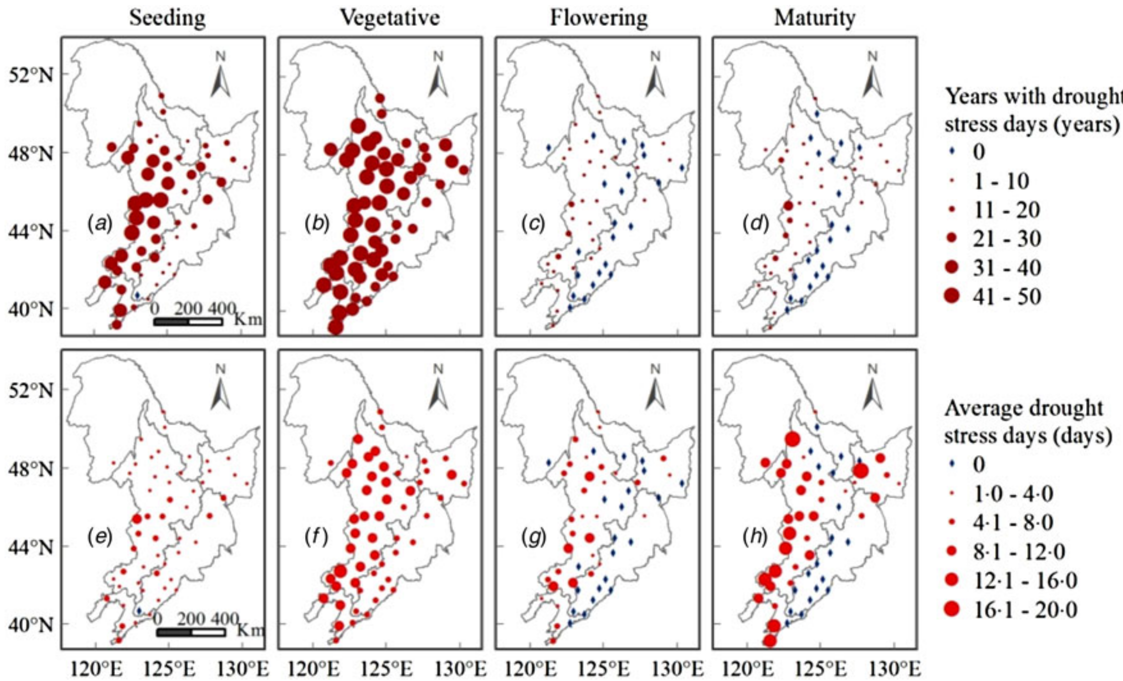

Fig. 7. Spatial variation of (*a–d*) years with drought stress days and (*e–h*) average drought stress days excluding the zero values during 1961–2010 in NFR for different maize growth phases, where drought stress days means the days with water deficit, and years with drought stress days represent the number of years that the drought stress days were larger than 0. Colour online.

When including the other three climatic factors in the analysis, 1 mm less irrigation would lead to decreases of 9·3, 3·9, 4·1 and 2·1 kg/ha in maize yield in the seeding, vegetative, flowering and maturity phases, respectively (Table 2).

DISCUSSION

Model choice

Linear models were applied to estimate the relationship between maize yield and effects of year and climatic variables in the present study. Over the time period considered, maize yield increased from <2 t/ha to ~8 t/ha (Fig. S1, available from http://journals.cambridge.org/AGS). It may be expected that the influences of climatic variables will be influenced by the yield level, as higher yields increase yield variability and effects of drought are also more severe with increased production intensity (Trnka *et al.* 2012; Liu *et al.* 2013*a*). Increased variability in yields is also indicated in Fig. S1, which thus potentially invalidates the assumption of homoscedasticity in the statistical analyses. However, since the effects as shown in Fig. S1 do not seem to be major, in particular after 1970, the yield data were not transformed. Also the use of non-transformed variables makes the interpretations easier. However, both the increase in variability and the possible changes over time in responses of the crop to drought as a consequence of input levels demand caution when interpreting parameter estimates. Four different indicators of drought stress were tested in the linear mixed models and ranked approximately equal in terms of performance. However, the model using water deficit was slightly better than the other models. This would indicate that it is the relative water deficit in the different growth phases that best represents effects on yield.

