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Article

Climatic suitability and spatial distribution for summer maize cultivation in China at 1.5 and 2.0 °C global warming

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ABSTRACT

Evaluating climatic suitability of crop cultivation lays a foundation for agriculture coping with climate change scientifically. Herein, we analyse changes in the climatically suitable distribution of summer maize cultivation in China at 1.5 °C (GW1.5) and 2.0 °C (GW2.0) global warming in the future according to the temperature control targets set by the *Paris Agreement*. Compared with the reference period (1971–2000), the summer maize cultivation climatically suitable region (CSR) in China mainly shifts eastwards, and its acreage significantly decreases at both GW1.5 and GW2.0. Despite no dramatic changes in the CSR spatial pattern, there are considerable decreases in the acreages of optimum and suitable regions (the core of the main producing region), indicating that half-a-degree more global warming is unfavourable for summer maize production in China's main producing region. When the global warming threshold increases from GW1.5 to GW2.0, the centres-of-gravity of optimum areas shift northeastward under RCP4.5 and RCP8.5, the centres-of-gravity of both suitable and less suitable areas shift northwestward, though the northward trend is more prominent for the less suitable areas, and the centre-of-gravity of unsuitable areas shifts southeastward. Generally, half-a-degree more global warming drives the cultivable areas of summer maize to shift northward in China, while the west region shows a certain potential for expansion of summer maize cultivation.

1. Introduction

It is an indisputable fact that the world is growing warmer. The adverse impacts of global climate change on food production are higher than the positive impacts [1]. Both observational and simulation experiments show that climate change has adversely affected the total yields of major food crops, including wheat and maize, across many regions of the world, with negative impacts being more prevalent than positive impacts [2]. Thus, agro-meteorological disasters caused by increased extreme weather and climate events may further exacerbate the impacts on agriculture. According to the latest report of *Nature* [3], during 1964–2007, extreme weather disasters caused large-scale yield (maize, rice and wheat) reductions in the world, with an increased trend in the yield losses; for example, cereal yields were reduced 9%–10% by drought and extreme high-temperatures in different countries. To reduce this risk, nearly 200 parties of the United Nations Framework Convention on Climate Change (UNFCCC) agreed in concert to approve the *Paris Agreement*, which proposed keeping the global average temperature increase within 2.0 °C above the pre-industrial level and endeavouring to control it within 1.5 °C [4,5]. Accordingly, the UNFCCC commissioned the Intergovernmental Panel on Climate Change (IPCC) to issue a special report on GW1.5 in 2018, which would promote research into systematic projections of the impacts of GW1.5 on natural ecosystems and human socio-economics.

China is located in the monsoon climate zone. There is considerable inter-annual variation in the weather and climatic conditions of the country, while meteorological disasters occur frequently. Climate change has seriously affected the cultivation structure of China's grain crops and their distribution boundaries, phenophases and yields [6–11], thus seriously threatening food security in China and even the world. It is predicted that the global temperature will rise by 1.0–3.7 °C by the end of the 21st century [1], both temperature and precipitation extremes in China will increase [12–15], and this change may lead to more severe climate risks faced by the global and China's agricultural production [3,16]. Maize is among the cereal crops widely grown in the world, and it has become the most important grain crop in China. In 2016, the maize planting area in China reached 3.68×10^7 hm^2 [17], which plays a key role in safeguarding China's food security. Previous studies have paid more attention to the change of crop cultivation

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structure in and its distribution boundary [6–11,18,19] and maize yield [3,11,20–23] under climate change. Usually, the change of crop cultivation boundary caused by climate change was evaluated by using empirical meteorological factors [10,18]. He and Zhou [8,9,24] constructed the relationship of CSR of maize (spring maize and summer maize) with climate in China by using the MaxEnt method, and evaluated the CSR and its response to climate change. However, the maize CSR changes in China at GW1.5 °C and GW2.0 °C according to the temperature control targets set by the *Paris Agreement* have not been reported yet. To deal with the effects of climate change scientifically, it is urgent to identify the change of maize cultivation CSR in China.

In this study, the CMIP5 coupled climate models were used for climate projections under different scenarios for representative concentration pathways. We analysed the spatial patterns of and changes in summer maize cultivation CSR in China at GW1.5 °C and GW2.0 °C under RCP2.6, RCP4.5 and RCP8.5. We also quantitatively analysed the impact differences at GW1.5 and GW2.0 on maize cultivation. The results provide reference data for developing countermeasures to aid adaptation of summer maize to climate change.

