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Changes in production potentials of rapeseed in the Yangtze River Basin of China under climate change:

A multi-model ensemble approach

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Abstract: Rapeseed is one of the major oil crops in China and it is very sensitive to climate change. The Yangtze River Basin is the main rapeseed production area in China. Therefore, a better understanding of the impact of climate change on rapeseed production in the basin is of both scientific and practical importance to Chinese oil industry and food security. In this study, based on climate data from 5 General Circulation Models (GCMs) with 4 representative concentration pathways (RCPs) in 2011–2040 (2020s), 2041–2070 (2050s) and 2071–2100 (2080s), we assessed the changes in rapeseed production potential between the baseline climatology of 1981–2010 and the future climatology of the 2020s, 2050s, and 2080s, respectively. The key modelling tool – the AEZ model – was updated and validated based on the observation records of 10 representative sites in the basin. Our simulations revealed that: (1) the uncertainty of the impact of climate change on rapeseed production increases with time; (2) in the middle of this century (2050s), total rapeseed production would increase significantly; (3) the average production potential increase in the 2050s for the upper, middle and lower reaches of the Yangtze River Basin is 0.939, 1.639 and 0.339 million tons respectively; (4) areas showing most significant increases in production include southern Shaanxi, central and eastern Hubei, northern Hunan, central Anhui and eastern Jiangsu.

Keywords: climate change; rapeseed production; AEZ; Yangtze River Basin

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1 Introduction

Rapeseed is the third most important oilseed produced globally, and production has expanded remarkably in most of the major producing nations in recent years (FAOSTAT, 2015). Growing population, expanding affluence, rapid urbanization, and changing dietary preferences have driven the increase in global demand for edible oil products (Foley *et al*. 2005; Kastner *et al*. 2012). It has been estimated that global production of vegetable oils must nearly double by 2050 to meet FAO projections for food, fuel and industrial demands (FAO, 2003). China is the largest producer and consumer of rapeseed oil in the world, with more than 50% of the edible oil (being rapeseed oil) consumed in the country as a result of the dietary habit of the Chinese. The country is expected to import more than 15 million tons of edible oil to meet domestic consumer demand by 2030 (Tian *et al.*, 2014a). This heavy dependence of edible oil on imports has attracted great concerns about the domestic supply capability and the associated food security risk for China. Rapeseed is mainly distributed in the Yangtze River Basin, which is the world's largest rapeseed production area and accounts for more than 80% of national total production in China. Therefore, an in-depth study on the impact of future climate change on rapeseed production in the Yangtze River Basin is of great significance for Chinese edible oil industry and food security.

Supply capability concerns are further amplified by climate change, because rapeseed production is very sensitive to climate conditions. To address the concerns on rapeseed production capability under future climate change, this paper employs the well-known Agro-Ecological Zone (AEZ) model to simulate the impact of future climate change on rapeseed production potential in the Yangtze River Basin in China. The simulations are carried out for the climate change predictions of 5 General Circulation Models (GCMs) with 4 representative concentration pathways (RCPs) in 2011–2040 (2020s), 2041–2070 (2050s) and 2071–2100 (2080s). The ensemble outputs of the AEZ simulations give a probabilistic assessment of the changes in production potentials of rapeseed in the Yangtze River Basin under climate change.

Crop simulation models are useful tools in climate impact studies as they can integrate the soil-plant-atmosphere continuum and trace how multiple climate factors interact with crop growth and yield processed (Challinor *et al.*, 2014). Many crop models have been developed and applied in climate impact assessment, production estimation, cultivation and management for rapeseed, including APSIM (Agricultural Production Systems Simulator), CSM-CROPGRO-Canola, EPIC (Environmental Policy Integrated Climate), and the AEZ model. The APSIM model (Holzworth *et al.*, 2014) simulates crop growth processes and accounts for farming system management, soil processes, and climate in a dynamic way across sites and seasons. Farre *et al.* (2002) concluded that the APSIM-Canola model, together with long-term weather data, can be reliably used to quantify yield expectation for different cultivars, sowing dates, and locations in the grain belt of Western Australia. The APSIM-Canola model was applied to simulate the impacts of future climatic changes on the growth and yield of rapeseed in China under the regional climate model PRECIS, showing a decrease in rapeseed yields in each considered period (Zhang *et al.*, 2011). EPIC is a cropping system model that has been widely used for estimating soil productivity in the world since it was published in 1985. Based on the EPIC model and the RegCM3 model, the impact of climate change on the major grain and oil crops in the Loess Plateau of China was analyzed and rapeseed yield in the semi-humid region of the Loess Plateau found to increase between 2001–2050 compared to the 1961–2000 baseline (Wang *et al*., 2011). The CSM-CROPGRO model (Boote *et al*., 1998) was adapted in the DSSAT (Decision Support System for Agro-technology Transfer) to simulate spring canola (Saseendran *et al*., 2010). The DSSAT model (Deligios *et al*., 2013) was used to simulate the development, growth and distribution of rapeseed in the Mediterranean environment, showing high accuracy.

