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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Impacts of climate change on maize and winter wheat yields in China from 1961 to 2010 based on provincial data

C. CHEN[1]*, G. S. ZHOU[2] AND Y. M. PANG[1]

[1] *Institute of Plateau Meteorology, China Meteorological Administration, Chengdu 610072, People's Republic of China*
[2] *Chinese Academy of Meteorological Sciences, Beijing 100081, People's Republic of China*

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SUMMARY

The impacts of climate change on maize and winter wheat yields in China from 1961 to 2010 were studied in the current paper, based on provincial data. The results indicated that rising average temperatures resulted in decreased maize yield in most of the study regions, and reduced maize production at a national scale by *c.* 3·4% relative to the average from 1961 to 2010. Moreover, the warming resulted in a decrease of winter wheat yield in the Huang-Huai-Hai and southwest regions and led to an overall loss in production of *c.* 5·8% at a national scale. The decrease of diurnal temperature range (DTR) affected maize yield adversely in the west and central regions, but a beneficial DTR effect was observed in the other provinces. The changes in DTR resulted in increased maize production at a national scale by *c.* 0·6%. However, the generally decreasing trends for DTR resulted in an increasing winter wheat yield in the northwest and south regions but a decreasing yield in the other provinces, and the production of winter wheat at a national scale was reduced by *c.* 2·9% because of changes in DTR. Changes in precipitation increased maize and winter wheat yields in some provinces but reduced crop yield in others. There was no significant effect of precipitation on maize production at a national scale, but the contribution of precipitation change reached *c.* 1·6% for winter wheat production.

INTRODUCTION

From 1906 to 2005, the earth's average surface temperature rose by 0·74 °C, with the increase in temperature from 1956 to 2005 contributing *c.* 0·65 °C, i.e., the rate of warming over nearly 50 years was almost twice that seen over the last 100 years. In the next 100 years the global average surface temperature may rise by 1·1–6·4 °C (IPCC 2007).

In the past 100 years, China has experienced significant climate change. The average air temperature has increased by 0·5–0·8 °C over the last 100 years in China, which is slightly higher than the global average (Ding *et al*. 2006). During 1951–2001, the average air temperature increased by 1·1 °C in China (Ding *et al*. 2007), and the increase in the average air temperature has been particularly significant since the 1980s (NARCC Committee 2007). The diurnal temperature range (DTR, the difference between the maximum and minimum temperature) shows a downward trend in most areas of China (Liu *et al*. 2004; NARCC Committee 2007), which is because the increase in temperature is greater at night than in the daytime. Precipitation has increased by 10–15% per decade in western China, but decreased in most of northern China. A climatic model has projected that by 2050 the annual mean temperature might rise by 2·3–3·3 °C and precipitation might increase by 5–7% in China (Qin *et al*. 2006).

A number of studies show that climate change has affected crop yields (Chmielewski & Potts 1995; Nicholls 1997; Peng *et al*. 2004; Tao *et al*. 2006, 2008*a*; Schlenker & Roberts 2009; Liu *et al*. 2010; Zhang & Huang 2012) and will influence global crop production now and in the near future (Parry *et al*. 2004; Schmidhuber & Tubiello 2007; Lobell 2007; Lobell *et al*. 2008). Currently, many studies focus on the effects of increasing temperature on

* To whom all correspondence should be addressed. Email: chenchao16306@sina.com

yield. However, the impacts of climate change on crop yields from those studies are very different. Peng *et al.* (2004) reported that increasing the minimum temperature would result in a decrease of rice yield, but Sheehy *et al.* (2006) re-analysed the experimental data of Peng *et al.* (2004) and found that the decrease in rice yield might be a combined effect of increasing minimum temperature and decreasing solar radiation. Therefore, changes in crop yield are the result of interacting climatic factors (Lobell & Oritiz-Monasterio 2007; Zhang *et al.* 2010). Moreover, climate-yield relationships are scale-dependent: large-scale statistical data and regional climate datasets are important for investigating general response patterns of crop production to climate change and variability (Lobell 2007; Lobell *et al.* 2008).

Maize and wheat are the major cereal crops cultivated in China and offer staple foods for the Chinese people. Research on how climate change will influence the yields of maize and wheat in China will be helpful for understanding the potential effects of future climate change and for developing scientific countermeasures. The aim of the present study was to systematically investigate climate-yield relationships and the impacts of climate trends over the last 50 years on maize and winter wheat yields at provincial levels throughout China in a spatially explicit way.

MATERIALS AND METHODS

Study region and data sources

Maize and winter wheat are grown throughout China: the regions studied in the current paper are shown in Fig. 1. Maize was common in most of the area and the majority was cultivated in the summer. Winter wheat occupied a high portion of the area in the north and northwest provinces.

