Comparison of the Impacts of Climate Change on Potential Productivity of Different Staple Crops in the Agro-Pastoral Ecotone of North China

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ABSTRACT

The aim of this study is to compare the impacts of climate change on the potential productivity and potential productivity gaps of sunflower (*Helianthus annuus*), potato (*Solanum tuberosum*), and spring wheat (*Triticumaestivum* Linn) in the agro-pastoral ecotone (APE) of North China. A crop growth dynamics statistical method was used to calculate the potential productivity affected by light, temperature, precipitation, and soil fertility. The growing season average temperature increased by 0.47, 0.48, and 0.52℃ per decade (p < 0.05) for sunflower, potato, and spring wheat, respectively, from 1981 to 2010. Meanwhile, the growing season solar radiation showed a decreasing trend ($p < 0.05$) and the growing season precipitation changed non-significantly across APE. The light–temperature potential productivity increased by 4.48% per decade for sunflower but decreased by 1.58% and 0.59% per decade for potato and spring wheat. The climate–soil potential productivity reached only 31.20%, 27.79%, and 20.62% of the light–temperature potential productivity for sunflower, potato, and spring wheat, respectively. The gaps between the light–temperature and climate–soil potential productivity increased by 6.41%, 0.97%, and 1.29% per decade for sunflower, potato, and spring wheat, respectively. The increasing suitability of the climate for sunflower suggested that the sown area of sunflower should be increased compared with potato and spring wheat in APE under future climate warming.

Key words: crop potential productivity, climate warming, sunflower, potato, spring wheat, soil fertility

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1. Introduction

The agro-pastoral ecotone (APE) of North China is distributed across seven provinces and autonomous regions, and represents an intersection and transition zone of traditional agriculture and animal husbandry (Wu, 2003; Liu et al., 2009). The annual average precipitation of APE is less than 400 mm, with high interannual variability (Wang et al., 1999). Water shortage is a major limiting factor for crop production in APE (Zhao and Qiu, 2001; Pan et al., 2010; Xia et al., 2010), and soil fertility has also limited the level of improvement in crop yields due to poor soil conditions in the area (Zhang et al., 2011; Yang and Liu, 2014). How to increase the rainfall use efficiency and ensure stable crop yields under the warming climate is a key problem for agricultural production in APE(Hu et al., 2015). For several decades, growing more than one crop in a season in different fields has been a commonly applied cropping system method in this area, aimed at reducing the production risk of only planting a single crop in a large region (Duan et al., 2013; Hou et al., 2013). Staple crops in APE include sunflower (*Helianthus annuus*), potato (*Solanumtuberosum*), and spring wheat (*Triticumaestivum* Linn), which occupy 15.60%, 46.80%, and 24.40% of the total grain yield

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in this area, respectively. In recent years, the sown area of potato and sunflower has been increasing because of higher yields and drought tolerance compared with spring wheat (Hou et al., 2009). However, the climate adaptability of these three crops against the climate change background has rarely been investigated. Due to its unique geographical location and climate conditions, APE is highly sensitive to climate change, which has had significant impacts on crop production in this region (Qiu et al., 2001, Dong et al., 2012). Determining the impact of climate change on the potential productivity of staple crops can help in our understanding of the yield-limiting factors involved, as well as guide appropriate measures to adapt to climate change (Wang et al., 2014). Crop potential productivity can be classified into four levels: photosynthetic, light–temperature, climate, and climate–soil potential productivity limited by light, light–temperature, light–temperature–precipitation, and light–temperature–precipitation–soil fertility under the control of insect pests and weeds, and optimal agricultural management (Huang, 1985; Li et al., 2010; Yuan et al., 2012; He et al., 2014). The gaps between the light–temperature and climatic potential productivity, the climate and climate–soil potential productivity reflect the yield loss due to water stress and soil fertility stress (He et al., 2014). A large number of studies have investigated crop potential productivity and potential productivity gaps by using mechanism-based empirical methods (Higgins et al., 1982; Ma and Guo, 1995; Wang et al., 2005; He et al., 2014), crop growth models (Lobell and Ortiz-Monasterio, 2006; Wang et al., 2012), and field experiments (Lobell et al., 2009).

In Northeast China, climate change has a negative impact on maize potential yield (Liu Z. J. et al., 2013; Lü et al., 2015). In the North China Plain, increased temperature and decreased radiation have led to a decrease in the potential yield of winter wheat and summer maize (Wang et al., 2012, 2014). In South China, the rice potential yield showed a decreasing trend between the 1980s and 2000s due to climate change (Liu L. L. et al., 2013). In Southwest China (SWC), the light–temperature and climatic potential productivity of maize has increased in the southwest of SWC but decreased in the northeast of SWC, caused by climate change, during the maize growing season (He et al., 2014).

In contrast to the well-studied main grain production regions, the impacts of climate change on the potential productivity and productivity gaps of staple crops in APE remain almost untouched. Quantifying the potential productivity and productivity gaps of staple crops could help determine, in a targeted approach, the space and plant structure distribution required for certain crops in APE. Therefore, the objective of this study was to compare the spatiotemporal changes in climate variables during the crop growing season and their effects on the potential productivity, potential productivity gaps, and climate suitability of staple crops in APE during 1981–2010.

2. Materials and methods

2.1 Study sites and data

Twenty-seven sites roughly uniformly distributed across APE were selected for this study (Fig. 1). Staple crops at these sites include sunflower, potato, and spring wheat, with a single crop in one year. Climate data, including daily maximum temperature, minimum temperature, air pressure, precipitation, and sunshine hours were available from the China Meteorological Administration. Daily solar radiation was estimated from daily sunshine hours based on the Ångström equation (Wang et al., 2015). The major phenological phases of crops, including sowing, seedling, flowering, and maturity dates were recorded at the 12 agro-meteorological observation sites (Fig. 1), which were measured by well-trained agricultural technicians following a standardized observation method across the sites. The dates of the major phenological phases at other sites were based on the nearest agro-meteorological observation sites (Table 1).

Soil data for each site, including soil type, soil organic carbon content, soil edaphic volume, level of gleyzation, level of pseudo-gleyzation, etc., were obtained from National Soil Survey Data (http://www.soil.csdb.cn/).