However, most of the previous studies and simulation models have focused on site-level analysis and not paid sufficient attention to cultivars adaptation at a large scale. The Yangtze River Basin is vast and significant differences exist in observed climatic changes in the upper, middle and lower reaches (Tian *et al*., 2013). In addition, because of the spatial variability of climate and soil, there are often mismatches between the crop varieties (with their respective growth calendar) in the model and the actual varieties in the area. Existing simulations of rapeseed production potentials have shown a lack of attention to cultivars adaptation under the historical and forthcoming climate change. The AEZ model, which is an agro-ecological productivity model, has been extensively used in the impact assessment literature for agriculture. It can speedily assess the impact of climate, soil, and other factors on production potentials across grid cells of a large area. The AEZ model was used to analyze China's rapeseed production potential in different periods (Cai, 2007; Cai *et al.*, 2009). However, these estimations were based on the default cultivar parameters of the 2002 version of the AEZ, which represented prevailing rapeseed cultivars in the 1970s and included only one variety for winter and spring oilseed respectively. In this research, we enrich and update the rapeseed cultivars in the AEZ model based on the observation records of 10 representative sites in the Yangtze River Basin.

It should be noted that the estimates of climate change impacts on the growth and development of crops are characterized by large uncertainties, mainly because of the choice of carbon emission scenarios, climate models, and crop models (Trnka *et al*., 2014). By considering the uncertainties of climate change forecasting, the multi-model ensemble simulation method can be used to describe a range of possibility for future climate projection (Yang *et al*., 2017). Many studies have used this approach to construct a set of probability estimation, so as to express and assess the impact of climate change on agriculture (Hansen *et al.*, 2006; Tao *et al.*, 2009; Tebaldi *et al.*, 2008). Tang *et al*. (2015) used the projections derived from four global gridded crop models (GGCropMs) to assess the effects of future climate change on the yields of major crops (i.e., maize, rice, soybean and wheat) in China. Masutomi *et al*. (2009) used a combined set of 49 GCMs in three emission scenarios to assess the impact of climate change on rice production. Yang *et al.* (2017) assessed the effects of heat stress on wheat yields in China using the ensemble method with climate projections based on 30 Atmosphere-Ocean General Circultaion Models (AOGCMs) under representative concentration pathway scenarios in the Coupled Model Inter-Comparison Project Phase 5 (CMIP5). However, most of Multi-Model climate prediction methods are applied to simulate the impact of climate change on food crops. There are still few studies on the possible impact of climate change on future rapeseed production in China with this ensemble method.

We develop a probabilistic estimation of the effects of climate change on rapeseed in the Yangtze River Basin by making use of multi-model ensemble output. More specifically, we use 5 GCMs under 4 RCP scenarios in the CMIP5 of the IPCC Fifth Assessment Report, for a total of 20 climate change scenarios in the 2020s, 2050s, and 2080s. In this way, we provide scientifically robust information for supporting the future regional planning of oilseed production in China.

2 Materials and methods

2.1 Study area

The Yangzte River Basin is located between 24º–35º and 90º–122ºE. The Qinghai-Tibet Plateau section of the Yangtze River basin is characterized by a plateau mountain climate, while the rest of the basin has a subtropical monsoon climate. Due to the rich agricultural climate resources such as sunshine, temperature, water and soil, the Yangtze River Basin has played an important role in China's grain production and has made important contributions to China's national economic development and social stability.

Our research area corresponds to the rapeseed dominant planting zone in China (Xiao, 2009). It is one of the most important winter rapeseed planting regions in China and includes the provinces of Sichuan, Yunnan, Guizhou, Chongqing, Shaanxi, Hubei, Hunan, Henan, Jiangxi, Anhui, Jiangsu, Zhejiang and Shanghai. It covers more than 2.2 million square kilometers and can be divided into upper, middle and lower reaches according to the climate and land resources (Figure 1). The humidity and temperature are very suitable for winter rapeseed growth.

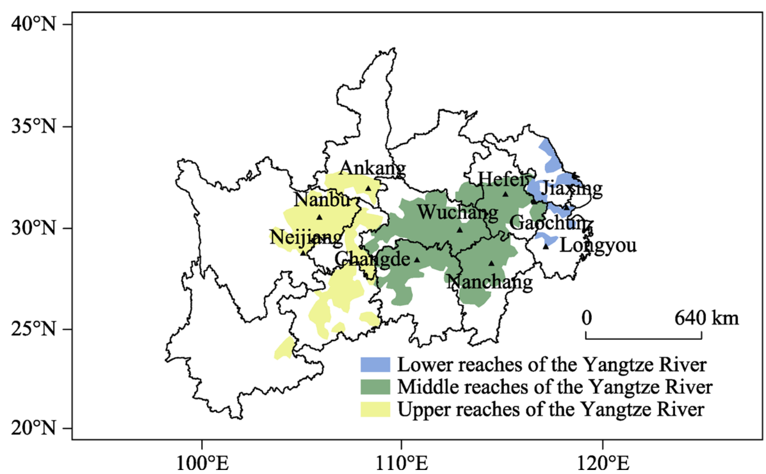

Figure 1 Distribution of rapeseed observation stations in China

2.2 Dataset

2.2.1 Observation stations

Ten agro-meteorological observation stations are selected out of 49 observation sites based on the following criteria: (1) representative sites in each section of the Yangtze River Basin; and (2) more than 15 years observations of rapeseed crop management information. General information on these stations is shown in Table 1.