Crop data were obtained from the Data Sharing Infrastructure of Earth System Science (Chinese Academy of Sciences 2011) and China's agricultural statistics (MOAPRC 2009), including provincial yields of maize and winter wheat. Additionally, the growing seasons of maize and winter wheat were derived from the Chinese Agricultural Phenology Atlas (Zhang 1987) (Table 1). The climate data were obtained from the National Meteorological Information Centre, China Meteorological Administration, which included data from 536 weather stations distributed over the study region. Climatic variables included daily

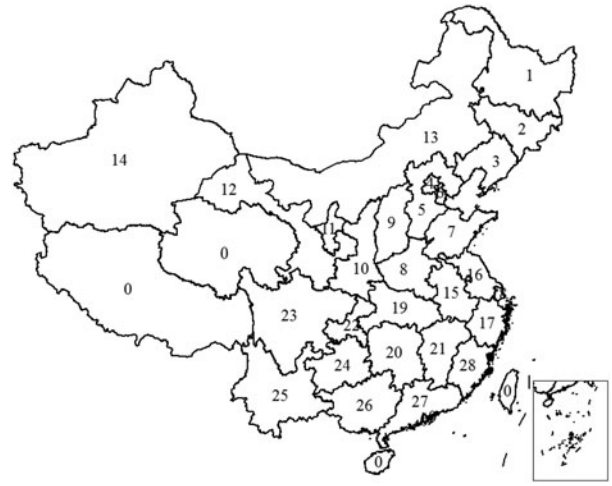

Fig. 1. Distribution of maize and winter wheat cultivation area in China. The provincial ID is numbered as: 0, non-study region; 1, Heilongjiang; 2, Jilin; 3, Liaoning; 4, Beijing; 5, Hebei; 6, Tianjin; 7, Shandong; 8, Henan; 9, Shanxi; 10, Shaanxi; 11, Ningxia; 12, Gansu; 13, Neimenggu; 14, Xinjiang; 15,Anhui; 16, Jiangsu; 17, Zhejiang; 18, Shanghai; 19, Hubei; 20, Hunan; 21, Jiangxi; 22,Chongqing; 23, Sichuan; 24, Guizhou; 25, Yunnan; 26, Guangxi; 27, Guangdong; 28, Fujian.

average temperature (T_{avg}), DTR and precipitation (Prcp). The average of each climate variable during the crop growing season was computed for each province.

To avoid the confounding influence of long-term variations such as changes in variety and crop management, and to focus on the relationships between climatic factors and yield, the climate variables and crop yield were converted to first-difference values by subtracting the prior year's value from each year (Nicholls 1997; Lobell *et al.* 2008).

Winter wheat is grown throughout China, but spring wheat is only grown in Northeast China. Climate-yield relationships were not studied for spring wheat.

Linear time trend

The linear time trend represents the change for each variable (Wei 2007). A simple linear regression equation between X_i and t_i can be expressed as follows:

$$X_i = a + bt_i (i = 1, 2, \ldots, n) \tag{1}$$

where X_i is the variable (e.g. climatic variables), t_i is time corresponding to X_i, n is the number of samples and a and b are regression coefficients. The trend rate of variables is represented by $10 \times b$.

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Table 1. *Growing seasons of maize and winter wheat for different regions of China*

Province	ID*	Maize		Winter wheat	
		Sowing	Harvest	Sowing	Harvest
Northeast					
Heilongjiang	1	May	September		
Jilin	2	May	September		
Liaoning	3	May	September		
North					
Beijing	4	June	September	October	June
Hebei	5	June	September	October	June
Tianjin	6	June	September	October	June
Shandong	7	June	September	October	June
Henan	8	June	September	October	June
Northwest					
Shanxi	9	May	September	October	June
Shaanxi	10	May	September	October	June
Ningxia	11	May	September	October	June
Gansu	12	May	September	October	June
Neimenggu	13	May	September		
Xinjiang	14	May	September	October	June
East					
Anhui	15	June	September	October	June
Jiangsu	16	June	September	November	May
Zhejiang	17	June	September	November	May
Shanghai	18	June	September	November	May
Centre					
Hubei	19	June	September	November	May
Hunan	20	June	September	November	May
Jiangxi	21	June	September	November	May
Southwest					
Chongqing	22	June	September	November	April
Sichuan	23	June	September	November	April
Guizhou	24	June	September	November	April
Yunnan	25	June	September	November	April
South					
Guangxi	26	March	August	November	March
Guangdong	27	March	August	November	March
Fujian	28	March	August	November	April

* ID corresponds to the numbers shown in Fig. 1.

Effects of climate variables on yield

To avoid the confounding influence of long-term variations such as changes in crop management, and to focus on the relationships between climatic factors and yield, the climate variables (T_{avg}, DTR and Prcp) and crop yield (Yield) were converted to first-difference values by subtracting the prior year's value from each year (Nicholls 1997; Lobell *et al*. 2008). A multiple linear regression model could be used to compute the climate-yield relationship with the first-difference values of the climate variables (ΔT_{avg}, ΔDTR and $\Delta Prcp$) as explanatory variables and yield ($\Delta Yield$) as the response variable:

$$\Delta Yield = \beta_o + \beta_{T_{avg}} \Delta T_{avg} + \beta_{DTR} \Delta DTR + \beta_{Prep} \Delta Prep + \varepsilon \quad (2)$$

where $\Delta Yield$, ΔT_{avg}, ΔDTR and $\Delta Prcp$ represent the first difference values of crop yield and growing season climate variables; β_o represents the model intercept; β_{Tavg}, β_{DTR} and β_{Prcp} represent the regression

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coefficients for climate variables; ε represents the model error.

