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RESEARCH ARTICLE

Diverse effects of crop distribution and climate change on crop production in the agro-pastoral transitional zone of China

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Abstract Both crop distribution and climate change are important drivers for crop production and can affect food security, which is an important requirement for sustainable development. However, their effects on crop production are confounded and warrant detailed investigation. As a key area for food production that is sensitive to climate change, the agro-pastoral transitional zone (APTZ) plays a significant role in regional food security. To investigate the respective effects of crop distribution and climate change on crop production, the well-established GIS-based Environmental Policy Integrated Climate (EPIC) model was adopted with different scenario designs in this study. From 1980 to 2010, the crop distribution for wheat, maize, and rice witnessed a dramatic change due to agricultural policy adjustments and ecological engineering-related construction in the APTZ. At the same time, notable climate change was observed. The simulation results indicated that the climate change had a positive impact on the crop production of wheat, maize, and rice, while the crop distribution change led to an increase in the production of maize and rice, but a decrease in the wheat production. Comparatively, crop distribution change had a larger impact on wheat (-1.71×10^6 t) and maize (8.53×10^6 t) production, whereas climate change exerted a greater effect on rice production (0.58×10^6 t), during the period from 1980 to 2010 in the APTZ. This study is helpful to understand the mechanism of the effects of crop distribution and climate change on crop production, and aid policy makers in reducing the threat of future food insecurity.

Keywords EPIC model, crop production, climate trends, scenario designs, crop distribution

1 Introduction

Food production is an important requirement for food security. Particularly in recent years, continued population growth and the demand for high-quality food have placed new requirements on the food production industry (Godfray et al., 2010; FAO, IFAD and WFP, 2015). Consequently, it is critical to characterize the spatial and temporal dynamics of regional food production and quantitatively evaluate the impact of key driving forces on food production and food security.

Previous studies have shown that land use and climate change have notable effects on crop production (Wood et al., 2000; Lobell and Burke, 2010; Lobell and Gourdji, 2012), which are all subjects of worldwide concern. Numerous studies have assessed the impact of agricultural land use change on crop production (Foley et al., 2005; Metzger et al., 2006). By analyzing land use change over the past four decades, Wood et al. (2000) found that the global cropland area increased by 12%, which resulted in an increase in food production. In addition, many studies have assessed the impact of climate change on crop yield (Alexandrov and Hoogenboom, 2000). Using statistical data from the past few decades, Lobell et al. (2011) examined the change in climate trends and crop yields for the period from 1980 to 2010. Their results showed that the crop yields of wheat, maize, and soybeans had declined, whereas the rice yield increased in most regions of the world.

Land use and climate change are interacting factors that can together affect crop production. However, the studies aimed at evaluating the impacts of land use change on crop production typically do not eliminate the effects of climate change (Foley et al., 2005; Lorencová et al., 2013; Lawler et al., 2014). Moreover, very few studies have accounted

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for the individual impact of changes in climate or land use on crop production. Evaluating the individual impact of both land use and climate change is essential for understanding the relative magnitude of their roles in affecting crop production and adopting agricultural management measures to improve crop production for better food security.

Based on the above research problems, we selected the agro-pastoral transitional zone (APTZ) of northern China as the study area, which is important for grain production. Over the past few decades, the land use in this APTZ has changed significantly because of human activities and rapid urbanization (Liu et al., 2010; Cao et al., 2015; Wu et al., 2015). In addition, the climate has apparently changed during the past few decades, and that change is expected to be more evident in the future, particularly in the crop-planting areas (Pachauri et al., 2014). Therefore, this region offers an opportunity to evaluate the impact of land use and climate change on crop production. In this study, the GIS-based Environmental Policy Integrated Climate (EPIC) model was adopted and several simulation scenarios were designed to understand the response of crop production to crop distribution and climate change. Furthermore, we compared how crop distribution and climate change affected the crop production during the period from 1980 to 2010.

2 Materials and methods

2.1 Study area

The APTZ is one of the largest agro-pastoral transitional zones worldwide, covering approximately 7.26×10^5 km^2 (Fig. 1). It is located between 34°46′–48°32′ N and 100°55′–124°41′ E in northern China. The dominant land use types are farmland and grassland. It is an important area for food production, accounting for 7.7% of the total food production in China in 2010, according to the China Statistical Yearbook. Moreover, it is also a natural ecological shelterbelt because of its location (Kang et al., 2002). However, the ecosystem in this region is fragile and prone to instability (Zhang et al., 2007). Improper agricultural practices, deforestation, unreasonable grazing, and conversion from grassland to farmland can all lead to desertification. To prevent desertification and protect the ecological environment, several measures have been adopted, including ecological project construction, i.e., the reforestation of arable land and agricultural policy adjustment (Qi et al., 2012; Chen et al., 2015). Consequently, the landscape pattern in the APTZ has changed significantly (Wu et al., 2015). Moreover, this zone is located in the arid and semi-arid region, and is susceptible to climate change. The mean annual temperature is 7.83°C, and the mean annual rainfall is 399.37 mm.

2.2 Data acquisition

In this study, three categories of data were acquired: spatial data (crop distribution, soil types, irrigated areas, DEM, and slope), site data (climate and agro-meteorological data), and statistics (statistical yield of wheat, maize, and rice and the fertilizer application rate). The spatial distribution of the actual crop area in 1980, 1990, 2000, and 2010 were obtained from the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS), for which the resolution was 10 km × 10 km (Liu et al., 2015). The value in each