Influences of climatic factors on maize yield

The observed changes in mean temperature during the maize growing season in NFR were in line with other studies (Liu *et al.* 2009; Piao *et al.* 2010; Chen *et al.* 2011; Jia & Guo 2011). The current results indicated that the higher mean temperature in the seeding and maturity phases was beneficial for maize yield. The benefits of higher mean temperature stemmed from earlier sowing in the seeding phase and later harvest in the maturity phase. This extended the maize growing season and enhanced the yield (Tao *et al.* 2006, 2014; Chen *et al.* 2011; Olesen *et al.* 2011; Yuan *et al.* 2012). Although not significant, analysis

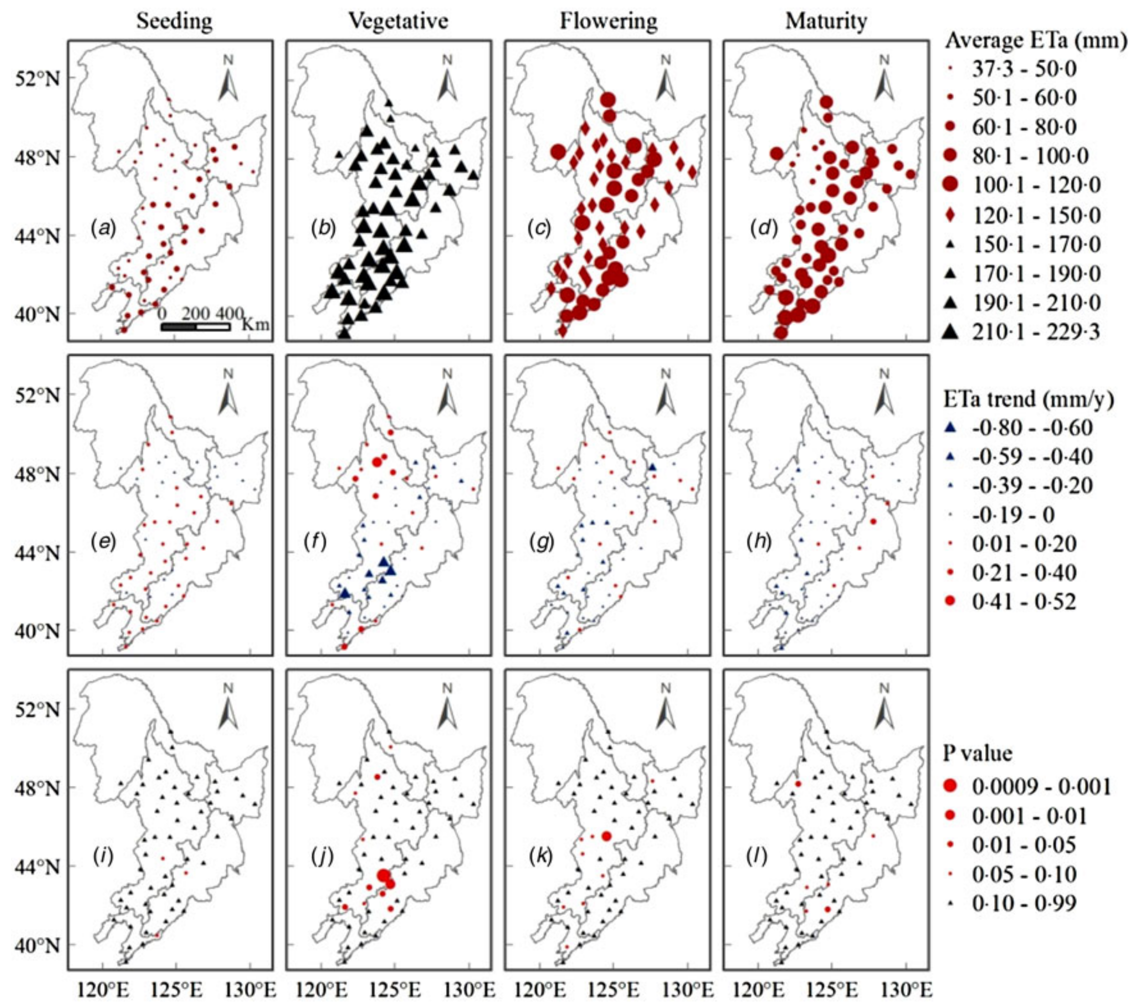

Fig. 8. Spatial variation of (*a*–*d*) average actual crop evapotranspiration (ETa), (*e*–*h*) ETa trends and (*i*–*l*) the correlations between ETa and year in different maize growth phases during 1961–2010 across NFR. The descriptions of symbols for the figure are similar to Fig. 3. Colour online.