To evaluate the percentage yield change for each additional climate variable, the percent regression coefficients were calculated using Eqn (3):

$$\beta_{\text{percent}} = \frac{\beta}{Mean_{\text{Yield}}} \quad (3)$$

where β and β_{percent} represent absolute and percent regression coefficients of certain climate variables (ΔT_{avg}, ΔDTR and $\Delta Prcp$), respectively. $Mean_{\text{Yield}}$ represents the mean crop yield in 1961–2010.

RESULTS

Climate change and variability during the maize and winter wheat growing seasons

Maize

Table 2 illustrates the average and linear time trend in climate during the maize growing season for the period 1961–2010. The average (T_{avg}) for the maize growing season was >17 °C in China over this period with the highest values in the areas of central and east China. There were general warming trends in most regions, and the warming was more significant in northern parts of China than in southern parts during the maize growing season from 1961 to 2010. Spatial distribution characteristics of the average DTR showed as a band, gradually increasing from the southeast to the northwest. There were general decreasing trends for DTR in most regions with a rate of −0·39 to 0 °C per decade during this period. For Prcp, spatial distribution characteristics of the average Prcp was also revealed as a band, gradually increasing from the northwest to the southeast. The Prcp showed an increasing trend in the south, central, east and Xinjiang regions and a decreasing trend in other provinces over the period.

Winter wheat

Table 3 illustrates the average and linear time trends in climate during the winter wheat growing season over the period 1961–2010. The average T_{avg} for the winter wheat growing season was >3 °C in China during this period with the highest values occurring in the areas of south China. There were general warming trends in the entire study region with a rate of 0 to 0·53 °C per decade in the winter wheat growing season from 1961 to 2010. The spatial distribution characteristics for average DTR showed as a band, gradually increasing from the southeast to the northwest. There were general decreasing trends for DTR in most regions with a rate of −0·47 to 0 °C per decade during this period. The spatial distribution characteristics of the average Prcp also showed as a band, this time gradually increasing from north to south. The Prcp showed an increasing trend in the north, east, south and Xinjiang regions of China and a decreasing trend in other provinces during the study period.

Effects of climate change on maize and winter wheat yields

Maize

Figure 2 shows the effects of climate variables on maize yield in China from 1961 to 2010. A positive value of the percent regression coefficient indicates a coincident pattern between the climate variables and yield, and a negative value reflects the opposite response of yield to additional climate variables.

The T_{avg} showed a negative effect on yields in most regions of China: each additional 1 °C in T_{avg} decreased maize yields by 0–17%. However, the provinces in the northeast and northwest regions showed a positive effect ranging between 0 and 7·5%/°C (Fig. 2(*a*)). The regions with increasing DTR included a number of provinces in the northeast, north, east and southwest regions with 0–22·4% yield loss for each additional degree celsius of DTR, while several provinces in the northwest and south showed a positive effect with 0–7% yield increases per 1 °C increase of DTR (Fig. 2(*b*)). As for Prcp, yield increases were associated with a higher Prcp in parts of northwest, north, Sichuan, Yunnan and Zhejiang, with 0–6·5% increases seen for Prcp increases of 100 mm, while the effects were negative in the south, central and northeast , varying between 0 and 7·3% yield loss per 100 mm (Fig. 2(*c*)).

The regression coefficients calculated with actual trends of T_{avg}, DTR and Prcp at the provincial level were used to evaluate the relative production change caused by climate variables over the period 1961–2010.

The warming caused a 0–13% reduction in maize production in most regions from 1961 to 2010. However, increased production of *c.* 0–11·6% was seen in the northeast, northwest and Guangxi

Table 2. *Average and linear time trend in climate during the maize growing season over the period 1961–2010*