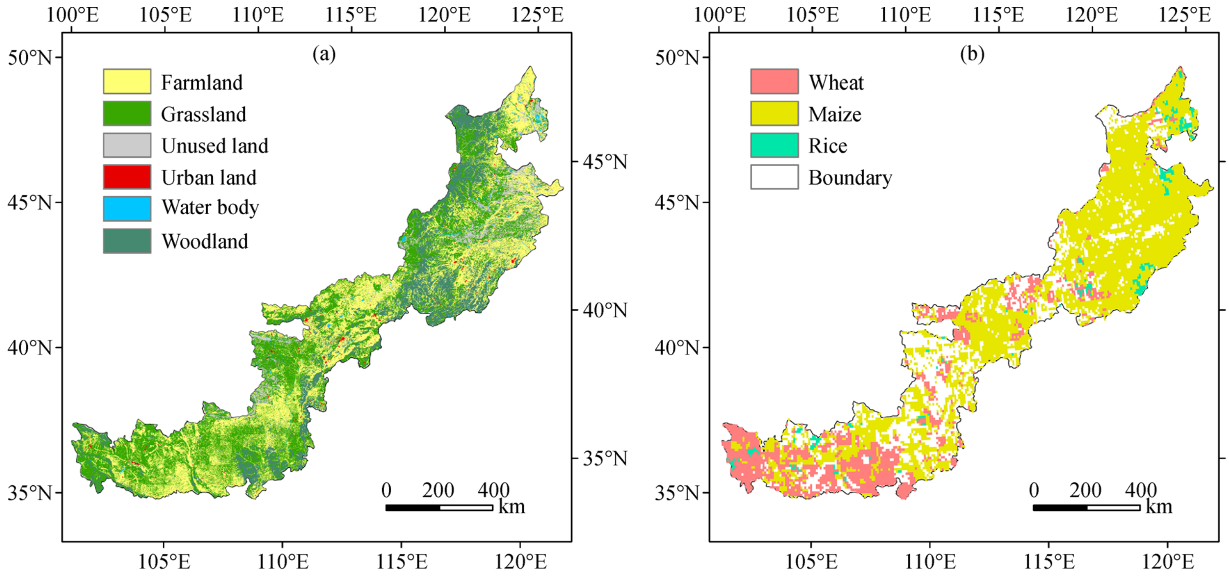

Fig. 1 Location of the agro-pastoral transitional ecozone in northern China, (a) land use and land cover in 2010, (b) crop distribution of major crops in 2010. Each grid cell contains one or more crops (wheat, maize, or rice). The grid value represents the major crop which has the largest cultivated area.

grid represents the corresponding crop sown area of wheat, maize, or rice. The soil data needed to run the EPIC model was derived from the Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn) and the resolution was 10 km × 10 km (Fischer et al., 2008). The map of irrigated areas (GMIA) (10 km) was obtained from the Food and Agriculture Organization of the United Nations (FAO) and denoted the areas that had irrigation (Siebert et al., 2005). The digital elevation model (DEM) and slope data were acquired from the Geospatial Data Cloud, Computer Network Information Center, and Chinese Academy of Sciences. It was resampled into 10 km × 10 km to match the other data.

The daily climate data for solar radiation, maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), precipitation, relative humidity, and mean wind speed and the agro-meteorological data from 1980 to 2010 were obtained from the National Meteorological Information Center (http://data.cma.cn/). Using kriging interpolation, climate variables could be acquired for each grid with a resolution of 10 km to run the GIS-based EPIC model. With the agro-meteorological data, we could derive the planting and harvest dates of wheat, maize, and rice within each municipal area.

The statistical yield of wheat, maize, and rice and the fertilizer application rate for each municipal area within the study area were obtained from the China Agricultural Statistics Yearbook for the period from 1980 to 2010.

2.3 Description of EPIC model

EPIC is a synthetic dynamic model that aims to quantitatively evaluate the major processes of “climate-soil-crop-management”. It consists of mainly five modules, i.e., crop growth, hydrology, soil erosion, nutrient cycling, and soil temperature (Sharpley and Williams, 1990) and has been widely applied since its publication in the early 1980s (Wang et al., 2012). The crop growth module is a mechanistic model based on crop physiological and ecological processes. With the specific crop parameters and field management parameters, it can simulate biomass accumulation, leaf area dynamics, dry matter distribution, crop yield, etc. The crop growth module first calculates the potential biomass using the method of Monteith (1977) and then calculates the actual biomass under the relevant environment stress. At the crop growth stage, the model allocates the new biomass to the root and aboveground part. As a result, the crop yields can be calculated along with the harvest index. In this study, the EPIC (version 0509) model was integrated with ARCGIS 10.1 to simulate the crop yield.

2.4 Model calibration

Model calibration is an important process for the localization of parameters which needs to adjust the sensitive parameters within a reasonable range. In this case, the simulation results are consistent with the observed data. Based on previous studies, the most sensitive parameters to crop yield are WA, HI, DMLA, DLAI, and WSYF (Huang et al., 2006; Wang et al., 2012). The definitions of the five parameters are as follows: WA is the potential radiation use efficiency, HI is the harvest index, DMLA is the maximum potential leaf area index, DLAI is the point in the growing season when the leaf area begins to decline due to leaf senescence, and WSYF represents the lower limit of harvest index (Williams et al., 2006). In this study, the lack of statistical yields at the grid scale made it difficult to calibrate and validate the EPIC model at that scale. Therefore, we used the statistical yield of each municipal area to calibrate the parameters of the EPIC model. By comparing the two indicators of root mean square error (RMSE) and the relative root mean square error (RRMSE) between the statistical and simulated yields, the sensitive parameters can be adjusted within a reasonable range (Sharpley and Williams, 1990).

2.5 Scenario design

In this study, eleven scenarios were designed to evaluate the impact of crop distribution and climate change on crop production from 1980 to 2010, which could be classified into three groups. Group I was used to evaluate the impact of crop distribution change on crop production, Group II was used to evaluate the impact of climate change on crop production, and Group III was used to compare the effects of both crop distribution and climate change (Table 1). Under all these scenarios, the fertilizer rates were held constant at their 1980 values to avoid any potential confusion due to fertilization, and the planting and harvest dates were fixed at the 2010 values. Moreover, the CO_2 concentration was fixed at a constant value of 389 ppm (parts per million) and the auto-irrigation option was chosen for the areas that had irrigation conditions.

In the L1 scenario, the crop spatial distributions of wheat, maize, and rice were varied from 1980 to 2010, while the climatic variables were fixed at the average value for the same period. Thus, we can quantify the impacts of crop spatial distribution change on crop production from 1980 to 2010. Under scenarios C1–C7, the crop spatial distributions were fixed at their 1980 levels, whereas the relevant climatic factor varied from 1980 to 2010. The remaining climatic factors under each scenario were fixed at the average value for the period from 1980 to 2010. This way, we could evaluate the impact of individual and integrated climatic factors on crop production. Under the LC1 scenario, the crop distributions were fixed at their 2010 levels while climatic factors were fixed at the average value for the period from 2008 to 2012. This averaging was done to represent the climatic conditions of 2010 and overcome the effects of short-term climatic fluctuations. Under the LC2 scenario, the crop distribution was fixed at the 2010 levels and the climatic factors were fixed at the average value for the period from 1978 to 1982. Under the LC3 scenario, the crop distribution was fixed at the 1980 levels, while climatic variables were the average of the period from 2008 to 2012. Using the simulation results for these three scenarios (LC1, LC2, and LC3), we could compare the effects of land use and climate change and determine the magnitude of their relative impact on crop production for the period from 1980 to 2010.