The crop growth records at the 10 agro-meteorological observation stations in the Yangtze

River Basin are from the Chinese Meteorological Administration (CMA) and cover the period 1981–2010. The records include detailed information on crop calendar, such as sowing date, emergence date, blossom date, and harvest date. They also include yield information, such as seed weight, the ratio between seed and stem, theoretical productivity and actual yield per unit area. These records can be used to update the cultivar parameters of the AEZ model.

Table 1 The location information of selected 10 stations

Station	Province	Latitude	Longitude
Neijiang	Sichuan	29°35′N	105°5′E
Nanbu	Sichuan	31°21′N	106°3′E
Ankang	Shaanxi	32°43′N	109°2′E
Changde	Hunan	29°3′N	111°41′E
Wuchang	Hubei	30°21′N	114°19′E
Nanchang	Jiangxi	28°33′N	115°57′E
Hefei	Anhui	31°52′N	117°14′E
Gaochun	Jiangsu	31°19′N	118°53′E
Longyou	Zhejiang	29°2′N	119°11′E
Jiaxing	Zhejiang	30°47′N	120°44′E

2.2.2 Climate data

CMIP5 used a ‘representative concentration pathways (RCPs)’ radiation forcing scenario that contains four radiation forcing concentrations, RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, respectively (Moss *et al.*, 2010). The RCP 2.6 scenario refers to radiation forcing reaching 2.6 W/m^2 in 2100, while temperature is expected to rise between 1.6–3.6℃. RCP 4.5 is an intermediate stable path, under which the radiation forcing will stabilize at 4.5 W/m^2, the equivalent of 650 ppm of CO_2 concentration. Under RCP 8.5, radiation forcing will be greater than 8.5 W/m^2 while CO_2 concentration will exceed 1370 ppm (Taylor *et al.*, 2012).

The climate scenario data included outputs from five global climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M) driven by the above four RCPs. Each global climate model has 7 climate variables, as included in the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP) dataset: surface air temperatures, precipitation, surface radiation (short and long wave down welling), near surface wind speed, surface air pressure, near surface relative humidity and CO_2 concentration (Warszawski *et al.*, 2014).

2.2.3 Soil data

Harmonized World Soil Database (HWSD) is employed as the soil input data into the AEZ model. The HWSD was developed by the Land Use Change and Agriculture Program of the International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization of the United Nations (FAO). The HWSD provides reliable and harmonized soil information at the grid cell level for the world, with a resolution of 1 km × 1 km for China (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). The China-AEZ Model evaluates crop-specific yield reduction due to limitations imposed by soil and terrain conditions.

2.2.4 Land use data

The cultivated land distribution data comes from the National Land Use Database of Resources and Environment Data Center of Chinese Academy of Sciences. The database is a multi-temporal land use dataset of 1:10000 scale covering the whole land area of China, which is supported by the National Science and Technology Support Program and the Knowledge Innovation Project of the Chinese Academy of Sciences. With the support of many major science and technology projects, the database has been established for a number of years (Liu *et al.*, 2000; Liu *et al.*, 2003; Liu *et al.*, 2005). The dataset uses Landsat terrestrial satellite remote sensing image as the main data source, and is generated by artificial visual interpretation. The land use types include six primary types (i.e., cultivated land, forest land, grassland, water area, residential land and unused land) and 25 secondary types. Through field investigation and field verification, the comprehensive evaluation accuracy of the land use type has reached 94.3% (Liu *et al.*, 2003; Liu *et al.*, 2010; Liu *et al.*, 2014). In this study, the spatial distribution data of cultivated land in the Yangtze River Basin were extracted from the land use datasets in 2015, overlaid with the rapeseed dominant planting zone in China (Xiao, 2009).

2.3 Model and methodology

2.3.1 The AEZ Model

The AEZ model was jointly developed by IIASA and FAO (Fischer *et al.*, 2002). AEZ Ver. 3.0 (IIASA/FAO, 2012) employs simple and robust crop models and provides standardized crop-modeling and environmental matching procedure to identify crop-specific limitations of prevailing climate, soil and terrain resources under assumed levels of inputs and management conditions. The standardized crop-modeling and environmental matching procedure in the AEZ makes it well suited for crop productivity assessment at regional, national and global scales. In this research, crop cultivar parameters in Land Utilization Types (LUTs) from the AEZ are enriched and updated based on the observation data.