		T_{avg}*			DTR†			Prcp‡		
Province	ID	Average (°C)	Trend (°C /10 year)	*P*	Average (°C)	Trend (°C /10 year)	*P*	Average (mm)	Trend (mm/10 year)	*P*
Northeast										
Heilongjiang	1	17·4	0·31	<0·001	11·9	−0·22	<0·001	433	−6·5	NS
Jilin	2	18·3	0·25	<0·001	11·6	−0·21	<0·001	503	−7·0	NS
Liaoning	3	20·5	0·18	<0·001	10·2	−0·15	<0·01	557	−12·3	NS
North										
Beijing	4	24·0	0·37	<0·001	10·2	−0·39	<0·001	442	−32·2	<0·05
Hebei	5	22·5	0·23	<0·001	10·9	−0·22	<0·001	410	−21·1	<0·05
Tianjin	6	24·5	0·18	<0·01	8·0	0·09	NS	444	−30·7	<0·05
Shandong	7	23·3	0·11	<0·05	8·3	−0·10	<0·05	498	−16·4	NS
Henan	8	24·6	−0·03	NS	9·7	−0·25	<0·001	477	9·9	NS
Northwest										
Shanxi	9	20·1	0·20	<0·001	12·8	0·02	NS	376	−11·3	NS
Shaanxi	10	20·7	0·15	<0·01	10·8	−0·05	NS	485	−5·4	NS
Ningxia	11	18·7	0·28	<0·001	12·8	−0·18	<0·01	229	−6·9	NS
Gansu	12	17·5	0·27	<0·001	13·2	−0·05	NS	232	−4·3	NS
Neimenggu	13	17·8	0·36	<0·001	13·4	−0·22	<0·001	255	−4·4	NS
Xinjiang	14	19·7	0·22	<0·001	14·3	−0·24	<0·001	98	4·5	<0·01
East										
Anhui	15	25·1	0·08	NS	8·2	−0·23	<0·001	626	16·8	NS
Jiangsu	16	25·3	0·14	<0·05	7·4	−0·18	<0·001	602	6·9	NS
Zhejiang	17	26·0	0·20	<0·001	6·8	0·02	NS	633	28·3	<0·05
Shanghai	18	22·6	0·43	<0·001	7·2	−0·11	<0·05	752	38·5	<0·05
Centre										
Hubei	19	25·7	0·07	NS	8·5	−0·11	NS	606	5·0	NS
Hunan	20	25·9	0·05	NS	8·1	−0·16	< 0·001	581	15·0	NS
Jiangxi	21	26·5	0·02	NS	8·5	−0·19	< 0·001	665	23·6	NS
Southwest										
Chongqing	22	25·4	0·10	NS	8·4	0·01	NS	657	−3·9	NS
Sichuan	23	19·3	0·14	<0·001	9·9	−0·04	NS	639	−7·9	NS
Guizhou	24	22·7	0·08	NS	8·5	−0·14	< 0·01	646	−0·6	NS
Yunnan	25	20·9	0·14	<0·001	8·5	−0·06	NS	747	−12·8	NS
South										
Guangxi	26	24·4	0·10	<0·05	7·3	−0·05	NS	1239	3·0	NS
Guangdong	27	24·9	0·13	<0·01	7·1	−0·06	NS	1325	28·9	NS
Fujian	28	22·1	0·13	<0·01	8·0	−0·07	NS	1148	20·0	NS

* T_{avg} represents average temperature.
† DTR represents diurnal temperature range.
‡ Prcp represents precipitation.

regions (Fig. 3(*a*)). For DTR, the decreasing trends in most regions resulted in decreased production (*c.* −8·2 to 0%) in the west and central regions, while several provinces in the northeast, north, east and southwest showed increased production with values of *c.* 0–21% (Fig. 3(*b*)). For Prcp, the changes increased production by 0–4·5% in the northeast, Xinjiang, Zhejiang and Guizhou regions, while the changes in other provinces decreased production by −5·3 to 0% (Fig. 3(*c*)).

Table 4 illustrates the average percent regression coefficients of climate variables and production

Table 3. *Average and linear time trend in climate during winter wheat growing season over the period 1961–2010*

		T_{avg}*			DTR†			Prcp‡		
Province	ID	Average (°C)	Trend (°C /10 year)	*P*	Average (°C)	Trend (°C /10 year)	*P*	Average (mm)	Trend (mm/10 year)	*P*
North										
Beijing	4	8·5	0·52	<0·001	11·1	−0·47	<0·001	181	10·4	NS
Hebei	5	6·4	0·36	<0·001	12·1	−0·32	<0·001	186	5·1	NS
Tianjin	6	8·7	0·32	<0·001	9·0	0·10	<0·05	188	11·5	<0·05
Shandong	7	8·7	0·31	<0·001	9·3	−0·13	<0·001	271	−1·1	NS
Henan	8	11·0	0·25	<0·001	10·7	−0·12	<0·05	362	−6·8	NS
Northwest										
Shanxi	9	5·5	0·32	<0·001	13·3	0·05	NS	188	−3·6	NS
Shaanxi	10	8·2	0·28	<0·001	11·0	0·09	NS	303	−11·6	<0·01
Ningxia	11	4·4	0·41	<0·001	13·3	−0·16	<0·01	113	−2·0	NS
Gansu	12	3·9	0·35	<0·001	13·2	−0·03	NS	130	−0·8	NS
Xinjiang	14	3·3	0·36	<0·001	13·0	−0·27	<0·001	90	5·8	<0·001
East										
Anhui	15	10·1	0·32	<0·001	9·2	−0·09	NS	542	−6·7	NS
Jiangsu	16	9·0	0·37	<0·001	8·6	−0·16	<0·01	376	0·9	NS
Zhejiang	17	11·5	0·32	<0·001	7·2	0·06	NS	663	3·5	NS
Shanghai	18	8·9	0·53	<0·001	7·4	−0·22	<0·001	381	10·5	NS
Centre										
Hubei	19	10·8	0·29	<0·001	8·5	0·04	NS	483	−7·1	NS
Hunan	20	11·5	0·23	<0·001	7·4	−0·01	NS	752	−10·2	NS
Jiangxi	21	12·3	0·20	<0·001	8·1	−0·06	NS	917	−0·1	NS
Southwest										
Chongqing	22	10·6	0·21	<0·001	6·5	0·00	NS	274	−7·8	NS
Sichuan	23	8·1	0·22	<0·001	12·0	−0·18	<0·001	146	1·5	NS
Guizhou	24	9·8	0·15	<0·05	7·7	−0·15	<0·05	246	−7·6	NS
Yunnan	25	12·7	0·25	<0·001	13·3	−0·21	<0·001	181	2·0	NS
South										
Guangxi	26	14·8	0·17	NS	7·4	−0·06	NS	246	2·4	NS
Guangdong	27	16·0	0·24	<0·01	8·0	−0·12	NS	267	2·3	NS
Fujian	28	13·1	0·21	<0·01	8·2	−0·09	NS	560	10·4	NS