3 Results

3.1 Model evaluation

Figure 2 shows that the simulated yield agreed well with the statistical yield of wheat, maize, and rice. The RMSE for the three crops (wheat, maize, and rice) was 0.64 t·ha^{-1}, 0.99 t·ha^{-1}, and 0.94 t·ha^{-1}, respectively. As for the RRMSE of wheat, maize, and rice, the largest value was less than 22%. In addition, the R^2 values for the three crops were higher than 0.6, especially for wheat, which had an R^2 value greater than 0.7. Considering that the model performance was tested at the regional scale, the performance of the EPIC model was robust and the simulation accuracy met the requirements for investigating the impacts of crop distribution and climate change on crop production of wheat, maize, and rice in the APTZ.

3.2 Impact of crop distribution change on crop production

From 1980 to 2010, the spatial distribution of actual crop area for wheat, maize, and rice showed a dramatic change (Figs. 3(a)–3(c)). During this period, the wheat-cultivated area decreased, especially in the mid-western region. Maize was distributed across the whole region and there was an increase in the cultivation area (73.6%), particularly in the mid-east. On the other hand, the increase in the cultivation area for rice (72.8%) was concentrated in the northeast of the APTZ. The wheat-cultivated area decreased by 34.2% from 1980 to 2010, and the maize area increased rapidly from 14.9 × 10^5 ha to 45.2 × 10^5 ha,

Table 1 Scenarios used in this study

Group		Scenario	Crop distribution	Sr	Pre	$T_{\max}$	$T_{\min}$	Rh	Ws
I	Impact of crop distribution change	L1	△	▲	▲	▲	▲	▲	▲
II	Impact of climate change	C1	□	△	▲	▲	▲	▲	▲
		C2	□	▲	△	▲	▲	▲	▲
		C3	□	▲	▲	△	▲	▲	▲
		C4	□	▲	▲	▲	△	▲	▲
		C5	□	▲	▲	▲	▲	△	▲
		C6	□	▲	▲	▲	▲	▲	△
		C7	□	△	△	△	△	△	△
III	Comparison of the effects between crop distribution and climate change	LC1	■	○	○	○	○	○	○
		LC2	■	●	●	●	●	●	●
		LC3	□	○	○	○	○	○	○

Note: A white triangle (△) indicates that the input variable changes from 1980 to 2010, while a black triangle (▲) represents the average values from 1980 to 2010; a white square (□) indicates that the input variable is fixed in 1980, while a black square (■) indicates that the input variable is fixed in 2010; a white circle (○) represents the average value from 2008 to 2010, while a black square (●) represents the average value from 1978 to 1982.

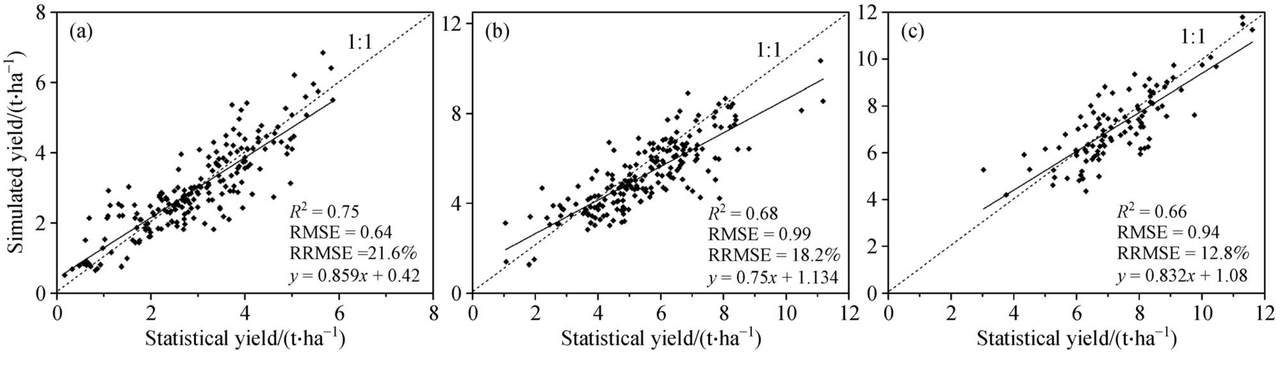

Fig. 2 Validation of the EPIC model, (a) wheat, (b) maize, and (c) rice.