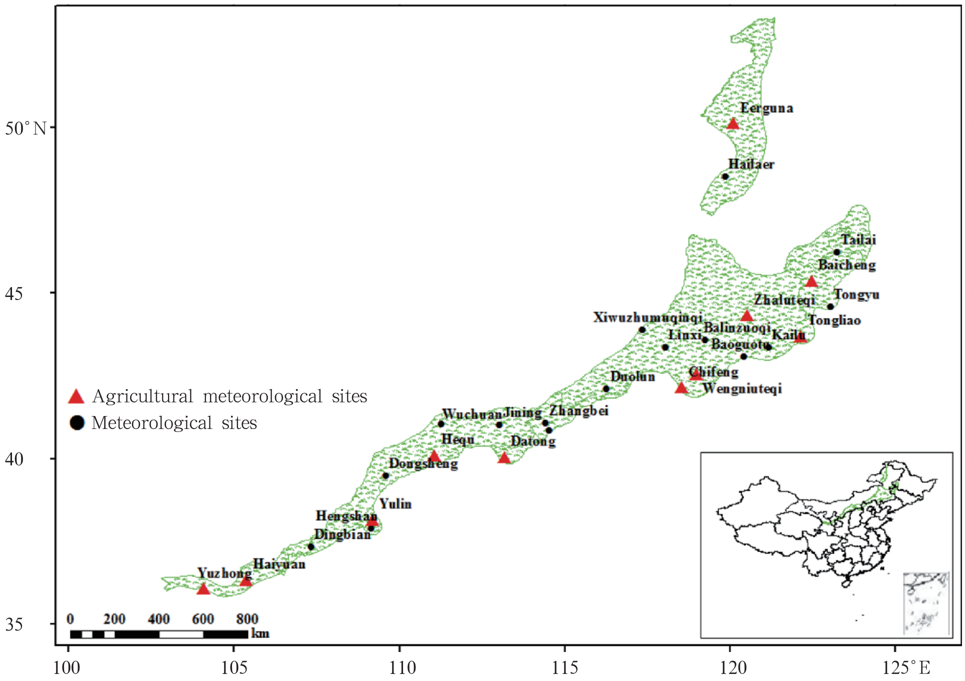

Fig. 1. The agro-pastoral ecotone (APE) region and the distribution of study sites.

2.2 Calculation of crop potential productivity

The photosynthetic, light–temperature, and climate–soil potential productivity of the staple crops in APE were calculated by using a crop growth dynamics statistical method (He et al., 2014). In order to compare with reported crop yields, the calculated crop potential productivity was converted to crop yield with a moisture content of 80% for potato, 9% for sunflower, and 13% for spring wheat.

2.2.1 Photosynthetic potential productivity

Photosynthetic potential productivity (YQ, 10^3 kg ha^{-1}) is the theoretical crop maximum productivity, which is calculated as follows (He et al., 2014):

$$\mathrm{YQ}=\sum_{j=1}^{4}\left(\sum_{i=1}^{\mathrm{gd}_j}(0.219\times C\times R_{\mathrm{s},i})\right), \tag{1}$$

where 0.219 is the Huang Bingwei coefficient (10^{-5} kg kJ^{-1}); C is the crop economic coefficient, taking the values of 0.39, 0.87, and 0.46 for sunflower, potato, and spring wheat, respectively (Zhang and Zhu, 1990); j represents each crop development stage; and gd_j is the length of each development stage for crop (Table 1). $R_{\mathrm{s},i}$ (kJ cm^{-2} day^{-1}) is the daily shortwave radiation during the crop growing season, which is calculated as

$$R_{\mathrm{s},i}=(a_{\mathrm{s}}+b_{\mathrm{s}}\frac{n_i}{N_i})R_{\mathrm{a},i}, \tag{2}$$

where $R_{\mathrm{a},i}$ (kJ cm^{-2} day^{-1}) is the daily extraterrestrial radiation; n_i (h) is the daily actual duration of sunshine; N_i (h) is the daily maximum possible duration of sunshine; and a_{s}=0.25 and b_{s}=0.50 are used for the estimation of $R_{\mathrm{s},i}$, as recommended by Allen et al. (1998).

2.2.1 Light–temperature potential productivity

Light–temperature potential productivity (YT) is calculated by correcting the photosynthetic potential productivity with the temperature stress coefficient as follows:

$$\mathrm{YT}=\sum_{j=1}^{4}\sum_{i=1}^{\mathrm{gd}_j}(0.219\times C\times R_{\mathrm{s},i}\times f(t_i)), \tag{3}$$

where $f(t_i)$ is the temperature stress coefficient, which can be calculated as follows (Li et al., 2010):

$$f(t_i)=\begin{cases}0 & t_i<t_{\mathrm{b}},t_i>t_{\mathrm{c}}\\ \frac{t-t_{\mathrm{b}}}{t_{\mathrm{o}}-t_{\mathrm{b}}} & t_{\mathrm{b}}\leqslant t_i<t_{\mathrm{o}}\\ \frac{t_{\mathrm{c}}-t}{t_{\mathrm{c}}-t_{\mathrm{o}}} & t_{\mathrm{o}}\leqslant t_i\leqslant t_{\mathrm{c}}\end{cases}, \tag{4}$$

Table 1. The major phenological phases of the three crops in the APE region of North China

	Sowing date			Initial stage (day)			Development (day)			Middle stage (day)			Late stage (day)			Length of the growing season (day)		
Site	SF	PT	SW	SF	PT	SW	SF	PT	SW	SF	PT	SW	SF	PT	SW	SF	PT	SW
Wuchuan, Hequ, Dongsheng, Jining	May 10	May 15	Apr 20	25	30	25	30	35	20	50	40	35	25	35	25	130	140	105
Chifeng, Baoguotu, Balinzuoqi	May 20	May 1	Apr 30	25	30	20	35	30	25	55	40	30	20	30	35	135	130	120
Haiyuan, Yuzhong	May 5	Apr 25	Apr 15	30	35	30	30	25	20	45	30	35	25	35	25	130	125	110
Tongliao, Kailu, Tailai, Tongyu, Hailaer, Eerguna, Zhalute	May 25	May 15	May 1	30	30	20	30	35	25	45	45	25	35	30	25	135	130	105
Wengniuteqi, Linxi, Xiwuzhumuqin, Baicheng	May 20	May 10	Apr 15	25	30	20	35	30	25	50	45	30	20	35	20	130	140	110
Yulin, Hengshan, Dingbian	May 15	May 20	Apr 10	25	35	25	25	35	35	50	50	35	25	25	20	125	135	115
Zhangbei, Datong, Zhangjiakou, Duolun	May 15	May 10	May 1	30	35	20	30	40	25	50	35	30	25	20	25	135	130	110

Notes: SF, sunflower; PT, potato; SW, spring wheat.

Table 2. The cardinal temperatures (℃) for the three crops

	Initial stage			Development			Middle stage			Late stage		
	SF	PT	SW	SF	PT	SW	SF	PT	SW	SF	PT	SW
$t_{\rm b}$	5.0	2.0	3.5	8.0	8.0	4.0	8.0	8.0	9.5	8.0	8.0	9.2
$t_{\rm o}$	29.0	18.0	22.0	31.0	18.0	25.0	31.0	18.5	21.0	31.0	18.0	21.0
$t_{\rm c}$	37.0	34.0	33.0	37.0	34.0	32.0	37.0	34.0	31.0	37.0	34.0	36.0

where t_i is the daily average temperature (℃); and $t_{\rm b}$, $t_{\rm o}$, and $t_{\rm c}$ are the base, optimum, and ceiling temperatures, respectively, of each growing stage for the crops (Table 2; Porter and Gawith, 1999; Gou et al., 2012).