Because of the spatial variability of climate and soil, there are often big differences between the crop varieties modelled and the actual varieties planted in the study area. A lack of attention to such differences would severely undermine the performance of the model simulations (Luo *et al.*, 2008). We detected such differences for the AEZ model as well. To enrich the crop cultivar parameters in land utilization types of the AEZ, it is necessary to improve the accumulated temperature thresholds and temperature demand distribution equation in the AEZ. In this study we carried out the modification of physiological and ecological parameters of rapeseed, including length of growth period, harvest index, accumulated temperature threshold and temperature distribution equation. Information on these factors was directly related to the growth and yield of rapeseed cultivars under different environments.

Temperature is a major determinant of crop growth and development. In the AEZ model, the effect of temperature on crops is characterized in each grid cell by thermal regimes, and the temperature demand distribution equation is an important one in thermal regimes. Based on our detailed observations and historical climate data, we reduced the proportion of the high temperature stage in the rapeseed growth stage in the temperature demand equation, and assigned specific temperature distribution requirements to newly added Chinese subtropical rapeseed varieties. In addition, we have also made improvements in the following aspects, as shown in Table 2. First of all, we added spring rapeseed varieties in Chinese subtropical rape-producing areas. Second, the length before (Cya) and after hibernation (Cyb) for winter rapeseed varieties was adjusted and the harvest index (HI) of spring rapeseed varieties increased. Finally, in view of the consistency with the correction of the temperature distribution, we reduced the minimum threshold (TS1n) and the maximum threshold (TS1x) of the optimum accumulated temperature during the growth period, so that the demand for high temperature during the growth period is reduced and the lower temperature conditions begun to adapt to rapeseed cultivation. The above enrichments lead to significant improvement in the ability and accuracy of the AEZ simulation at the site level, as we present in more details in Section 3.1.

Table 2 Comparison of cultivar parameters

Cultivar	Original parameters				New parameters			
	Cya+Cyb	HI	TS1n	TS1x	Cya+Cyb	HI	TS1n	TS1x
Wrs 1	35+105	0.25	1500	2100	55+85	0.25	1100	1600
Wrs 2	40+120	0.25	1600	2400	65+90	0.25	1200	1800
Wrs 3	45+135	0.25	1700	2700	75+95	0.25	1300	1950
Wrs 4	45+150	0.25	1800	3000	85+100	0.25	1400	2100
Srs 1	0+150	0.20	1400	1850	0+105	0.23	1200	2150
Srs 2	0+120	0.21	1500	2100	0+120	0.23	1300	2300
Srs 3	0+135	0.22	1600	2350	0+135	0.23	1400	2400
Srs 4	0+150	0.23	1700	2600	0+150	0.23	1500	2500
New 1					0+150	0.25	1500	2500
New 2					0+165	0.25	1650	2600
New 3					0+180	0.24	1800	2700
New 4					0+195	0.24	2000	2800
New 5					0+210	0.23	2150	2900
New 6					0+225	0.23	2300	3000

Wrs: Winter rapeseed; Srs: Spring rapeseed; New: newly added Chinese subtropical rapeseed varieties; Cya: the length before hibernation; Cyb: the length after hibernation; HI: harvest index; TS1n: the minimum threshold of the optimum accumulated temperature during the growth period; TS1x: the maximum threshold of the optimum accumulated temperature during the growth period.

2.3.2 Procedure

The physiological and ecological parameters of rapeseed including length of growth period, harvest index, accumulated temperature threshold and temperature distribution equation are calibrated and validated using the observations. Future climate impact on rapeseed production under 20 climate change projections are simulated in the 10 representative sites. Climate change in the Yangtze River Basin and its impact on rapeseed production in the 2050s is obtained with 2 global climate models under 4 RCP scenarios and used to provide scientific basis for rapeseed planting adaptation policy in the Yangtze River Basin. Figure 2 summarizes the procedure of our work.

3 Results

3.1 Model validation

We calibrated and validated the new AEZ rapeseed cultivar parameters under observed historical climate conditions. In order to validate the simulation capability of the AEZ model, four sites with long time series were extracted from the simulation results. By comparing the variation trend of simulated yield and observed yield with time, the simulation ability of the updated AEZ model is further evaluated. As Figure 3 shows, Changde, Wuchang, Hefei and Gaochun were selected as the verification sites in our study. The overall trend for the AEZ simulated production potential and the actual yield in 1981–2010 is basically the same, showing a significant correlation, which means that the improved AEZ model performs very well in these stations.