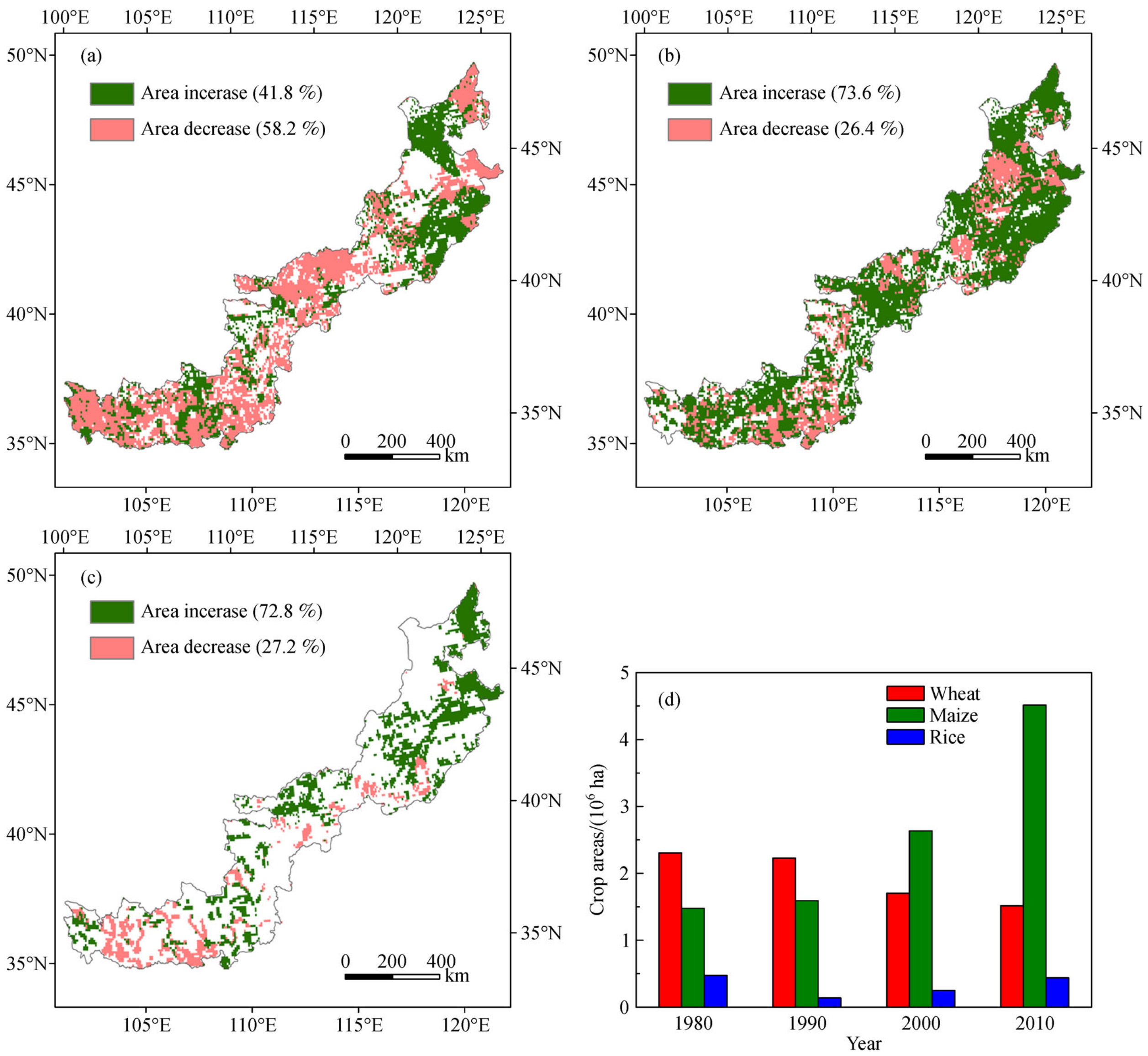

Fig. 3 Changes in crop cultivation areas from 1980 to 2010, (a) wheat, (b) maize, and (c) rice; (d) crop areas for wheat, maize, and rice in 1980, 1990, 2000, and 2010.

whereas the rice area decreased by 70.9% from 1980 to 1990 and then increased by 3 × 10^5 ha from 1990 to 2010 (Fig. 3(d)).

Based on the L1 scenario, the impact of crop distribution change on the crop production of wheat, maize, and rice was investigated (Fig. 4). Maize production was higher than wheat and rice production in 1980. By 2010, maize production increased by 3.54 × 10^6 t, making it the crop with the highest production. By 2010, wheat production decreased by 0.61 × 10^6 t owing to the decline in wheat-cultivated areas. From 1980 to 1990, rice production declined noticeably and then began to increase. By 2010, rice production was 0.33 × 10^6 t higher than the production in 1980. A significant decreasing trend (-2.05×10^5 t $\cdot$ yr^{-1}; $p < 0.05$) for wheat production was observed from 1980 to 2010, owing to the decline in wheat-cultivated areas (Fig. 4(b)). Maize production exhibited an upward trend (10^6 t$\cdot$$\mathrm{yr}^{-1}$; $p = 0.08$) from 1980 to 2010 (Fig. 4(c)). For rice, the crop distribution change had a positive effect on the crop production, owing to the increase in rice-cultivated areas (Fig. 4(d)).

3.3 Impacts of climate change on crop production

From 1980 to 2010, solar radiation exhibited an insignificant downward trend (-1.435 MJ$\cdot$$\mathrm{m}^{-2}$$\cdot$$\mathrm{yr}^{-1}$, $p = 0.39$; Fig. 5(a)) in the APTZ. However, both $T_{\max}$ and $T_{\min}$ showed a significant increasing trend with a variation rate of 0.051°C$\cdot$$\mathrm{yr}^{-1}$ ($p < 0.01$; Figs. 5(b) and 5(c)). During the period from 1980 to 2010, precipitation showed no