2.2.2 Climate–soil potential productivity

Climate–soil potential productivity (YW) is calculated by correcting the light–temperature potential productivity with the water stress coefficient and soil stress coefficient as follows (Li et al., 2010):

$$\begin{aligned}{\rm YW} = &\sum_{j=1}^{4}\sum_{i=1}^{{\rm gd}_j}(0.219 \times C \times R_{{\rm s},i} \times f(t_i)) \\ &\times f(w_j) \times f(s), \end{aligned} \tag{5}$$

where $f(w_j)$ is the water stress coefficient, which can be calculated as follows:

$$f(w_j) = \begin{cases} \frac{P_j}{{\rm ET}_{{\rm c},j}} & 0 \leqslant P_j < {\rm ET}_{{\rm c},j} \\ 1 & P_j \geqslant {\rm ET}_{{\rm c},j} \end{cases}, \tag{6}$$

where P_j (mm) is the total precipitation during each crop development stage, and ${\rm ET}_{{\rm c},j}$ (mm) is the total crop water requirement during each development stage, which can be calculated as:

$$ET_{{\rm c},j} = \sum_{i=1}^{{\rm gd}_j}({\rm ET}_{0,i} \times K_{{\rm c},j}), \tag{7}$$

where $K_{{\rm c},j}$ is the crop coefficient at different development stages (Table 3; Sun et al., 2002; Du et al., 2014; Hu et al., 2015).

${\rm ET}_{0,i}$ is calculated by the FAO Penman–Monteith equation (Allen et al.,1998):

$$\mathrm{ET}_{0,i} = \frac{0.408\Delta(R_{\mathrm{n}} - G) + \gamma\frac{900}{t+273}U_2(e_{\mathrm{s}} - e_{\mathrm{a}})}{\Delta + \gamma(1 + 0.34U_2)}, \quad (8)$$

where $\mathrm{ET}_{0,i}$ (mm day^{-1}) is the daily reference crop evapotranspiration, R_{n} (MJ m^{-2} day^{-1}) is the net radiation, G (MJ m^{-2} day^{-1}) is the soil heat flux, t (℃) is the daily average temperature at 2-m height, U_2 (m s^{-1}) is the wind speed at 2-m height, e_{s} (kPa) is the saturated vapor pressure, e_{a} (kPa) is the actual water vapor pressure, Δ (kPa ℃$^{-1}$) is the slope of the saturation vapor pressure versus temperature relationship, and γ (kPa ℃$^{-1}$) is the psychrometric constant. ET_0 is calculated in daily steps, and G is negligible in this study.

The parameter $f(s)$ represents the soil stress coefficient, which is calculated as follows (Lacatusu and Lacatusu, 2011):

$$f(s) = \frac{\mathrm{GIF}_{\mathrm{a}}}{\mathrm{GIF}_{\mathrm{m}}}, \quad (9)$$

where CIF is a complex indicator of soil fertility, calculated by the marking method (Eq. (10)); and $\mathrm{CIF}_{\mathrm{a}}$ and $\mathrm{CIF}_{\mathrm{m}}$ are the actual and theoretical maximum soil fertility indicators of the study site, respectively:

$$\mathrm{CIF} = \sum_{i=1}^{12}\mathrm{PO}_i - \sum_{p=1}^{4}\mathrm{PE}_p, \quad (10)$$

where PO_i and PE_p are the potentiating and penalty indicators related to soil fertility, respectively (Table 4). The potentiating and penalty indicators were divided into five levels; for the potentiating indicators, a score of 1–5 represented the soil fertility from low to high, and vice versa for the penalty factors. $\mathrm{CIF}_{\mathrm{a}}$ was

Table 3. Crop coefficient ($K_{\mathrm{c},j}$) at different development stages of the three crops

Crop	Initial stage	Development	Middle stage	Late stage
Sunflower^1	0.30	0.75	1.20	0.35
Potato^2	0.45	0.80	1.10	0.80
Spring wheat^3	0.57	1.36	1.70	0.80

^{1}Refer to Du et al. (2014); ^{2}refer to Hu et al. (2015); ^{3}refer to Sun et al. (2002).

Table 4. The potentiating [PO_i (i= 1–12)] and penalty [PE_p (p = 1–4)] indicators related to soil fertility

	1	2	3	4	5
PO_1 annual average precipitations (mm)	<400.0 or >1000.0	400.1–500.0	500.1–600.0	800.1–1000.0	600.1–800.0
PO_2 annual average temperature (℃)	<4.0 or >11.0	4.1–6.0	6.1–8.0	10.1–11.0	8.1–10.0
PO_3 edaphic volume (%)	<10.0	10.1–20.0	20.1–50.0	50.1–100.0	>100.0
PO_4 clay < 2μ (%)	<6.0 or >45.0	6–12	32.1–45.0	12.1–20.0	20.1–32.0
PO_5 AD (g cm^{-3})	<1.21 or >1.76	1.62–1.75	1.48–1.61	1.35–1.47	1.18–1.35
PO_6 pH	<3.5, 3.6–5.0 or 8.5–10.0	5.1–5.8	5.9–6.4 or 7.9–8.4	6.5–6.8 or 7.3–7.8	6.9–7.2
PO_7 level of gleyzation	Bogs	Gley soils	Gleyc soils	Gleyed soils	Soils with shallow groundwater table
PO_8 level of pseudo-gleyzation	Swamp stagnic soils	Stagnic soils	Mesostagnic soils	Hypomesostagnic soils	Bathystagnic soils
PO_9 N total (%)	<0.100	0.100–0.140	0.141–0.270	0.271–0.600	>0.600
PO_{10} P_{AL}(mg kg^{-1})	<8.0	8.1–18.0	18.1–36.0	36.1—72.0	>72.0
PO_{11} K_{AL}(mg kg^{-1})	<65.0	65.1–130.0	130.1–200.0	200.1–300.0	>300.0
PO_{12} humus content limits (%)	<0.4	0.4–0.89	0.9–1.79	1.8–4.09	4.1–7.0
PE_1 salinization level	Weak	Moderate	Strong	Very strong	Excessive
PE_2 carbonate content (%)	<5.0	5.1–10.0	10.1–25.0	25.1–40.0	>40.0
PE_3 pollution level	Contamination	Low pollution	Medium pollution	Strong pollution	Excessive pollution
PE_4 artifact percentage in the soil volume (%)	<10.0	10.1–15.0	15.1–25.0	25.1–50.0	>50.0

For potentiating indicators, a score of 1–5 represents the soil fertility from low to high, and vice versa for the penalty factors.

the actual soil indicator based on observed soil data at the study sites, while $\mathrm{CIF_m}$ was the theoretical maximum soil fertility indicator with the highest score for each indicator, except for observed annual precipitation and temperature, at the study sites.