revealed a tendency for higher mean temperature in the vegetative and flowering phases to lead to yield loss. The mean temperature in the vegetative and flowering phases is much higher compared with that in the seeding and maturity phases, leading to higher risk of heat stress. Heat stress affects several physiological processes negatively and may reduce biomass accumulation. Heat stress has frequently occurred in the vegetative and flowering phases of maize in NFR during the last 50 years (Fig. S2, available from http://journals.cambridge.org/AGS). The occurrence of heat stress at these critical crop development stages, especially in the late vegetative and flowering phases may be particularly harmful to grain yield by reducing seed setting (Schlenker & Roberts 2009; Eitzinger *et al.* 2013; Teixeira *et al.* 2013).

The decrease in solar radiation during the seeding, vegetative and flowering phases was in line with the decline of sunshine hours in NFR (Liu *et al.* 2009; Jia & Guo 2011). However, it was found that solar radiation increased in the maturity phase in most parts of NFR. The positive effects of solar radiation are probably related to the impacts of solar radiation on maize photosynthesis and net assimilation (Trnka *et al.* 2014). The negative effects of high solar radiation during the flowering phase may be linked to high-temperature stress, since high solar radiation during the periods of low soil water availability will increase canopy temperature (Siebert *et al.* 2014) and this will affect seed setting negatively during this sensitive period. Furthermore, negative effects of higher solar radiation may also be linked to other factors such as higher concentration of ozone, which decreases

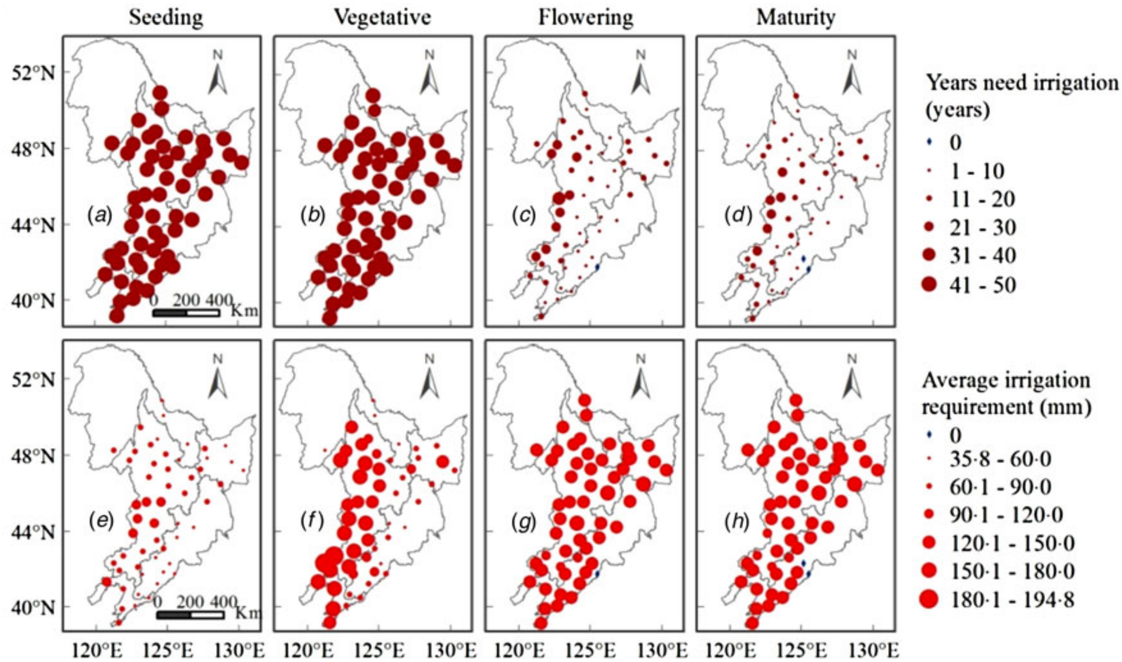

Fig. 9. Spatial variation of (*a–d*) years which need irrigation and (*e–h*) average irrigation requirement excluding zero values during 1961–2010 in NFR for different maize growth phases, where the years with need of irrigation represent the number of years that the irrigation requirement was larger than 0. Colour online.