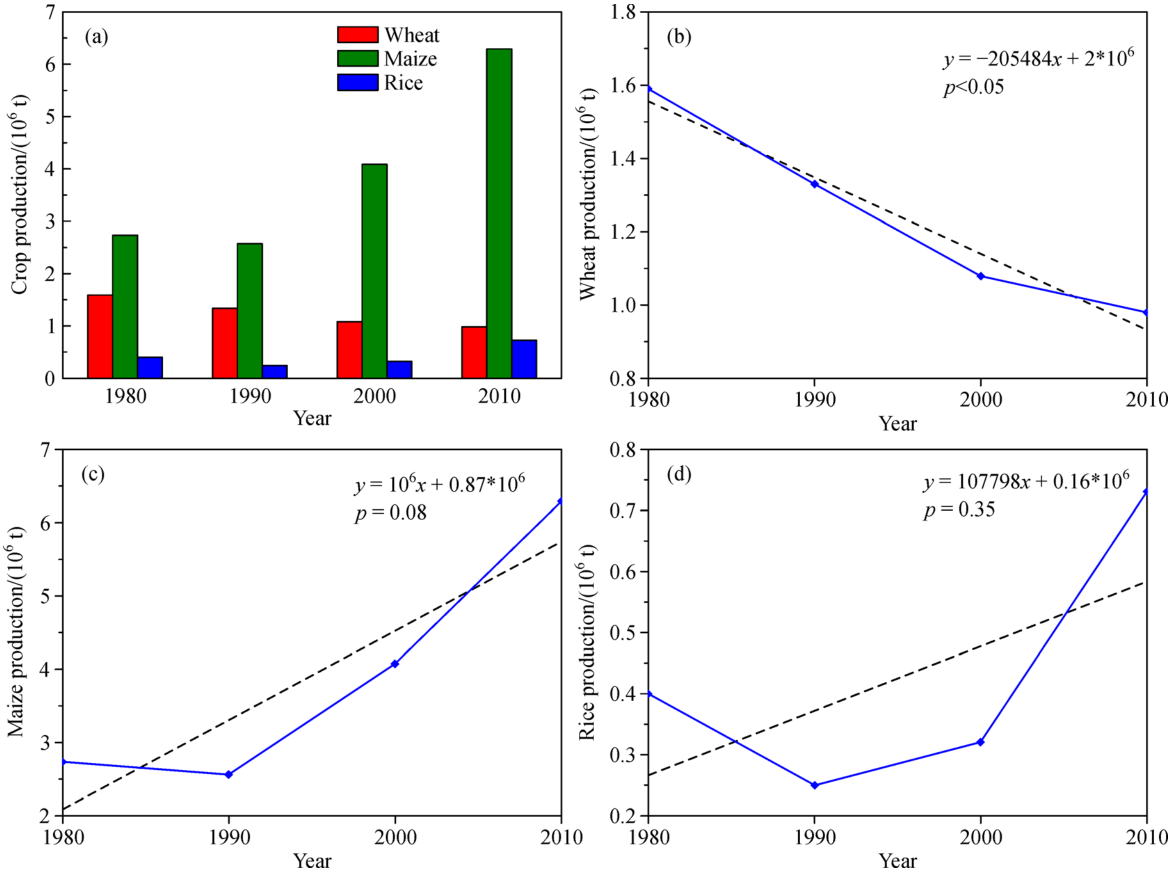

Fig. 4 (a) Crop production of wheat, maize, and rice from 1980 to 2010; the linear trend of crop production for (b) wheat, (c) maize, and (d) rice.

significant change, exhibiting only a slight decreasing trend (-0.719 mm·yr^{-1}, $p = 0.45$; Fig. 5(d)). In addition, relative humidity also showed a decreasing trend (-0.085%·yr^{-1}, $p = 0.07$; Fig. 5(e)) during the study period. Wind speed showed a significant decreasing trend with a variation rate of -0.01 (m·s^{-1}) ·yr^{-1} ($p < 0.01$; Fig. 5(f)) from 1980 to 2010 in the APTZ.

Based on scenarios C1–C7, the individual and integrated effects of solar radiation, $T_{\max}$, $T_{\min}$, precipitation, relative humidity, and wind speed on the crop production of wheat, maize, and rice were evaluated (Fig. 6). Overall, the total effects of climatic factors on the crop production were positive for wheat [4.24×10^4 t·yr^{-1}, $p < 0.01$; Fig. 7(a)(C7)], maize [3.23×10^4 t·yr^{-1}, $p < 0.01$; Fig. 7(b)(C7)], and rice [1.63×10^4 t·yr^{-1}, $p < 0.01$; Fig. 7(b)(C7)] in the APTZ. From 1980 to 2010, the variations in individual climatic factors led to an increase in the crop productions for wheat, maize, and rice. Figure 6 shows the spatial patterns of linear trend in the annual crop production of wheat, maize, and rice under scenarios C1–C7. The areas (80.1%), where the variation in total climatic variables had a positive impact on wheat production were mainly located in the southwestern region of the APTZ. Considering the combined impact of climatic factors on maize production, the proportion of areas with decreased maize production accounted for 13.2% of the maize-cultivated area, and was concentrated in the northeast. For rice, most of the cultivated area (95.3%) exhibited an increasing trend under scenario C7, and the maximum change was observed in the northeastern region of the APTZ.

3.4 Comparison of the impact of crop distribution and climate change on crop production

To compare the effects of crop distribution and climate change on crop production, we simulated the crop production under scenarios LC1, LC2, and LC3. The results are shown in Fig. 8 and Fig. 9. Under LC1, the high production areas of wheat were mainly concentrated in the southwestern areas of APTZ. The high production areas for maize appeared mainly in the mid-eastern region, whereas the high production areas for rice were concentrated in the northeast. Under LC2, the spatial patterns of crop production were almost the same as under LC1. However, under LC2, the total wheat production was 0.95×10^6 t lower than under LC1. The total production of maize under LC2 was 4.64×10^6 t lower than under LC1, and that for rice was 0.62×10^6 t lower than under LC1.

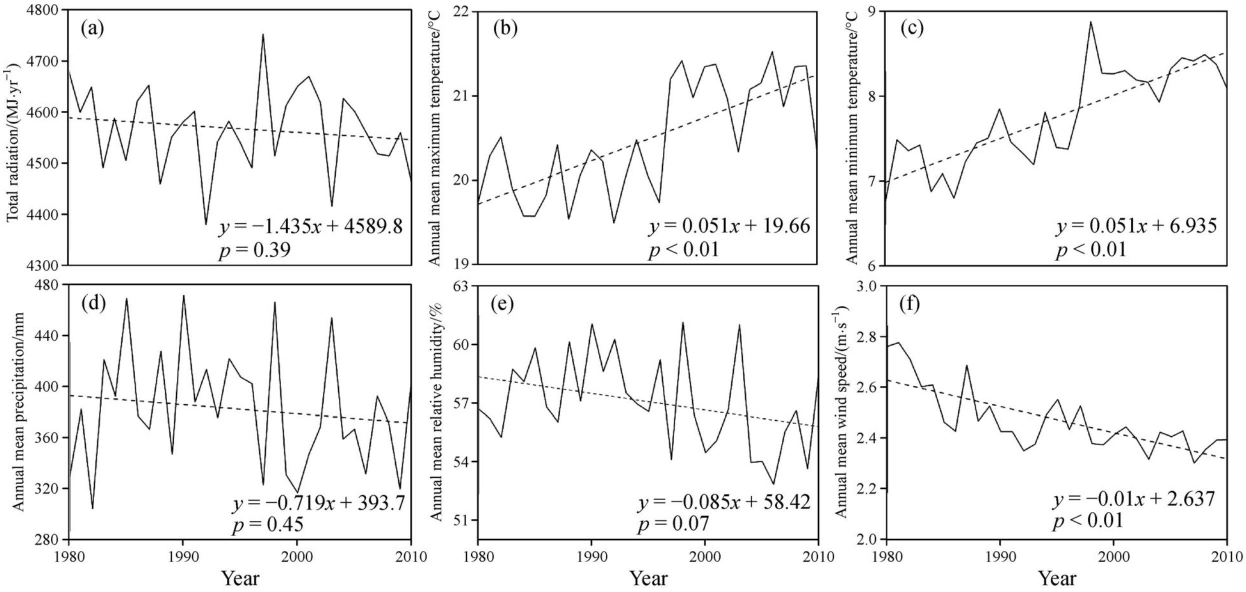

Fig. 5 The change in climatic variables in the APTZ from 1980 to 2010, (a) total radiation, (b) annual mean maximum temperature, (c) annual mean minimum temperature, (d) annual mean precipitation, (e) annual mean relative humidity, and (f) annual mean wind speed.