* T_{avg} represents average temperature.
† DTR represents diurnal temperature range.
‡ Prcp represents precipitation.

change caused by climate variables for maize in the whole study region from 1961 to 2010. The results showed that a negative T_{avg} effect of −3·8%/°C (95% CI of −7·4 to −0·2%/°C), and a yield decrease of 0·8% for per degree increase of DTR with 95% CI of −7·3 to 5·6%/°C. On average, the Prcp effect reached 5·5% per additional 100 mm (1·0–10·0% per 100 mm with 95% CI).

The regression coefficients calculated with actual trends of T_{avg}, DTR and Prcp at the national scale were used to evaluate the relative production change and actual production change caused by climate variables in the whole study region over the period 1961–2010. For maize, T_{avg} caused decreased production with values of *c.* −3·4% (95% CI of −6·5 to −0·2%), and the actual production change was *c.* −114·0 kg/hm^2 (95% CI of −220·7 to −7·2 kg/hm^2). The production was increased by *c.* 0·6% (95% CI of −4·0 to 5·2%) as the result of changes in DTR, and the actual production change reached *c.* 20·3

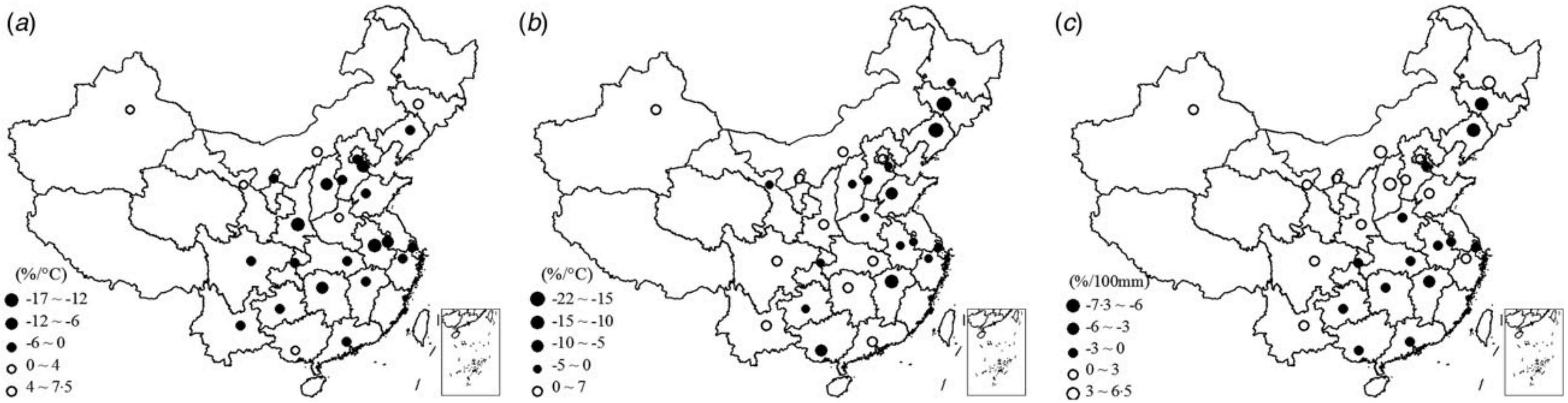

Fig. 2. Percent regression coefficients of (*a*) T_{avg}, (*b*) DTR and (*c*) and Prcp on maize yield over the period 1961–2010.