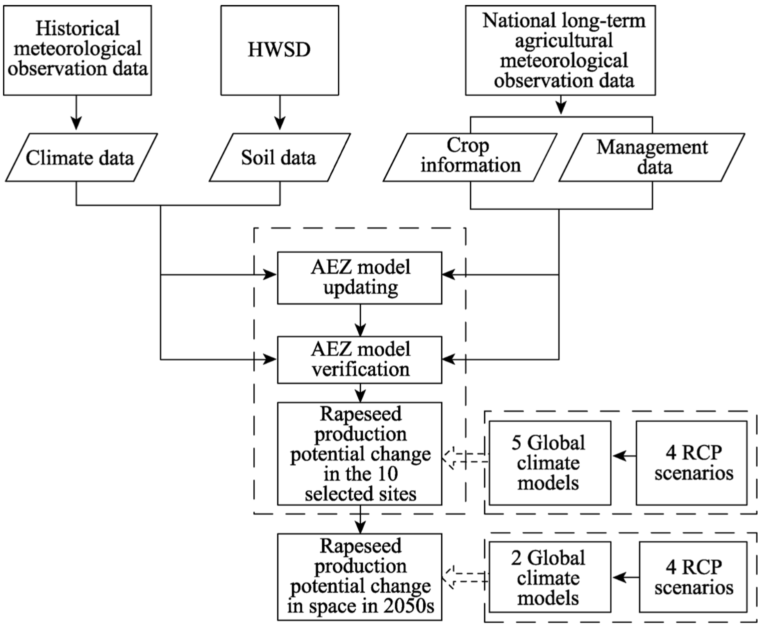

Figure 2 Technological roadmap

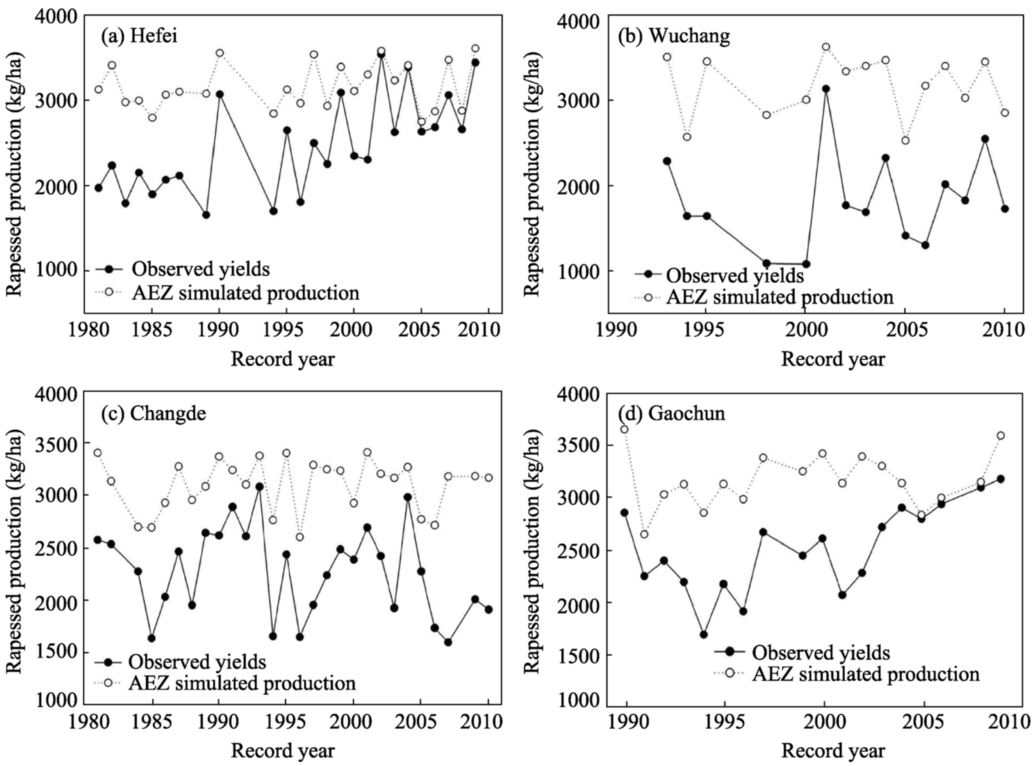

Figure 3 Comparison of simulated attainable yields with observed yields

3.2 Changes in the rapeseed productive potentials at the station level under the future climate scenarios

Figure 4 shows the ensemble yield changes relative to the baseline under the rain-fed condition. In the early 21st century (2020s), Neijiang and Ankang show increasing production possibilities relative to the baseline, while Nanbu, Changde, Nanchang and Longyou have a significance probability of yield reduction. In the mid-21st century (2050s), the production of 8 stations is expected to increase relative to the 2020s, especially at the Hefei station, where the median value of rapeseed production will exceed the baseline. By the end of the 21st century (2080s), 6 of the 10 stations have a big possibility in production increasing relative to baseline. It also shows that the length of the histogram increases with time, which means that the range of fluctuation in rapeseed production changes is increasing, implying an increase in the uncertainty associated with the impact of climate change on rapeseed.