Under LC3, the spatial patterns of wheat and maize production were almost the same as under LC1. In contrast to LC1, the high production area for rice was mainly concentrated in the southwest. Under LC3, the total production of wheat was 1.71×10^6 t higher than under LC1. The total production of maize under LC3 was 8.53×10^6 t lower than under LC1, and for rice, the total production under LC3 was 0.58×10^6 t lower than that under LC1. By comparing the simulated production under LC1 and LC2, we quantified that climate change led to an increase in the production of wheat, maize, and rice from 1980 to 2010. However, by comparing the simulated production under LC1 and LC3, we determined that the crop distribution change led to a decrease in the wheat production and an increase in maize production from 1980 to 2010. In addition, crop distribution change had a positive impact on the rice production. During the period from 1980 to 2010, the crop distribution change had a greater impact on wheat and maize production than climate change, whereas climate change had a larger impact on the rice production.

4 Discussion

4.1 Impact of crop distribution and climate change on crop production

In order to explore the impacts of crop distribution change on crop production, this study analyzed the spatial-temporal distribution of wheat, maize, and rice in the APTZ over the period from 1980 to 2010. Since 1980, the spatial distribution and crop cultivation areas of wheat, maize, and rice changed significantly. The trends of variation in the wheat, maize, and rice production were approximately consistent with the changes in their cultivated areas. However, the rice production had a sharp increase from 1990 to 2010. This could be attributed to the decrease in the rice-planting area in the southwestern region and a concurrent increase in the northeastern region of the APTZ. The climatic conditions in the northeast of APTZ were more favorable for rice growth (Tao et al., 2008; Zhang et al., 2015). Furthermore, the soil types in the northeastern region are mainly black and meadow soils (Zhang et al., 2007), which were suitable for rice growth. This might be another important reason that led to the sharp increase in the rice production.

Climate warming was obvious in the APTZ from 1980 to 2010 (Figs. 5(b) and 5(c)), and was consistent with the records in China (Qin et al., 2005). However, the impact of climate change on crop production exhibited uncertainty, and the respective effects of individual climatic factors need to be further analyzed. In this study, we designed seven scenarios (C1–C7) to investigate the individual and integrated impacts of climatic variables on crop production. We found that the variation in individual climatic factors led to an increase in crop production from 1980 to 2010 in the APTZ. However, the trend of variation in crop production in scenario C7 was not equal to the sum of trends in scenarios C1–C6 (Table 2). This indicates that the impact of climatic variables on crop production is not independent, and when predicting the future crop production, all the climatic variables related to crop production need to be fully considered.

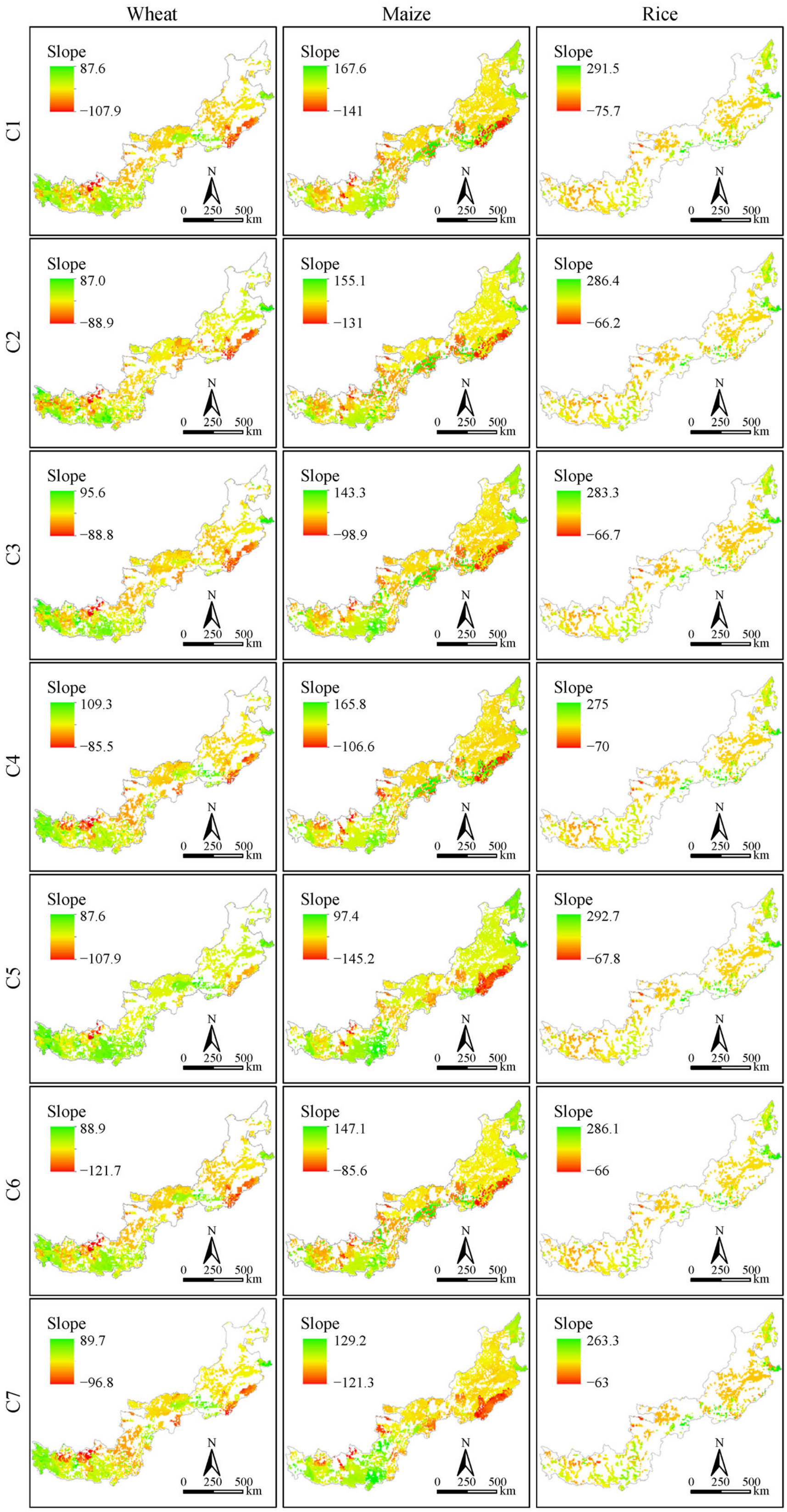

Fig. 6 Spatial patterns of linear trends in annual crop production for scenarios C1–C7 from 1980 to 2010.