2.3 Calculation of climate suitability for crops

The climate suitability $S(C)$ for the three crops, ranging from 0 to 1, was calculated as follows (Zhao et al., 2003):

$$S(C) = \sum_{j=1}^{4} a_j \times S(C)_j, \tag{11}$$

where a_j is the weighting coefficient of each development stage in the whole growing season (Table 5); $S(C)_j$ means the climate suitability for crops at different development stages, calculated as follows:

$$S(C)_j = b_{Sj} \times S(S)_j + b_{Tj} \times S(T)_j \times b_{Pj} \times S(P)_j, \tag{12}$$

where b_{Sj}, b_{Tj}, and b_{Pj} are the weighting coefficients of sunshine hour, temperature, and precipitation, respectively (Table 5).

$S(S)_j, S(T)_j$, and $S(P)_j$ are the climate suitability of sunshine hour, temperature, and precipitation at the development stage j, respectively, calculated as follows:

Table 5. The weighting coefficient (a) of each development stage in the whole growing season and the weighting coefficients of sunshine hour (b_S), temperature (b_T), and precipitation (b_P) for each stage

	Initial stage			Development			Middle stage			Late stage		
	SF	PT	SW	SF	PT	SW	SF	PT	SW	SF	PT	SW
a	0.25	0.26	0.24	0.30	0.24	0.28	0.20	0.24	0.19	0.25	0.26	0.29
b_S	0.35	0.34	0.36	0.33	0.46	0.31	0.31	0.32	0.24	0.27	0.32	0.34
b_T	0.40	0.26	0.27	0.33	0.34	0.35	0.34	0.34	0.37	0.38	0.32	0.34
b_P	0.25	0.40	0.37	0.34	0.20	0.34	0.35	0.34	0.39	0.35	0.36	0.32

$$S(S)_j = \frac{\sum_{i=1}^{\mathrm{gd}_j} \begin{cases} \frac{n_i}{N_0} & n_i < N_0 \\ 1 & n_i \geqslant N_0 \end{cases}}{\mathrm{gd}_j}, \tag{13}$$

$$S(T)_j = \frac{\sum_{i=1}^{\mathrm{gd}_j} \frac{(t_i - t_\mathrm{b})(t_\mathrm{c} - t_i)^{\frac{t_\mathrm{c}-t_\mathrm{o}}{t_\mathrm{o}-t_\mathrm{b}}}}{(t_\mathrm{o} - t_\mathrm{b})(t_\mathrm{c} - t_\mathrm{o})^{\frac{t_\mathrm{c}-t_\mathrm{o}}{t_\mathrm{o}-t_\mathrm{b}}}}}{\mathrm{gd}_j}, \tag{14}$$

$$S(P)_j = \begin{cases} \frac{P_j}{\mathrm{ET}_{\mathrm{c},j}} & 0 \leqslant P_j < \mathrm{ET}_{\mathrm{c},j} \\ \frac{\mathrm{ET}_{\mathrm{c},j}}{P_j} & P_j \geqslant \mathrm{ET}_{\mathrm{c},j} \end{cases}, \tag{15}$$

where n_i is the daily actual duration of sunshine hours; N_0 represents the optimal sunshine hour, taking 70% of the daily maximum possible duration of sunshine in hour; and P_j and $\mathrm{ET}_{\mathrm{c},j}$ are the total precipitation (mm) and crop water requirement (mm), respectively, during each development stage.

2.4 Statistical analysis

Linear regression analysis was used to analyze the trends in climate variables during the crop growing season, the potential productivity, the potential productivity gaps, and climate suitability of the three crops. The slope of the linear regression line was evaluated by using the Student's t-test at the 95% and 99% confidence levels.

3. Results

3.1 Comparison of change trends in climate variables during the growing season of the three crops

The growing season solar radiation (Figs. 2a, 2d, and 2g) decreased by 7.25, 8.30, and 9.24 MJ $\mathrm{m^{-2}}$ per decade ($p < 0.05$) across APE for sunflower, potato, and spring wheat, respectively, with significant decreasing trends at 44%, 41%, and 48% of the study sites from 1981 to 2010. The sites with increasing trends in growing season solar radiation were in the northeastern, southwestern, and mid–eastern areas of the APE region. The growing season average temperature (Figs. 2b, 2e, and 2h) increased by 0.47, 0.48, and 0.52°C per decade ($p < 0.05$) across APE for sunflower, potato, and spring wheat, respectively, with a significant increasing trend at 41% of the study sites from 1981 to 2010. The growing season precipitation (Figs. 2c, 2f, and 2i) decreased by 18.45, 18.98, and 19.22 mm per decade ($p > 0.05$) across APE from 1981

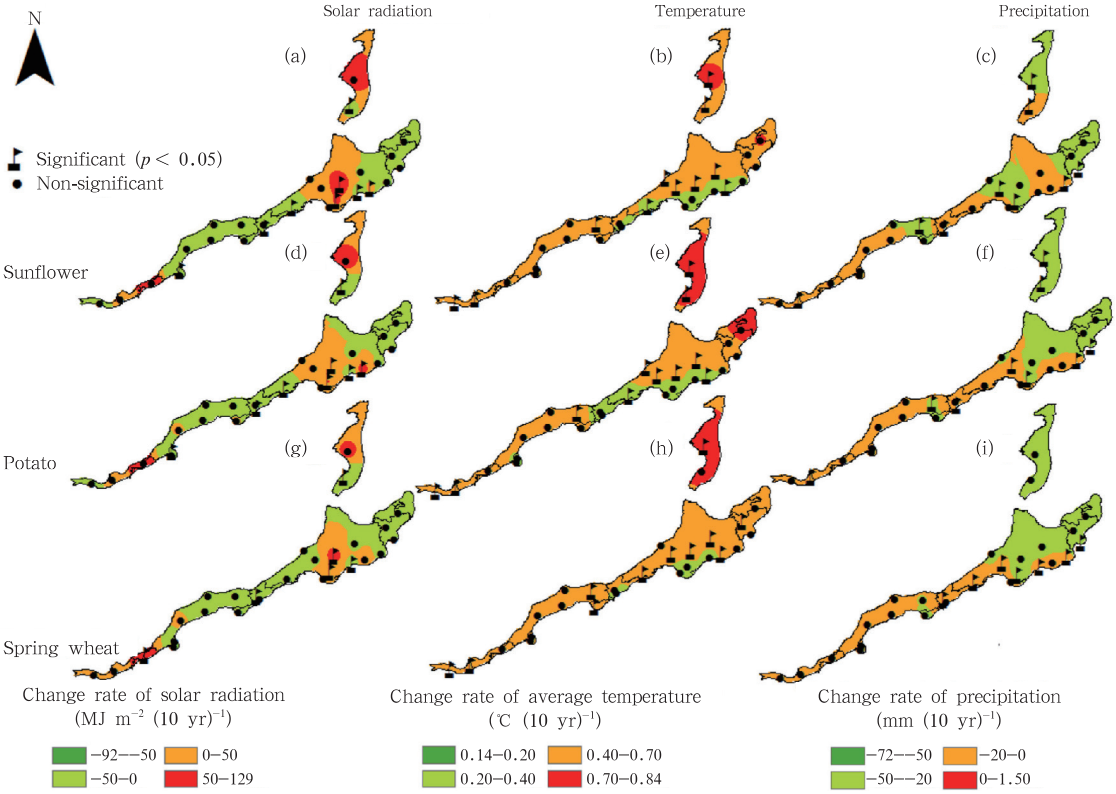

Fig. 2. Change rates per decade of (a, d, g) solar radiation (MJ m^{-2}), (b, e, h) average temperature (℃), and (c, f, i) precipitation (mm) during the growing season of (a–c) sunflower, (d–f) potato, and (g–i) spring wheat in the APE region from 1981 to 2010.

to 2010 for sunflower, potato, and spring wheat, respectively. However, the sites with significant decreasing trends in growing season precipitation only accounted for 33%, 33%, and 27% of the study sites from 1981 to 2010 for sunflower, potato, and spring wheat, respectively.