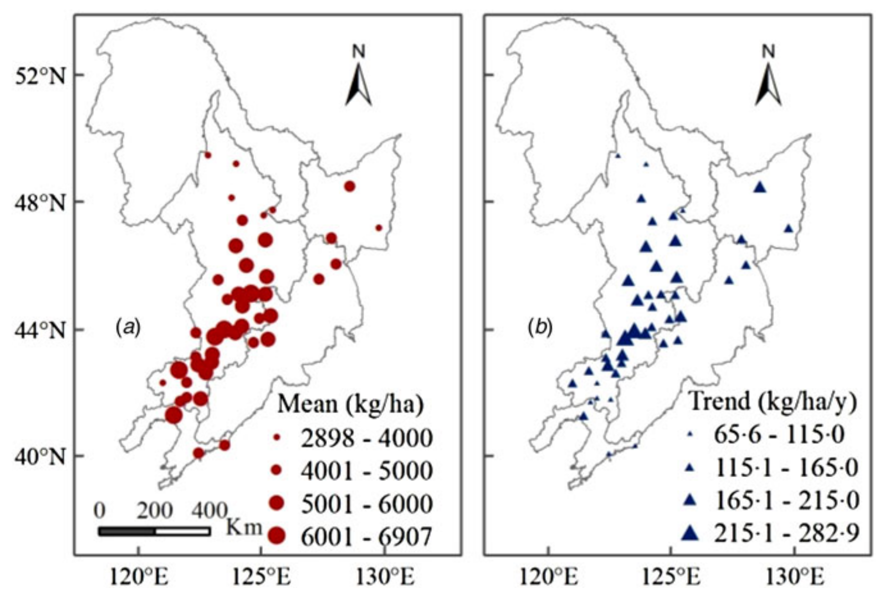

Fig. 10. Distributions of (*a*) the average maize yield and (*b*) the maize yield trend from 1961 to 2010 across NFR, the trends for all stations are significant at level $P < 0{\cdot}001$. Colour online.

photosynthesis and contributes to yield loss (Feng & Kobayashi 2009; Zhang *et al.* 2014*a*).

Declining rainfall has been reported by most studies for the whole maize growing season (Liu *et al.* 2009; Piao *et al.* 2010; Chen *et al.* 2011; Jia & Guo 2011). However, the present study found that effective rainfall increased in southern NFR in the seeding phase and in Songliao in the vegetative phase. Effective rainfall is a very important factor in maize production under rain-fed conditions in NFR; however, when effective rainfall was considered together with other factors, effective rainfall was found

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Table 1. *Correlations between either mean temperature (Tmean), average solar radiation (R), effective rainfall (Peff) and actual crop evapotranspiration (ETa), water deficit (W_d), drought stress days (Dsd) or irrigation requirement (Ir), and de-trended maize yield in each growth phase, and the unit of the de-trend yield is kg/ha*