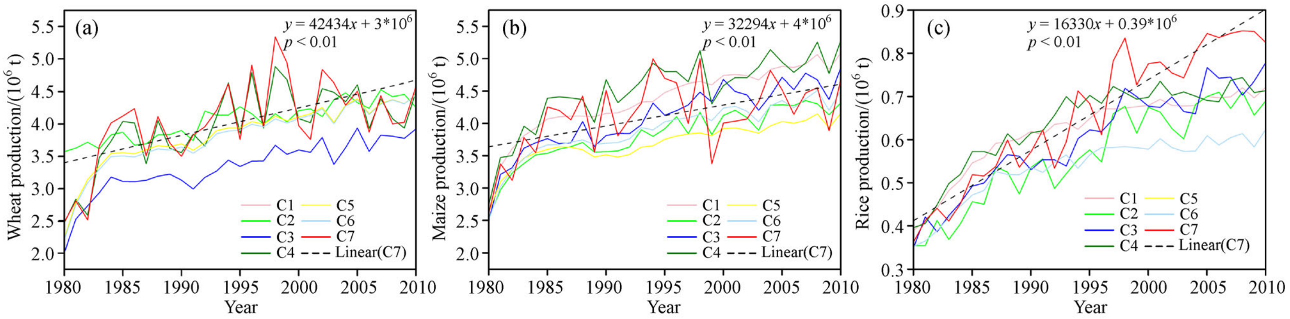

Fig. 7 Variation of crop production under C1–C7 scenarios for wheat (a), maize (b), and rice (c) from 1980 to 2010 in the APTZ.

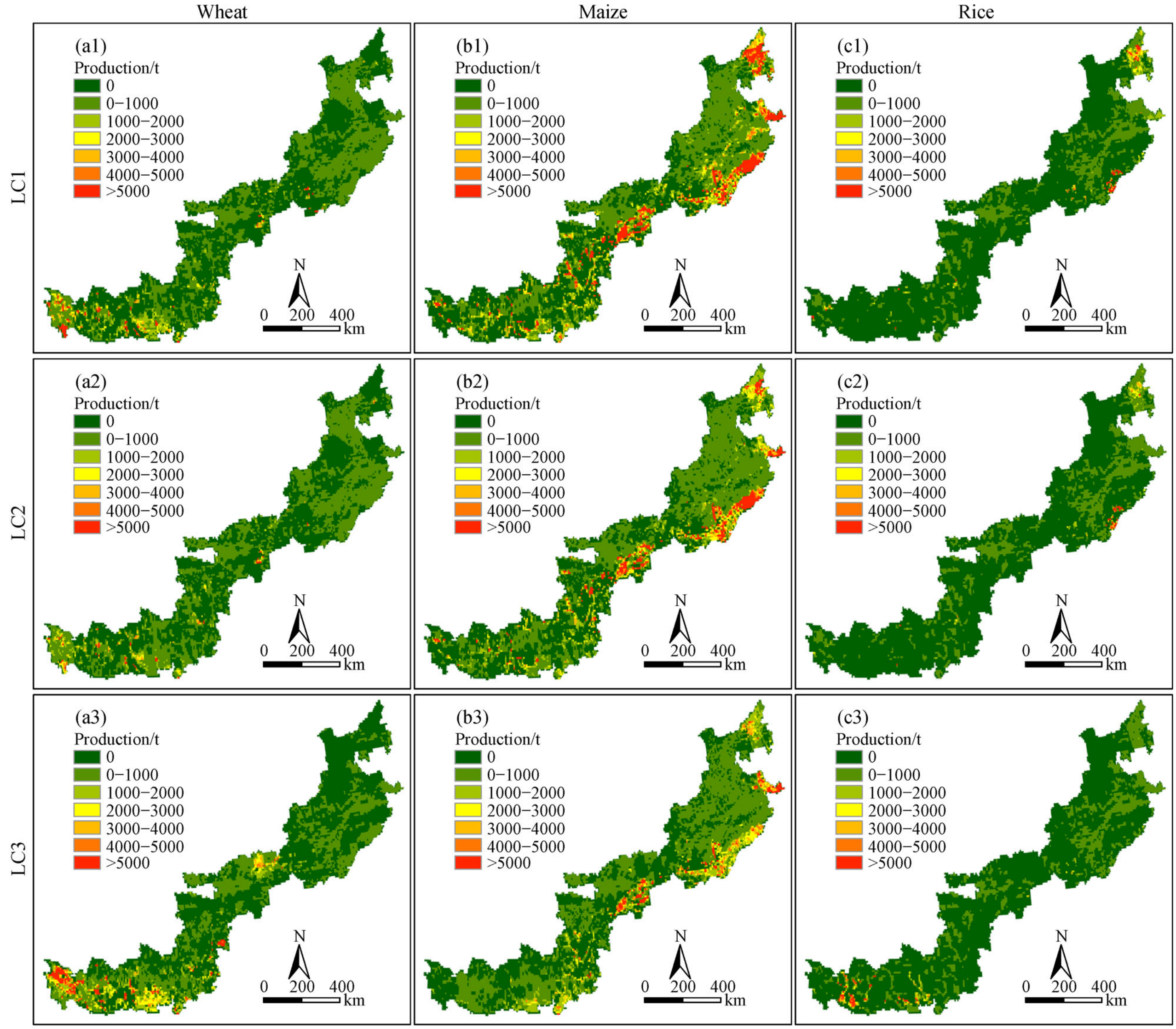

Fig. 8 Spatial patterns of crop production under different scenarios. Scenario LC1 denotes the crop distribution for the three crops and the climate in 2010. Scenario LC2 denotes the crop distribution for the three crops in 2010 and the climate in 1980. Scenario LC3 denotes the crop distribution for the three crops in 1980 and the climate in 2010.