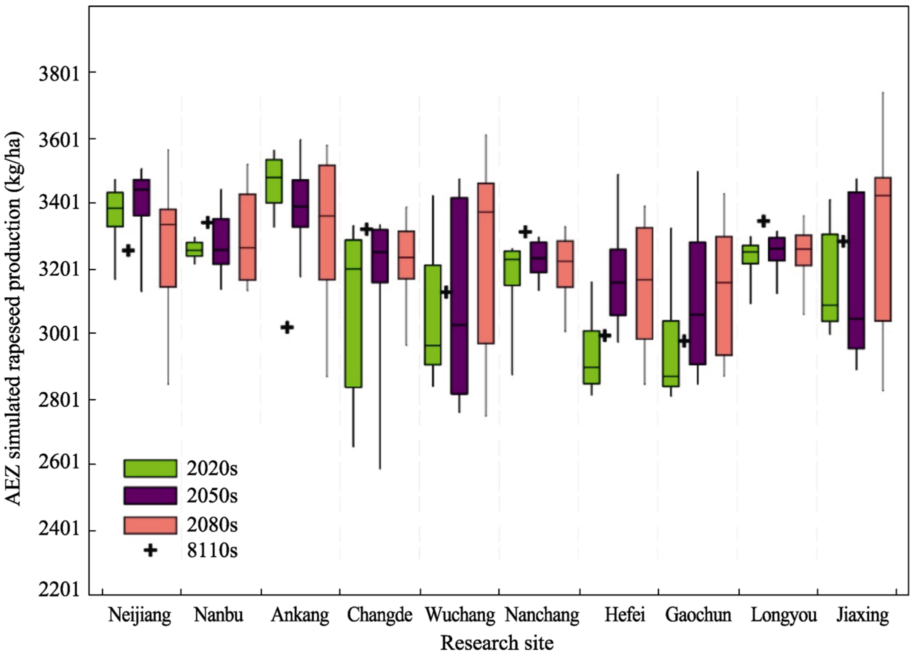

Figure 4 The ensemble yields of rain-fed winter rapeseed in the 2020s (green), 2050s (purple), and 2080s (red). The plus represents the 30-year average rain-fed rapeseed yield from 1981 to 2010 simulated with the observation data as the baseline. The horizontal line denotes the ensemble median.

Based on the rapeseed production simulated by the AEZ model with 5 GCMs and 4 RCPs under 3 future periods at the ten stations, we conduct a t-test analysis of potential impact of future climate change on rapeseed production. The results are reported in Table 3. T-test uses T-distribution theory to infer the occurrence probability of differences, to determine whether the difference between the two mean value is statistically significant or not. Based on Figure 4 and Table 3, we find that t-test results of Changde, Nanchang and Longyou are significant at the 1% level for all three periods, indicating that these three sites are significantly affected by future climate change and have a high likelihood of yield reduction. The significant level at Neijiang, Nanbu, Ankang and Jiaxing is less than 5% in the 2020s and 2050s, while not significant under the climate condition of the 2080s, the latter of which indicated statistically insignificant difference between the 2080s and baseline. Neijiang and Ankang show a yield increase in the 2020s and 2050s, whereas Nanbu and Jiaxing may experience yield decrease in these two periods. Compared to the baseline, there is no significant differences for the rapeseed yield in Hefei and Gaochun during the 2020s, while it is more likely to increase in the 2050s and 2080s. The t-test results at Wuchang station show a significance at 10% level for the 2080s only, indicating a moderately significant chance for this station to have yield increase in that period.

Table 3 T-test analysis of rapeseed yield variation in the Yangtze River Basin under future climatic conditions

Sites	Baseline (kg/ha)	Scenarios	Sig	Significance
		2020s	5.37E-04	***
Neijiang	3252	2050s	1.41E-06	***
		2080s	8.52E-01	
		2020s	9.59E-14	***
Nanbu	3338	2050s	7.27E-03	***
		2080s	1.28E-01	
		2020s	9.75E-16	***
Ankang	3207	2050s	1.53E-07	***
		2080s	1.04E-01	
		2020s	3.19E-04	***
Changde	3317	2050s	9.57E-03	***
		2080s	7.26E-03	***
		2020s	1.05E-01	
Wuchang	3125	2050s	7.30E-01	
		2080s	5.35E-02	*
		2020s	1.65E-04	***
Nanchang	3309	2050s	2.13E-04	***
		2080s	1.44E-04	***
		2020s	6.54E-02	*
Hefei	2992	2050s	5.69E-06	***
		2080s	1.34E-03	***
		2020s	5.92E-01	
Gaochun	2975	2050s	1.71E-02	**
		2080s	1.60E-03	***
		2020s	9.98E-09	***
Longyou	3342	2050s	4.33E-08	***
		2080s	3.06E-03	***
		2020s	1.47E-03	***
Jiaxing	3280	2050s	1.95E-02	**
		2080s	5.04E-01	

Note: *, **, and *** denote the level of significance at 10%, 5%, and 1%, respectively.

3.3 Changes in rapeseed production potential in the Yangtze River Basin by the 2050s

Table 4 shows the changes in total rapeseed production potential for the upper, middle and lower reaches of the Yangtze River Basin under 2 GCMs driven by 4 RCP scenarios in the 2050s relative to the baseline.