	Mean	Positive	Negative
Tmean (°C)			
Seeding	0·06 (0·69)	**1**, *3*, 21	**1**, *2*, 16
Vegetative	0·04 (0·78)	**4**, *5*, 16	**1**, 2, 16
Flowering	−0·04 (0·78)	**1**, *1*, 18	**2**, *1*, 21
Maturity	0·17 (0·25)	**2**, *0*, 26	**0**, *0*, 16
R (MJ/day/m^2)			
Seeding	−0·10 (0·51)	**1**, *1*, 21	**0**, *1*, 20
Vegetative	−0·29 (0·04)	**1**, *3*, 19	**3**, *0*, 18
Flowering	−0·30 (0·04)	**0**, *1*, 16	**7**, *3*, 17
Maturity	−0·08 (0·60)	**4**, *3*, 27	**3**, *0*, 7
Peff (mm)			
Seeding	0·003 (0·98)	**3**, *1*, 15	**2**, *0*, 23
Vegetative	0·23 (0·11)	**5**, *5*, 16	**2**, *0*, 16
Flowering	0·10 (0·49)	**0**, *2*, 21	**3**, *0*, 18
Maturity	−0·06 (0·70)	**0**, *0*, 18	**2**, *3*, 21
W_d			
Seeding	−0·16 (0·27)	**0**, *0*, 21	**0**, *2*, 21
Vegetative	−0·30 (0·03)	**1**, *1*, 15	**7**, *3*, 17
Flowering	−0·27 (0·05)	**0**, *1*, 6	**14**, *3*, 20
Maturity	−0·17 (0·24)	**1**, *0*, 13	**7**, *0*, 23
Dsd (days)			
Seeding	−0·28 (0·05)	**0**, *1*, 15	**0**, *2*, 26
Vegetative	−0·05 (0·74)	**2**, *0*, 23	**1**, *1*, 17
Flowering	−0·21 (0·14)	**0**, *0*, 4	**3**, *4*, 13
Maturity	−0·12 (0·42)	**0**, *0*, 8	**5**, *0*, 21
ETa (mm)			
Seeding	0·05 (0·72)	**1**, *4*, 18	**1**, *1*, 19
Vegetative	0·06 (0·65)	**2**, *2*, 26	**2**, *2*, 10
Flowering	−0·01 (0·93)	**7**, *0*, 23	**1**, *0*, 13
Maturity	0·14 (0·34)	**6**, *2*, 23	**0**, *2*, 11
Ir (mm)			
Seeding	−0·14 (0·35)	**0**, *0*, 22	**1**, *1*, 20
Vegetative	−0·28 (0·05)	**1**, *1*, 12	**6**, *4*, 20
Flowering	−0·17 (0·24)	**0**, *1*, 13	**6**, *2*, 22
Maturity	−0·03 (0·81)	**0**, *2*, 20	**0**, *3*, 19

Values in brackets is the *P* level.
Mean shows the correlation between the average de-trend maize yield and the average climate factors in NFR during 1961–2010. The positive and negative shows number of stations with positive or negative correlation coefficients between de-trend yield and climatic factors in each phase. The first value in bold shows the number of stations where the significance level is $P < 0·05$; the second value in italics shows the number of stations where the significance level is $0·05 \leqslant P < 0·1$; the last value shows the number of stations where the significance level is $0·1 \leqslant P < 1$, i.e. not significant.

to have significant negative effects on maize yield in the seeding and flowering phases. Even though the increase of effective rainfall is expected to mitigate drought, the uneven distribution of rainfall may be the key factor that caused maize yield loss that was observed in the present study. Flooding frequently affects the NFR due to the uneven distribution of precipitation with intense rainfall during the last decades (PINC Archives 2011; Gao *et al.* 2012; Zhang *et al.* 2014*b*). Generally, excessive rainfall in the seeding phase would affect maize sowing, thus delaying the maize growing season, which increases the risk of

Table 2. *Regression models of maize yield for average mean temperature (Tmean), average solar radiation (R), effective rainfall (Peff) and either actual crop evapotranspiration (ETa), water deficit (W_d), drought stress days (Dsd) or irrigation requirement (Ir) in different maize phases*