3.2 Comparison of the impacts of climate change on the potential productivity of the three crops in the APE region

The light–temperature potential productivity of sunflower varied from 9200 to 16400 kg ha^{-1}, the high- and low-value areas of which were concentrated in the southeastern and northeastern parts of APE, respectively (Fig. 3a). The light–temperature potential productivity for potato varied from 190750 to 237200 kg ha^{-1}, with low values in northeastern and eastern APE (Fig. 3b). The light–temperature potential productivity for spring wheat varied from 16990 to 22700 kg ha^{-1}, with high values in southeastern and southwestern APE (Fig. 3c). The light–temperature potential productivity of sunflower, positively correlated with the growing season average temperature ($R^2 = 0.86$, $p < 0.01$) and growing season solar radiation ($R^2 = 0.52$, $p < 0.01$), increased by 4.47% per decade across the study area. This suggested a higher positive impact of the increase in temperature than the negative impact of the decrease in solar radiation on the light–temperature potential productivity of sunflower from 1981 to 2010. For potato, the light–temperature potential productivity was positively correlated with growing season solar radiation ($R^2 = 0.52$, $p < 0.01$), but negatively correlated with growing season average temperature ($R^2 = 0.26$, $p < 0.05$). Therefore, the decrease in solar radiation and increase in temperature led to a decline by 1.58% in the light–temperature potential productivity of potato. For spring wheat, the light–temperature potential productivity was only sig-

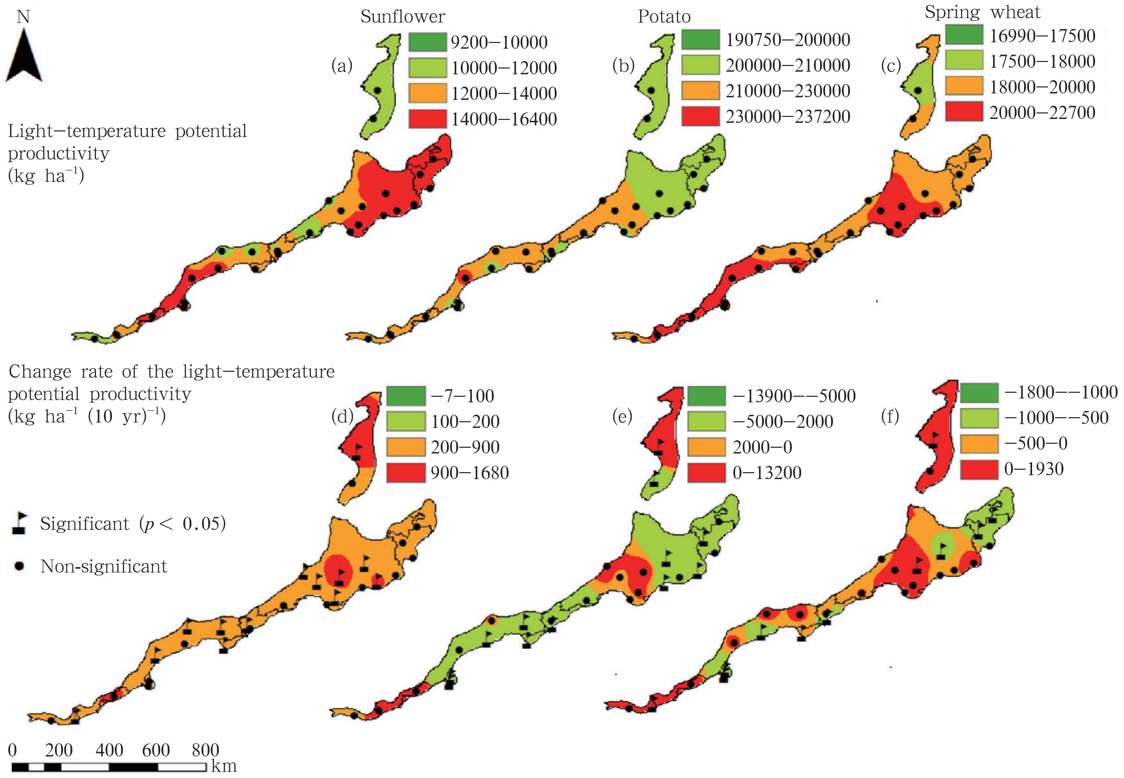

Fig. 3. (a–c) Light–temperature potential productivity (kg ha^{-1}) and (d–f) its change rate (kg ha^{-1} (10 yr)$^{-1}$) for (a, d) sunflower, (b, e) potato, and (c, f) spring wheat.

nificantly and positively correlated with growing season solar radiation ($R^2 = 0.57$, $p < 0.01$). Therefore, the decline in solar radiation decreased the light–temperature potential productivity of spring wheat by 0.59% per decade from 1981 to 2010. For sunflower, the sites with increased light–temperature potential productivity accounted for 96% of the total. For potato and spring wheat, the light–temperature potential productivity decreased at 74% and 44% of the study sites, respectively.

The climate–soil potential productivity varied from 2120 to 6350 kg ha^{-1} for sunflower (Fig. 4a), from 28500 to 93700 kg ha^{-1} for potato (Fig. 4b), and from 1960 to 6760 kg ha^{-1} for spring wheat (Fig. 4c), with high-value areas in eastern, northeastern and southwestern APE. The climate–soil potential productivity was positively correlated with growing season precipitation ($R^2 = 0.63$, $p < 0.01$ for potato; $R^2 = 0.73$, $p < 0.01$ for spring wheat), but negatively correlated with growing season average temperature ($R^2 = 0.45$, $p < 0.01$ for potato; $R^2 = 0.32$, $p < 0.05$ for spring wheat). For sunflower, the climate–soil potential productivity was only positively correlated with growing season precipitation ($R^2 = 0.28$, $p < 0.05$). Due to the significant increase in growing season average temperature but insignificant change in growing season precipitation, the climate–soil potential productivity increased by 0.21% per decade for sunflower but decreased by 8.20% and 7.82% per decade for potato and spring wheat, respectively, across APE.