In the upper reaches of the Yangtze River Basin, except for climate model GFDL-ESM2M driven by RCP 6.0, our simulations under all other scenarios show a yield increase compared with the results in baseline. The average increase in total production potential of the 8 combinations for the upper reaches is 0.939 million tons. The largest increase is 1.911 million tons under the NorESM1-M and RCP 2.6 scenario.

Table 4 Total rapeseed production changes for the upper, middle and lower reaches of the Yangtze River in the 2080s (million tons)

Scenarios	climate models	Upper reaches (mt)	Middle reaches (mt)	Lower reaches (mt)
RCP2.6	GFDL-ESM2M	0.826	2.528	0.507
	NorESM1-M	1.911	2.583	0.385
RCP4.5	GFDL-ESM2M	0.802	3.316	0.927
	NorESM1-M	1.441	2.263	0.223
RCP6.0	GFDL-ESM2M	–0.122	–2.333	–0.217
	NorESM1-M	0.748	1.705	0.241
RCP8.5	GFDL-ESM2M	0.779	0.240	–0.005
	NorESM1-M	1.130	2.810	0.648
Average		0.939	1.639	0.339

In the middle reaches of the Yangtze River Basin, our simulations under 7 of the 8 combinations show an increase. The average increase in total production potential is 1.639 million tons, while the largest increase is 3.316 million tons under the GFDL-ESM2M and RCP4.5 scenario. NorESM1-M produces an increase with all 4 RCPs scenarios.

In the lower reaches of the Yangtze River Basin, which include Jiangsu, Zhejiang and Shanghai, our simulations under 6 of the 8 combinations show an increase. The average increase is 0.339 million tons. The NorESM1-M once again produces an increase with all of the 4 RCPs scenarios. The largest increase in production potential is 0.927 million tons under the GFDL-ESM2M and RCP4.5 combination.

The above results indicate that our simulations under the GFDL-ESM2M and RCPs scenarios show more variation than under the NorESM1-M and RCPs scenarios in terms of rapeseed production in the Yangtze River Basin in the 2050s.

Figure 5 shows the changes in rapeseed yield at the grid-cell level between the baseline and the middle of the 21st century produced under the combined scenarios of RCPs and GFDL-ESM2M and NorESM1-M, respectively. In the upper reaches of the Yangtze River Basin, our simulations under almost all of the 8 combinations show a yield increase in southern Shaanxi and northern Chongqing. In contrast, except for the climate model NorESM1-M driven by RCP 2.6, our simulations under all other combinations show a slight yield decrease (0–250 kg/ha) in the east of Sichuan Province.

In the middle reaches of the Yangtze River Basin, our simulations under all 8 combinations of GCMs and RCPs show a yield increase in central and eastern Hubei, northern Hunan and central Anhui. In Jiangxi Province, nevertheless, the rapeseed yield is expected to slightly decrease under the 8 combinations in the 2050s.

In the lower reaches of the Yangtze River Basin, the upper coastal part of Jiangsu Province shows a significant yield increase under the 8 combinations by the end of the century. In the rest of the regions, rapeseed yield may keep a relatively stable level or slight decrease, in comparison with the baseline.