	Seeding	Vegetative	Flowering	Maturity	Intercept	Year	R^2	RMSE
Tmean (°C)	82·0 (<0·001)	−0·9 (NS)	−8·8 (NS)	53·8 (NS)	−322·6 (NS)	143·9 (<0·001)	0·80	1217
R (MJ/day/m^2)	0·8 (NS)	106·1 (<0·001)	−100·8 (<0·001)	72·9 (<0·01)				
Peff (mm)	−10·6 (<0·001)	−1·3 (0·02)	−3·0 (<0·001)	−0·6 (NS)				
W_d	−5287 (<0·001)	−3978 (<0·001)	−1453 (<0·001)	−784 (⩽0·01)				
Tmean (°C)	55·5 (⩽0·01)	−59·0 (NS)	−47·1 (NS)	83·3 (<0·01)	1459·0 (NS)	144·1 (<0·001)	0·79	1238
R (MJ/day/m^2)	−9·4 (NS)	61·1 (<0·05)	−121·1 (<0·001)	81·0 (<0·01)				
Peff (mm)	−4·5 (<0·05)	0·9 (⩽0·05)	−2·1 (<0·001)	−0·1 (NS)				
Dsd (days)	−56·1 (<0·001)	5·1 (NS)	−58·7 (<0·01)	−21·2 (<0·05)				
Tmean (°C)	38·0 (NS)	−66·4 (0·12)	−56·1 (0·10)	77·5 (0·01)	1134·0 (NS)	149·3 (<0·001)	0·79	1235
R (MJ/day/m^2)	−25·6 (NS)	76·6 (⩽0·01)	−178·6 (<0·001)	60·5 (<0·05)				
Peff (mm)	−7·0 (0·006)	−0·1 (0·86)	−2·6 (<0·001)	−0·9 (NS)				
ETa (mm)	12·7 (<0·01)	1·3 (NS)	10·5 (<0·001)	5·1 (⩽0·05)				
Tmean (°C)	80·0 (<0·001)	16·0 (NS)	−33·6 (NS)	49·7 (NS)	−314·4 (NS)	140·3 (<0·001)	0·79	1224
R (MJ/day/m^2)	15·7 (0·49)	101·3 (0·001)	−97·0 (<0·001)	93·7 (<0·001)				
Peff (mm)	−6·4 (<0·001)	−0·9 (NS)	−3·2 (<0·001)	−0·3 (NS)				
Ir (mm)	−9·3 (<0·001)	−3·9 (<0·001)	−4·1 (<0·001)	−2·1 (<0·001)				

The unit of maize yield is kg/ha. There are total 2200 observations used in the mixed model. *P* level shown in parentheses.

chilling damage in late autumn and incomplete maturation in some cases. Furthermore, higher rainfall in the flowering and maturity phases is always accompanied by strong winds, which would easily lead to maize lodging thus causing maize yield loss.

Impacts of drought risks on maize yield

Both water deficit and drought stress days were used to assess drought risks in maize growth phases. It is apparent that the increasing rainfall reduced water deficit in the seeding and vegetative phases, especially in the seeding phase. Similarly, decreasing rainfall in the flowering and maturity phases enhanced the water deficit, particularly in the maturity phase in Western Songliao where rainfall is smaller compared with other regions. Although most of the rainfall was concentrated in the vegetative phase, the uneven distribution of rainfall and the long vegetative phase made the number of years affected by drought stress in this period larger compared with other phases. However, higher rainfall in the flowering phase is the major reason for fewer years with drought stress. Therefore, higher frequency of drought risk was concentrated in the seeding and vegetative phases and the most severe drought risk occurred in western NFR in the maturity phase, as also observed by other studies in NFR (Zhang 2004; Zhang *et al.* 2011; Gao *et al.* 2012).

Drought frequently occurred in the seeding phase throughout NFR. The results showed that both the increase of water deficit and drought stress days would lead to large yield losses. Drought in the seeding phase negatively affects seedling emergence, which influences crop establishment, plant growth and plant population (Ma *et al.* 2014). All such effects during crop establishment have strong effects on yield potential. Water deficit in the vegetative phase also had significant negative impacts on maize yield in NFR. This is supported by findings from other studies that water deficit results in reduction in leaf area, leaf photosynthetic ability, biomass and delayed crop phenology and leads to yield loss (Muchow & Carberry 1989; Abrecht & Carberry 1993; Çakir 2004; Ji *et al.* 2012). In contrast to water deficit, drought stress days in the vegetative phase did not affect yield negatively. This was caused by the different effects of effective rainfall in the two models. In the flowering phase, both water deficit and drought stress days had significantly negative effects on maize yield, indicating that this phase is particularly sensitive to water scarcity. Previous studies also reported that drought stress in this period seriously affected leaf photosynthetic ability and seed sink capacity, as well as ear size and the number of kernels per spike (Musick & Dusek 1980; Ouattar *et al.* 1987; Xu *et al.* 1995; Ji *et al.* 2012). In spite of greater water deficit and drought stress days in the maturity phase, drought stress would cause less yield loss compared with other phases. This may be because drought stress mainly affects crop photosynthesis and net assimilation in the reproductive stage, since leaf area and grain number are fixed before the onset of this phase.