3.3 Comparison of the impacts of climate change on the potential productivity gaps of the three crops in the APE region

The gaps between the light–temperature potential productivity and the climate–soil potential productivity varied from 5100 to 13080 kg ha^{-1} for sunflower, from 112400 to 188400 kg ha^{-1} for potato, and from 11900 to 19500 kg ha^{-1} for spring wheat (Figs. 5a–c). Low potential productivity gaps existed in northeastern APE, where growing season precipitation was higher than in other regions. Due to the higher increa-

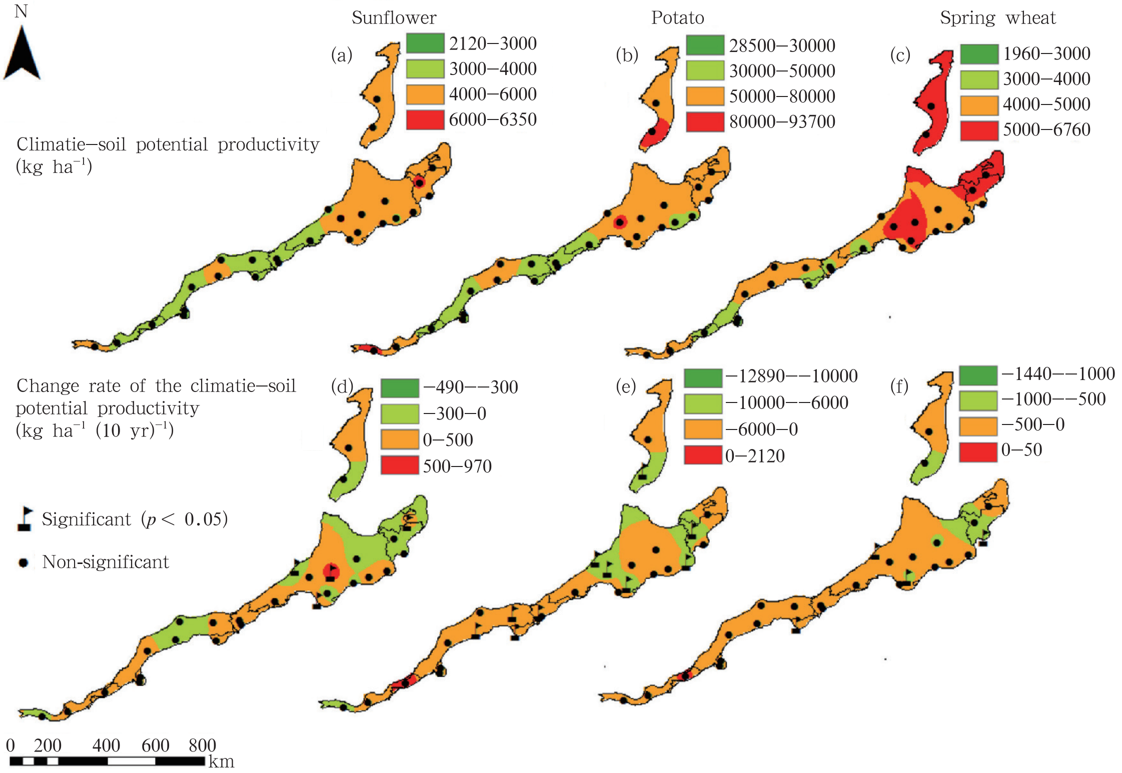

Fig. 4. (a–c) Climate–soil potential productivity (kg ha^{-1}) and (d–f) its change rate (kg ha^{-1} (10 yr)$^{-1}$) for (a, d) sunflower, (b, e) potato, and (c, f) spring wheat.

se in the light–temperature potential productivity than the climate–soil potential productivity, the potential productivity gaps increased by 590 kg ha^{-1} for sunflower across APE from 1981 to 2010 (Fig. 5d). However, the potential productivity gaps increased by 1470 kg ha^{-1} and 200 kg ha^{-1} per decade for potato and spring wheat, respectively, across APE from 1981 to 2010, owing to the higher decrease in the climate–soil potential productivity than the light–temperature potential productivity (Figs. 5e and 5f). The largest increase in the potential productivity gaps for the three crops occurred in the northeastern and mid–eastern APE regions. The above results showed that increasing temperature enlarged the gaps between the light–temperature potential productivity and the climate–soil potential productivity at 96%, 56%, and 59% of the study sites for sunflower, potato, and spring wheat, respectively.

3.4 Comparison of the climate suitability of the three crops in the APE region

The climate suitability ranged from 0.67 to 0.79 for sunflower (Fig. 6a), from 0.70 to 0.81 for potato (Fig. 6b), and from 0.59 to 0.73 for spring wheat (Fig. 6c). Although the climate suitability for potato was the highest among the three crops, it had been decreasing at 89% of the study sites since the 1980s. The climate suitability for spring wheat was the lowest among the three crops and decreased at 89% of the study sites from 1981 to 2010. However, the climate suitability for sunflower showed an increasing trend at 63% of the study sites from 1981 to 2010, suggesting that climate change had a positive impact on sunflower but a negative impact on potato and spring wheat across APE.

4. Summary

Our study reveals that the light–temperature potential productivity increased for sunflower but decreased for potato and spring wheat across the APE region during the study period. Meanwhile, the climate–soil potential productivity increased by 0.21% for sunflower but decreased by 8.20% and 7.82% per decade for potato and spring wheat, respectively, after the