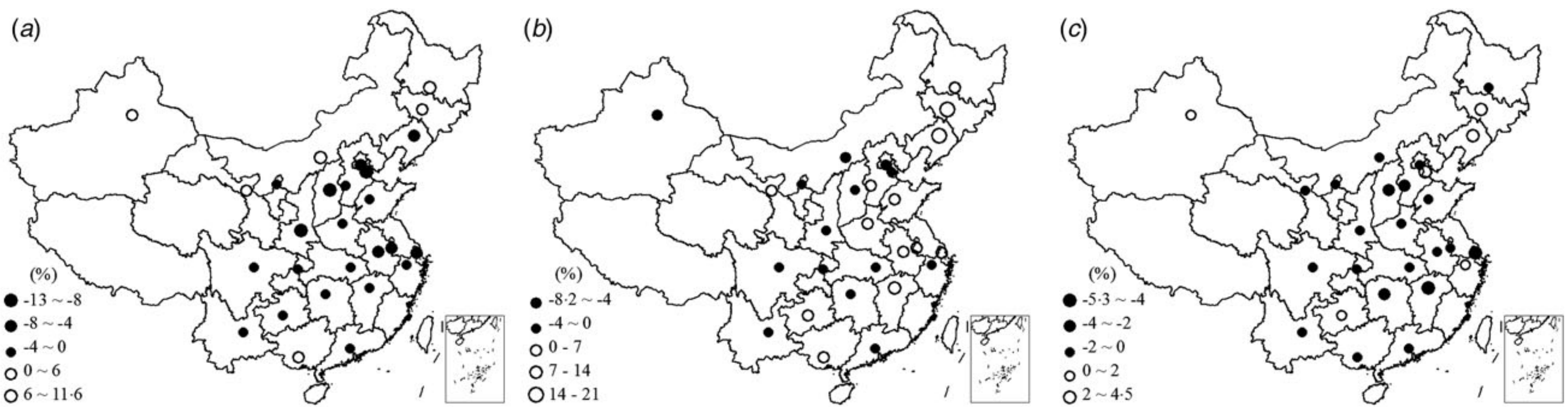

Fig. 3. Relative production change caused by (*a*) T_{avg}, (*b*) DTR and (*c*) Prcp for maize over the period 1961–2010.

Table 4. *Average percent regression coefficients of climate variables and 95% confidence interval(CI), average production change and 95% CI caused by climate variables for maize over 1961–2010*

Climate variable	Percent regression coefficient		Relative production change (%)		Actual production change (kg/hm^2)	
	Average	95% CI	Average	95% CI	Average	95% CI
ΔT_{avg}	−3·8%/°C	−7·4 to −0·2%/°C	−3·4	−6·5 to −0·2	−114·0	−220·7 to −7·2
ΔDTR	−0·8%/°C	−7·3 to 5·6%/°C	0·6	−4·0 to 5·2	20·3	−135·8 to 176·4
ΔPrcp	5·5%/100 mm	1·0 to 10·0%/100 mm	0	−0·1 to 0	−0·9	−1·7 to −0·2

kg/hm^2 (95% CI of −135·8 to 176·4 kg/hm^2). However, the effect of Prcp on maize production was not significant at the national scale (Table 4).

Winter wheat

Figure 4 shows the percent regression coefficients of T_{avg}, DTR and Prcp on the yield of winter wheat in China from 1961 to 2010. The results showed a negative effect of increasing temperature on yield in the north and southwest of China: each additional 1 °C of T_{avg} decreased winter wheat yield by 0–7·6%. However, the provinces in the west and central regions showed a positive effect ranging between 0 and 7·7%/°C (Fig. 4(*a*)). The changes in DTR led to higher yield in most regions except Xinjiang and Jiangxi, varying between −3·6 and 10·0% yield increase per degree (Fig. 4(*b*)). For Prcp, yield increases were associated with a higher Prcp in most areas, with 0–13·6% increases for a 100 mm increase in Prcp (Fig. 4(*c*)).

The increase in T_{avg} decreased winter wheat production by −10·5 to 0% in the Huang-Huai-Hai and southwest regions from 1961 to 2010. However, the increase in T_{avg} in the northwest and central regions caused an increased production with values of *c*. 0–13·6% (Fig. 5(*a*)). For DTR, the general decreasing trend resulted in increased production with values of *c*. 0–2·7% in the northwest and south regions, while other provinces of the study region showed decreasing production with values of *c*. −14·2 to 0% (Fig. 5(*b*)). For Prcp, the changes resulted in increased production by 0–1·6% in the north, Sichuan, Guizhou, Shanghai and Jiangsu, while changes in other provinces decreased production by −5·7 to 0% (Fig. 5(*c*)).

Table 5 illustrates the average percent regression coefficients of climate variables and production change caused by climate variables for winter wheat in the study region from 1961 to 2010. The results showed a negative T_{avg} effect of −2·5%/°C (95% CI of −5·8 to 0·7%/°C), but a yield increase of 3·9% for per degree increase of DTR with 95% CI of −1·4 to 9·2%/°C. On average, the Prcp effect reached *c*. 7·5% with per additional 100 mm (3·4–11·6% per 100 mm with 95% CI).

For winter wheat, T_{avg} caused a decrease in production with values of *c*. −5·8% (95% CI of −13·1 to 1·6%), and the actual production change reached *c*. −138·5 kg/hm^2 (95% CI of −316·5 to 39·5 kg/hm^2). Production was reduced by *c*. −2·9% (95% CI of −7·0 to 1·1%) because of changes in DTR, and the actual production change reached *c*. −70·8 kg/hm^2 (95% CI of −167·2 to 25·6 kg/hm^2). Production improved by *c*. 1·6% (95% CI of 0·7–2·4%) due to the changes of Prcp, and the actual production change was *c*. 37·3 kg/hm^2 (95% CI of 16·8–57·8 kg/hm^2) (Table 5).