Effects of actual crop evapotranspiration and irrigation requirement on maize yield

The current results showed that the spatial and temporal variations of ETa and effective rainfall were very similar, as ETa is heavily dependent on the timing and amount of rainfall within the given growing season and the application of irrigation would lead to increased ETa during dry periods (Payero *et al.* 2008; Djaman *et al.* 2013). The present results also indicated that higher ETa in the seeding and flowering phases would lead to greater yield increase, which corresponded to the effects of irrigation. In addition, Payero *et al.* (2009) demonstrated that ETa and maize yield was positively correlated in Nebraska, USA.

The distribution of years that required irrigation corresponded with the years with stress days. The irrigation requirement in Western Songliao was larger compared with other parts of NFR, with higher drought risks and less rainfall during maize growth phases (Zhang *et al.* 2011). The present results indicated that unfulfilled irrigation requirements had significantly negative effects on maize yield in all growth phases across NFR during the last 50 years, as supported by previous studies (Payero *et al.* 2006; Djaman *et al.* 2013). Application of 0·80 of the irrigation required may be sufficient to obtain optimal grain yield and high water use efficiency (Yazar *et al.* 1999). According to Li *et al.* (2005), the optimal irrigation schedule for maize production in western Songliao is four times each season: with 10 mm of irrigation applied before sowing and 60 mm in the late vegetative, early flowering and early maturity phases, respectively, maize yield increased by ~44% with irrigation compared with rain-fed conditions. Although the most beneficial water use was reported

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to be achieved by irrigation in the flowering phase (Çakir 2004), the present results indicated that the most significant effects of irrigation demand were in the seeding phase in NFR. This is related to maize emergence and crop establishment (Li *et al.* 2005; Ji *et al.* 2012; Ma *et al.* 2014).

Perspectives and implications

With increasing temperature in the future (IPCC 2013), late maturing cultivars and cultivars with more heat tolerance and earlier sowing would favour maize production in NFR. Maize yield was generally limited by drought during all growth phases. Solar radiation is also a key factor in maize growth, although the current results about the negative effects of solar radiation in the flowering phase need to be verified and further study is required to clarify possible causes of this effect. Since water is in general a scarce resource in the region, water saving technologies such as deficit irrigation should be considered in maize production in NFR, especially in Songliao (Li *et al.* 2005; Liu *et al.* 2006). In addition, the present results provide a potential irrigation requirement for maize production in each growth phases across NFR. The results clearly show that with the effects of water scarcity on crop yield, priority should be given to irrigation in the crop establishment and flowering phases. The present study also indicated that excessive rainfall had significant negative effects on maize yield in particular in the seeding and flowering phases, which means that maize in the seeding and flowering phases are very sensitive to precipitation. Rainfall has been projected to increase in NFR in the future, and more extreme rainfall events may occur (Zhao & Luo 2007; Piao *et al.* 2010). Therefore, both irrigation and drainage systems should be extensively implemented to enhance or maintain maize production, in particular in the seeding and flowering phases. This may need to be complemented with other adaptation measures such as optimizing crop management and tillage practices to better conserve soil water for crop use.

CONCLUSIONS

During 1961–2010, maize yield increased significantly across NFR. Mean temperature increased significantly in all growth phases over the 50-year period, while solar radiation decreased significantly in southern NFR in all growth phases except in the maturity phase. Effective rainfall increased in the seeding and vegetative phases reducing water deficit over the period, whereas decreasing effective rainfall over time in the flowering and maturity phases enhanced water deficit. Higher drought stress was concentrated in western NFR, where larger volumes of irrigation would be needed in each growth phase. The current results indicate that higher mean temperature in the seeding and maturity phases was beneficial for maize yield, whereas excessive rainfall would damage maize yield, in particular in the seeding and flowering phases. Water deficit in all growth phases would reduce yield, and the effect of drought stress was particularly strong in the seeding and flowering phases, indicating that these periods should be given priority for irrigation.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0021859616000150

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