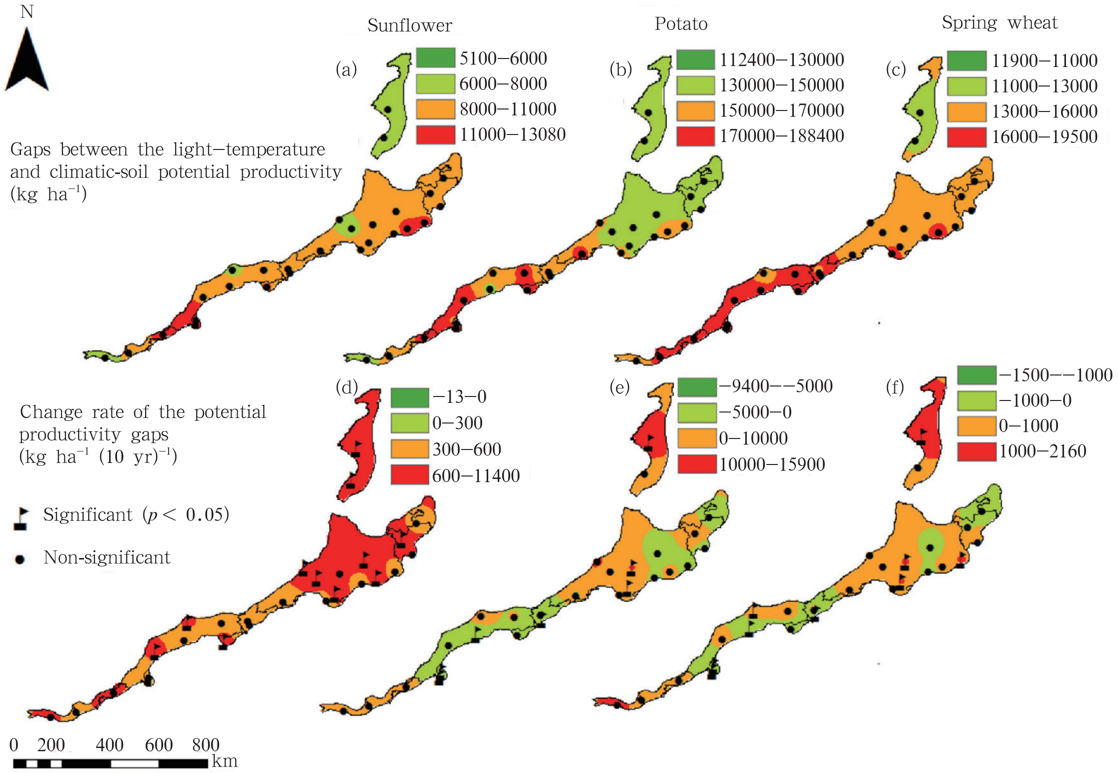

Fig. 5. (a–c) Gaps between the light-temperature and climate–soil potential productivity (kg ha^{-1}) and (d–f) their change rates (kg ha^{-1} (10yr)$^{-1}$) for (a, d) sunflower, (b, e) potato, and (c, f) spring wheat.

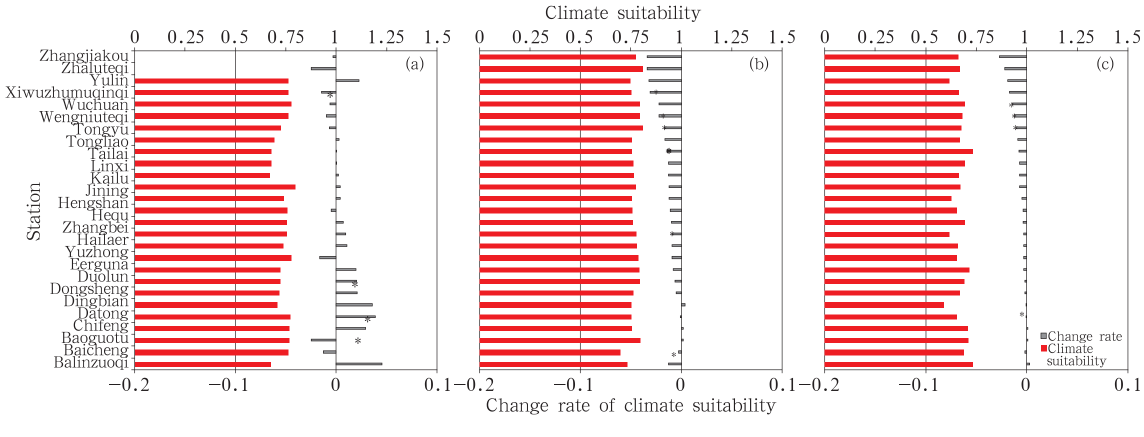

Fig. 6. Climate suitability (upper x-axis) and its change rate (lower x-axis) in the APE region for (a) sunflower, (b) potato, and (c) spring wheat. Asterisks indicate statistical significance at $p < 0.05$.

1980s. Climate change during 1981–2010 broadened the gaps between the light–temperature and climate–soil potential productivity for sunflower, potato and spring wheat in the APE region. The climate change during the past 30 years has led to a decrease in the climate suitability for potato and spring wheat, but an increase in the climate suitability for sunflower. Our findings suggest that the sown area of sunflower should be increased compared with that of potato and spring wheat in this region under future climate warming.

High crop diversity in the APE region could help ensure yield stability under harsh climate conditions.

Therefore, farmers in the study area are accustomed to planting multiple crops in a season in different fields. Since the mid-1990s, the sown area of potato and sunflower has been increasing, while that of spring wheat has decreased obviously in the APE region (Fig. 7). Our study investigated the impact of climate change during the past 30 years on the potential productivity, the potential productivity gaps, and the climatic suitability for sunflower, potato, and spring wheat to assist with future decisions regarding plant structure distribution in the APE region of North China.

The average light–temperature potential productivity of potato in the study area was 2.09×10^5 kg ha^{-1}, which is much higher than the average value of 0.94×10^5 kg ha^{-1} in subtropical SWC (He et al., 1998), because of the lower growing season temperature in the APE region. It is also much higher than the average value of 1.1×10^5 kg ha^{-1} in Chile (Haverkort et al., 2014), because of the higher harvest index used in our study. Furthermore, the climate–soil potential productivity of sunflower and spring wheat in the APE region of North China is much lower than that in Europe, owing to the shorter frost-free period in the study area (Harrison and Butterfield, 1996). In general, the actual highest yield could reach 80% of the potential yield calculated by crop growth dynamical statistical methods and crop growth models (Grassini et al., 2011). Comparison between the reported actual highest yield and the ratio of actual highest yield to the light–temperature potential productivity of stable crops in the APE region showed that the reported actual highest yield has reached and even exceeded the light–temperature potential productivity calculated by our study (Table 6), which suggests that crop growth dynamical statistical methods could be used as a tool for estimating theoretical crop potential productivity.

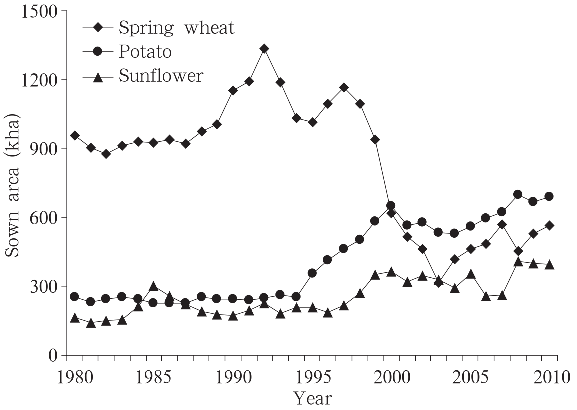

Fig. 7. Changes in the sown areas of staple crops in the APE region from 1981 to 2010.

Our results showed that the light–temperature potential productivity increased for sunflower but decreased for potato and spring wheat across the APE region. The climate–soil potential productivity increased by 0.21% for sunflower but decreased by 8.20% and 7.82% per decade for potato and spring wheat, respectively, after the 1980s. The rates of decrease were sharper than those of potato and spring wheat (0.13% and 0.8%, respectively) in Europe (Supit et al., 2010), due to the more significant changes in temperature and precipitation in the study area. Figure 8 shows the observed actual yield, the climatic yield by detrending the actual yield with a 5-yr moving average, and the change trends in climatic yields of staple crops in APE at typical sites from 1981 to 2010. The observed crop yield showed an increasing trend at most of sites, caused by the use of new modern cultivars together with improved agronomic management techniques (Xiong et al., 2014; He et al., 2015; Mi et al., 2015). The change trend in climatic yields was similar to that of the climate–soil potential productivity calculated in our study, indicating that the change in climate–soil potential productivity could reflect the impact of climate change on crop yield in the APE region.