DISCUSSION

The present study shows the general response patterns of agricultural productivity to climate change; however, the key response mechanisms still need to be researched further. The physiological mechanisms by which climate variables may affect crop yields have been partly revealed (Matsui & Horie 1992; Tao *et al*. 2006, 2008*b*). Global warming may have harmful or beneficial impacts on crop production in low or high latitude areas, depending on whether the current temperature is generally more or less than the optimal temperature for crop production (IPCC 2001). This mechanism underlies crop response patterns to temperature change in the current paper. Taking maize as an example, the present study showed that growing season average temperature was positively related to maize yield in some provinces of the northeast and northwest regions. This suggests that the present growing season average temperature might be in the optimal temperature

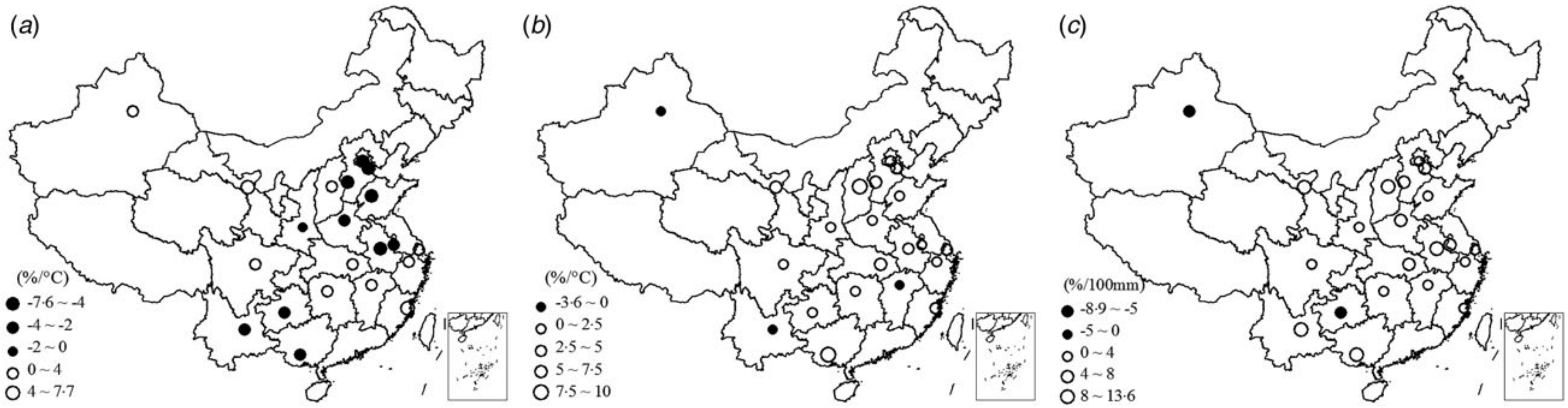

Fig. 4. Percent regression coefficients of (*a*) T_{avg}, (*b*) DTR and (*c*) Prcp on the winter wheat yield over the period 1961–2010.

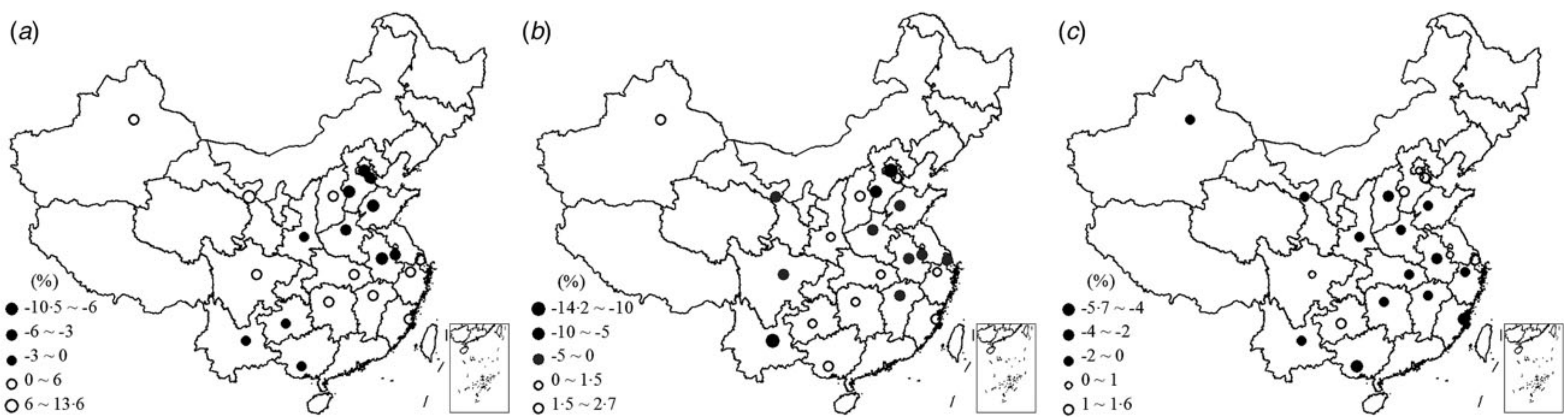

Fig. 5. Relative production change caused by (*a*) T_{avg}, (*b*) DTR and (*c*) Prcp for winter wheat over the period 1961–2010.