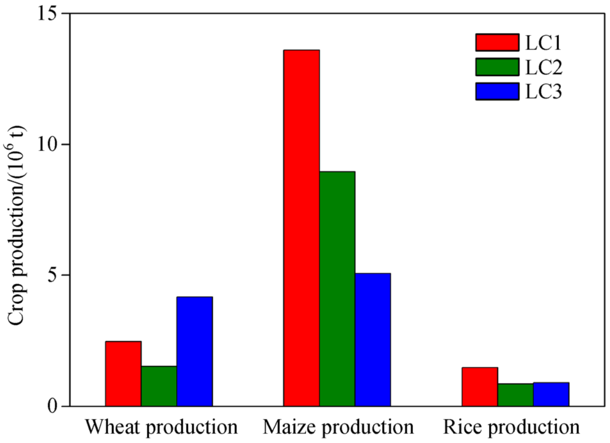

Fig. 9 Crop production of wheat, maize, and rice under different scenarios.

Among the climatic factors, we found that the most important climatic factors for wheat, maize, and rice were precipitation, $T_{\min}$, and $T_{\min}$, respectively in the APTZ (Table 2). The APTZ is located in arid and semi-arid regions where the climate is cold and rainless. Therefore, water is the primary limiting factor for vegetation growth (Hao et al., 2016), particularly for the central areas which has little precipitation. Although the regional annual mean precipitation decreased, the seasonal precipitation was unevenly distributed in the APTZ. The spring precipitation in northeast shows an increasing trend, along with an increase in the summer precipitation in the southwest (Zhang et al., 2011b). The crop distribution for wheat, maize, and rice were mainly concentrated in the northeast and southwest, where the precipitation has increased. Therefore, the variation in precipitation led to the increase in crop production. Furthermore in this study, the auto-irrigation option was chosen for the areas which had irrigation conditions owing to the lack of irrigation data. This option exerted effects on accuracy when evaluating the impact of precipitation on crop production. However, the area with irrigated conditions was very small and thus had little effect on the overall estimation of total crop production. Moreover, temperature played a significant role in the variation of crop production due to the regional climate characteristics. The warming trend extended the grain-filling duration and increased the crop production, particularly in the cold areas (i.e., northeast of the APTZ) (Tao et al., 2008). In addition, as the primary driving factor in wind erosion, the decreased wind speed reduced the soil carbon loss due to soil erosion (Zhang et al., 2011a), thus increasing the crop production. Although air humidity could indirectly exert effects on crop production by affecting the processes of crop evaporation and transpiration in crops (Sharpley and Williams, 1990; Mo et al., 2009), it is not the primary factor for crop production in this region (Table 2). There was sufficient solar radiation in the APTZ due to the low number of rainy days, and thus the changes in solar radiation played a small role in the variation of crop production, compared with other climatic variables from 1980 to 2010.

Crop distribution and climate change have comprehensive effects on crop production. However, the effects of these two key drivers are usually combined (Lorencová et al., 2013). Numerous studies have been carried out to investigate the impact of climate change on crop production (Yao et al., 2007; Wu et al., 2014; Yin et al., 2015), whereas few studies have evaluated the effects induced by crop distribution change. Decoupling the effects of crop distribution and climate change on the crop production of wheat, maize, and rice is challenging. Although using controlled experiments for solving ecological questions is nearly impossible, particularly for large regions (Walters and Holling, 1990; Zhang et al., 2014), ecological models with scenario designs provide an effective way to investigate the environmental issues (Nemani et al., 2003). In this study, to compare the impact of crop distribution and climate change on crop production from 1980 to 2010, three scenarios (LC1, LC2, and LC3) were designed. Our study indicated that the crop distribution change was the leading factor, which led to variation in the production of wheat and maize, whereas climate change was the predominant factor for rice.

Table 2 Linear trend of crop production under different scenarios

Group		Scenario	Wheat		Maize		Rice	
			Slope/(t· yr^{-1})	*p*	Slope/(t· yr^{-1})	*p*	Slope/(t· yr^{-1})	*p*
I	Impact of crop distribution change	L1	2.05×10^5	< 0.05	1.0×10^6	0.08	1.08×10^5	0.35
II	Impact of climate change	C1	3.85×10^4	< 0.01	4.34×10^4	< 0.01	0.91×10^4	< 0.01
		C2	2.85×10^5	< 0.01	4.23×10^5	< 0.01	1.16×10^5	< 0.01
		C3	4.15×10^4	< 0.01	5.21×10^4	< 0.01	0.84×10^4	< 0.01
		C4	4.48×10^4	< 0.01	5.03×10^4	< 0.01	0.95×10^4	< 0.01
		C5	3.86×10^4	< 0.01	3.08×10^4	< 0.01	0.72×10^4	< 0.01
		C6	3.00×10^4	< 0.01	4.35×10^4	< 0.01	0.74×10^4	< 0.01
		C7	4.24×10^4	< 0.01	3.23×10^4	< 0.01	1.63×10^4	< 0.01

4.2 Implications for agricultural management

Our study indicated that the local agricultural policies could be adjusted to increase crop production and mitigate the unfavorable effects of climate change. First, as the predominant factor affecting crop production is the crop distribution, we could improve crop production by directly adjusting the crop cultivation areas. Second, moisture played an important role in determining the crop production for arid and semi-arid regions. In order to mitigate the effects of precipitation scarcity, more irrigation facilities should be developed in this region. Third, low temperatures are critical stress factors for crop production due to the climate characteristic of the APTZ. Therefore, plastic film technology should be applied in this region to mitigate the effects of low temperature and improve the crop production.

5 Conclusions

In this study, we investigated the relative impact of crop distribution and climate change on the crop production of wheat, maize, and rice from 1980 to 2010, using the GIS-based EPIC model under different scenario designs. The approach we used here could be applied in other similar studies. The simulation results showed that both crop distribution and climate change had a positive impact on crop production in the APTZ during the study period, except for wheat production, which decreased due to the crop distribution change. Moreover, crop distribution change exerted a larger impact on wheat and maize production, whereas climate change had a greater effect on rice production, during the study period. This study can help guide agricultural policy adjustments to improve crop production and mitigate the threat of future food insecurity due to crop distribution and climate change.

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