Climate change during 1981–2010 broadened the gaps between the light–temperature and climate–soil potential productivity for sunflower, potato, and spring wheat in the APE region. The results were similar to those of several other crops in a larger number of studies (He et al., 2014; Wang et al., 2014). In other climatic regions, such as Northeast China, the Huang–Huai–Hai Plain, and SWC, there is great potential to increase the crop potential productivity by increasing irrigation (Albersen et al., 2002; Wang et al., 2012; He et al., 2014). However, this is an unrealistic approach in the APE region of North China because of the low

Table 6. The reported actual highest yield and the ratio of actual highest yield to the light–temperature potential productivity of stable crops in the APE region of North China

Crop	Station	Reported actual highest yield (kg ha^{-1})	Ratio of the reported actual highest yield to the light–temperature potential productivity
Potato	Zhalantun	197000	94.30%
Sunflower	Linhe	27000	>100%
Spring wheat	Dongsheng	15000	75.31%

Note: the actual highest yield data were obtained from http://zzys.agri.gov.cn.

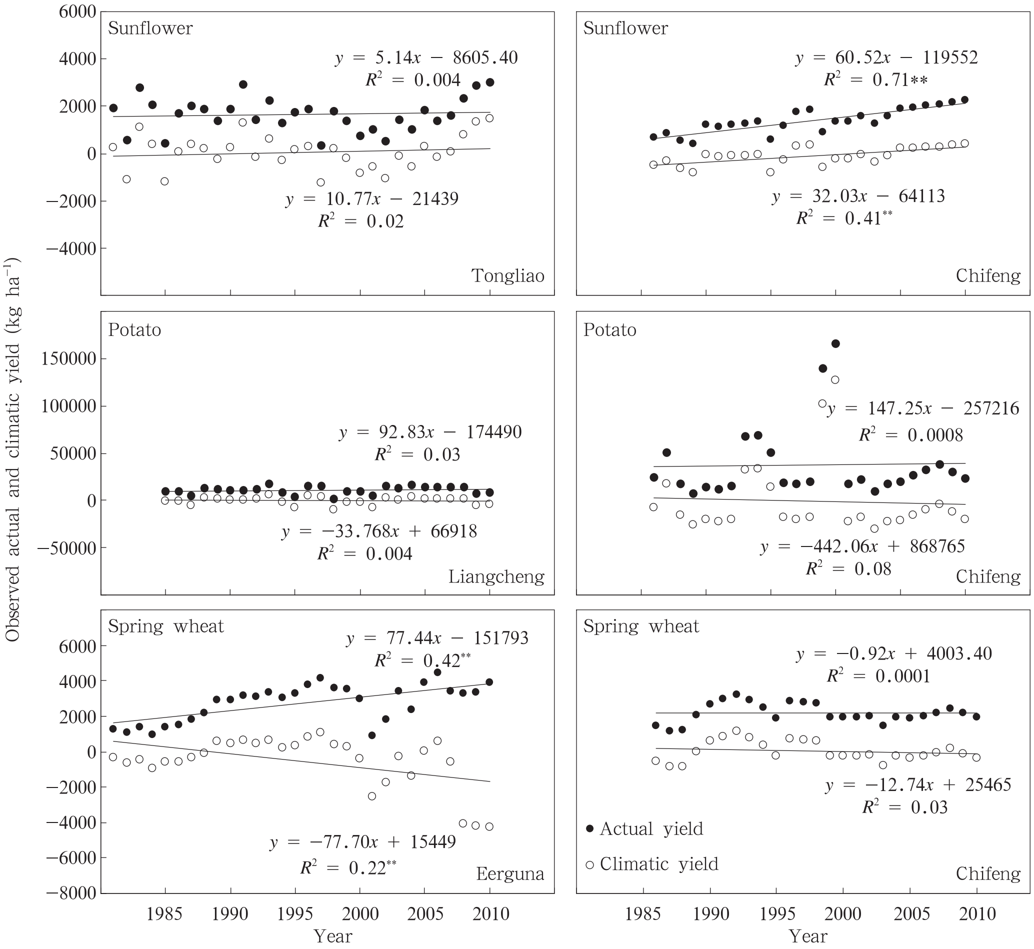

Fig. 8. The observed actual yield, climatic yield, and change trends in climatic yields of staple crops at typical sites in the APE region from 1981 to 2010 (** denotes results significant at $p < 0.01$).

annual precipitation and low availability of surface and ground water (Xia et al., 2010). In fact, the regional average crop yield has not reached the climatic potential productivity due to below-optimum crop management and inferior soil fertility. Although many studies have focused on enhancing soil fertility in this region, it is difficult to achieve for the whole region due to the low precipitation and soil weathering (Pan et al., 2003).

Our study found that the climate change during the past 30 years led to a decrease in the climate suitability for potato and spring wheat, but an increase in for sunflower. Sensitivity analysis showed that the light–temperature potential productivity and climatic-soil potential productivity decreased for potato and spring wheat but increased for sunflower, with increases in temperature by 1, 2, and 3℃ (Table 7). The sensitivity of the climate–soil potential productivity to precipitation change showed spring wheat to be the most sensitive, followed by potato and sunflower (Table 8). The results suggest that the sown area of sunflower should be increased to adapt to future climate warming and drying in this region.

Table 7. The sensitivity of the potential productivity to an increase in average temperature by 1℃, 2℃, and 3℃

Change in T	Sunflower		Potato		Spring wheat	
	LTPP	CSPP	LTPP	CSPP	LTPP	CSPP
1℃↑	7.34%↑	5.86%↑	3.31%↓	6.54%↓	2.34%↓	4.96%↓
2℃↑	14.68%↑	11.57%↑	8.46%↓	14.11%↓	6.46%↓	12.34%↓
3℃↑	22.02%↑	17.13%↑	15.07%↓	22.54%↓	12.57%↓	19.75%↓

Notes: T, temperature; ↑, increase; ↓, decrease; LTPP, light–temperature potential productivity; CSPP, climate–soil potential productivity.

Table 8. The sensitivity of the climate-soil potential productivity to precipitation change

Change of precipitation	Sunflower CSPP	Potato CSPP	Spring wheat CSPP
15%↑	5.35%↑	6.60%↑	7.28%↑
10%↑	7.68%↑	9.71%↑	10.72%↑
10%↓	6.18%↓	7.00%↓	7.98%↓
15%↓	9.62%↓	10.88%↓	12.22%↓

Our study analyzed the impact of climate change on crop production with a crop growth dynamics statistical method. The method is simple and feasible for evaluating the crop potential productivity in a large area. However, it could not be used to unravel the relative contribution of climate and non-climatic factors to crop production. In further research, crop growth models should be used to explore the interactive impact of changes in climate, crop varieties, and agronomic management on crop production in the APE region of North China, as has been successfully used in agricultural production in the North China Plain and Northeast China.

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