Table 5. *Average percent regression coefficients of climate variables and 95% confidence interval (CI), average production change and 95% CI caused by climate variables for winter wheat over 1961–2010*

	Percent regression coefficient		Relative production change (%)		Actual production change (kg/hm^2)	
Climate variable	Average	95% CI	Average	95% CI	Average	95% CI
ΔT_{avg}	−2·5%/°C	−5·8 to 0·7%/°C	−5·8	−13·1 to 1·6	−138·5	−316·5 to 39·5
ΔDTR	3·9%/°C	−1·4 to 9·2%/°C	−2·9	−7·0 to 1·1	−70·8	−167·2 to 25·6
ΔPrcp	7·5%/100 mm	3·4 to 11·6%/100 mm	1·6	0·7 to 2·4	37·3	16·8 to 57·8

range for maize production and maize yield could be increased due to a warming trend, which is consistent with some recent research (Yang *et al*. 2008; Liu *et al*. 2010). In contrast, maize yield in most of the study regions showed a negative relationship with growing season average temperature, suggesting that the present average temperature is at or above the optimum for maize production and that yield could be reduced due to a warming trend, which is consistent with other studies (Peng *et al*. 2004; Tao *et al*. 2006; Sheehy *et al*. 2006).

Evaluation of the effects of climate change on maize and winter wheat yields should consider the effects of all climatic factors (Lobell & Oritiz-Monasterio 2007; Zhang *et al*. 2010). Firstly, the impact of DTR was bilateral. An increase in DTR during the growing season, which has warming days and cooling nights, is beneficial for crop growth because warming days will increase photosynthetic rate and cooling nights will reduce the respiration rate (Leopold & Kriedemann 1975). However, an increase in DTR may also reduce yield because the associated increase in maximum temperature results in reductions in net photosynthetic rates or increasing water stress (Dhakhwa & Campbell 1998; Tao *et al*. 2006). In the present study, the decreases in DTR during the growing season increased maize production on a national level by causing a decrease in cold damage, but decreases in DTR during the growing season reduced winter wheat production at a national level by causing an increase in night-time maintenance respiration rates (Ryan 1991) and consequently biomass consumption. Secondly, precipitation during the maize growing season had a negative relationship with yield in most areas of southern China, but a positive relationship with yield in most regions of northern China. These results were consistent with the ground truth in the past few decades. In southern China, the climate is humid and too much precipitation often occurs during the maize growing season leading to yield losses from insects, disease and insufficient sunshine (Tao & Yokozawa 2005). In northern China, the climate is arid and semi-arid; water stress is the most important limiting factor for rainfed crop yields (Tao *et al*. 2003).

Uncertainties of the results as mentioned above may come from several sections. Firstly, the data in the present study are from the provincial scale over 50 years. However, research using data collected on different spatial or temporal scales may give different conclusions (Tao *et al*. 2006; Liu *et al*. 2012). Therefore, research on the response of crop yield to changes in climatic factors should be extended to these different spatial and temporal scales. Secondly, it is very difficult to fully consider the effects of technology and management, as well as weather variability, disease, insects, etc., occurring in the five decades of observations. To some extent, the effects could disturb the results of trend analysis. For instance, crop yields may have increased because of the increasing use of modern technology and newer higher yielding cultivars during the study period. If so, the changes in crop productivity resulting from climate change may actually be larger or smaller than those estimated in the present study. In addition, the effects of extreme climatic conditions (high and low temperatures, and floods) on crop yield are not considered in the present study. With the increasing frequency of extreme climate events and frequent agricultural meteorological disasters, research on the effects of extreme climate events on crop production should be emphasized in the future.

CONCLUSIONS

The present study revealed the evidence of climatic effects on maize and winter wheat over 1961–2010 and highlighted the changes in maize and winter wheat production because of the past warming trend using climatic and crop data in China at the provincial level.

Results indicated that warming trends were observed over 1961–2010 during maize and winter wheat growing seasons. The warming resulted in a decrease of maize yield in most of the study regions but an increasing yield in the northeast, northwest and Guangxi regions: the increases in T_{avg} reduced maize production on average by *c.* 3·4% for the whole country. Moreover, the warming adversely affected winter wheat yield in the Huang-Huai-Hai and southwest regions and produced an overall loss in production at a national scale by *c.* 5·8%.

There were general decreasing trends for DTR in most regions over 1961–2010 in maize and winter wheat growing seasons. It was found that decreases in DTR during the growing season adversely affected maize yield in the west and central regions but a beneficial DTR effect was observed in the northwest, north, east and southwest regions: the changes in DTR resulted in an increased production on average by up to approximately 0·6% for maize in the whole study region. However, the general decreasing trends for DTR resulted in an increasing winter wheat yield in the northwest and south regions but a decreasing yield in other provinces. The production of winter wheat at a national scale was reduced by *c.* 2·9% because of changes in DTR.

For precipitation, there was an increasing trend in some provinces but a decreasing trend in other provinces during the maize and winter wheat growing seasons. Results indicated that the change in precipitation increased maize yield in the northeast, Xinjiang, Zhejiang and Guizhou regions but caused decreasing yield in other regions. There was no significant effect of precipitation on maize production at a national scale over the period 1961–2010. However, the change in precipitation increased winter wheat yield in the north, Sichuan, Guizhou, Shanghai and Jiangsu but caused decreased yield in other provinces, and the increasing average production reached *c.* 1·6% due to changes of precipitation in the whole study region.

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