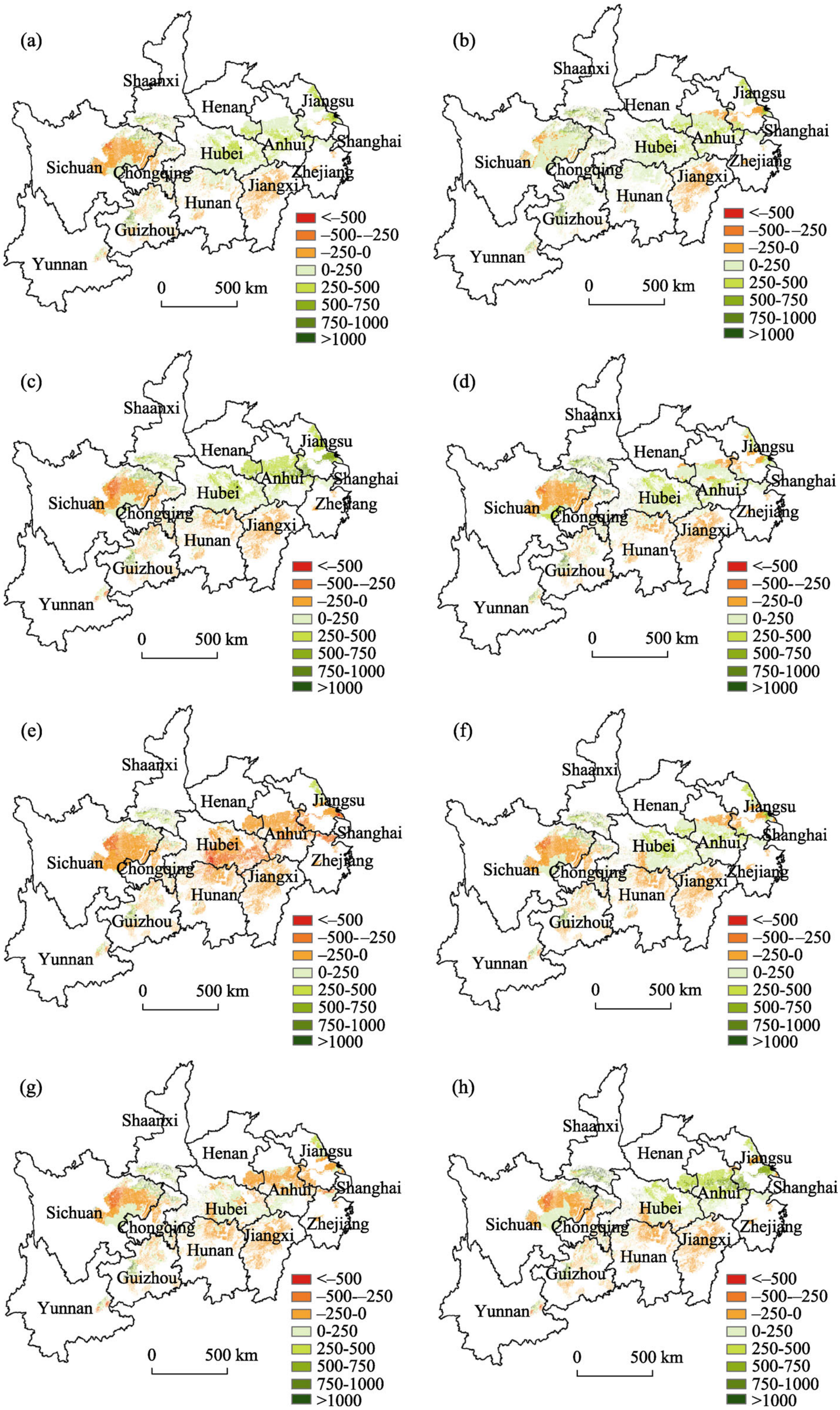

Figure 5 Rapeseed yield change from the baseline to the mid-21st century (2050s) under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios produced with GFDL-ESM2M (a–d) and NorESM-M (e–h) climate models

4 Discussion and conclusion

In this study, the cultivar parameters of rapeseed in the AEZ model were calibrated and validated using the observations in 10 representative sites in the Yangtze River Basin. Based on the updated AEZ model, we simulated rapeseed production in the future under 20 sets of climate change projections. We first estimated the probability of change in rapeseed production potentials relative to the baseline for the 10 representative sites, and then we assessed the total rapeseed production change for the whole basin and yield changes across grid-cells of the basin in the 2050s. We found that the uncertainty of the impact of climate change on rapeseed production increases with time. There are some differences between the different scenarios and climate models, but the production change in space was overall consistent across these climate predictions. In the middle of the century, the average increase in the total production potential under the 8 scenario combinations for the upper reaches will be 0.939 million tons, mainly distributed in southern Shaanxi and northern Chongqing. For the middle reaches, there will be a significance possibility of increasing rapeseed production in central and eastern Hubei, northern Hunan and central Anhui. As for the lower reaches of the Yangtze River Basin, our simulations under 6 of the 8 scenario combinations show an increase in yield, mainly distributed in eastern Jiangsu Province along the coast. Deniel *et al*. (2009) examined the potential climate change impacts on the productivity of five major crops in eastern China: canola, corn, potato, rice and winter wheat. Their simulations are performed with and without the enhanced CO_2-fertilization effect. Their results indicate that aggregated potential productivity increases by 8.3% for canola. However, without the enhanced CO_2-fertilization effect, potential productivity declines by 2.5% to 12%. Wang *et al*. (2014) selected 3 experimental sites in the Yangtze River Basin, and analyzed the changes of rapeseed production potential in the future (2021–2050) relative to the reference period (1959–2009) based on the A2, B2 and A1B emission scenarios in the SRES report and the multi-year daily projected meteorological data. They showed that biomass and yield at these sites increased to different extents. Our research also showed a significant probability of increase in total production potentials for rapeseed in the Yangtze River Basin in the future.

Some limitations of this study are worth mentioning and could be overcome by future research. Firstly, the observation-based calibration method of the AEZ model on rapeseed varieties needs to be improved. Results show that the performance of the new AEZ model is not satisfactory at some sites in some years, which needs to be further improved. The crop mechanism model, which simulates the dynamic growth process of crops, can be coupled with the AEZ model to improve the AEZ varieties parameters. Secondly, improvements can be done with respect to the climate model selection. This paper uses the GCM-RCPs scenario data proposed in the IPCC AR5, which show some improvements compared to CMIP3 in mode resolution and experimental design. However, large uncertainties remain in the model simulation results, and the application of these data in agricultural production research is still far from mature. Some of the concentration pathways may need to be further explored. Finally, monthly climatic factors are used in the study (for example, monthly cumulative rainfall and monthly mean temperature) and changes in production potential do not include the effects of extreme weather events, which should also be explored in the future research.

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