2. Data and methods

2.1. Crop distribution and meteorological data

The data including crop geographical distribution and corresponding meteorological conditions were used to find the relationship between crop cultivation distribution and climate. The geographical distribution data on summer maize cultivation in China were obtained from the 1991 to 2010 dataset of crop growth and development status at the National Meteorological Information Centre (NMIC), China Meteorological Administration (CMA). This dataset includes geographical distribution data for summer maize cultivation from 188 agricultural meteorological observation stations (AMOS). Because crop cultivation is usually influenced by both climate and human activities (e.g., irrigation), in order to avoid the human effects on crop cultivation, the selected AMOS should have the cultivation history of more than 5 years. Based on this principle, 108 AMOS were further selected to provide the distribution data for summer maize cultivation (Fig. 1). Meteorological data including daily temperature (mean, maximum and minimum) and precipitation were obtained from the

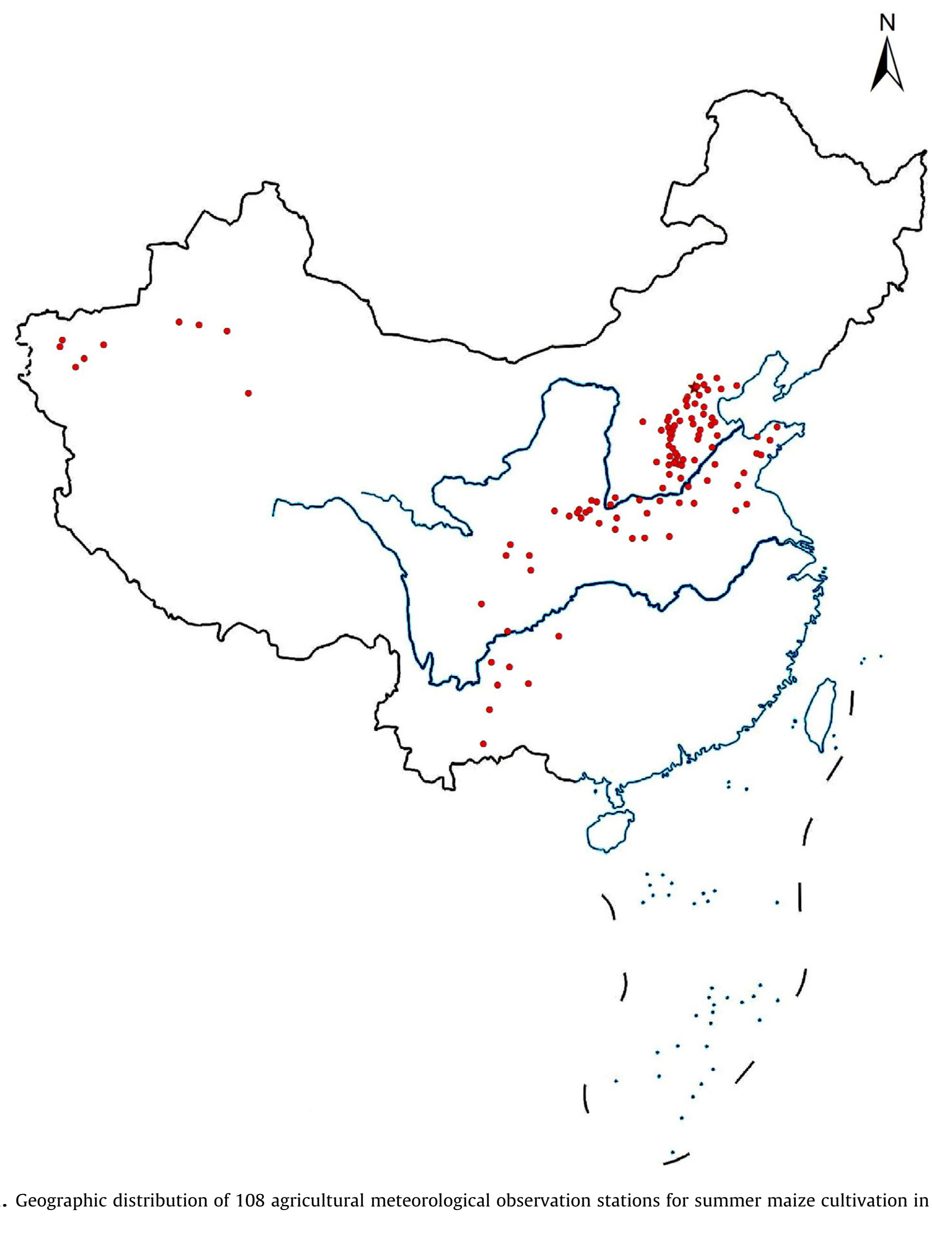

Fig. 1. Geographic distribution of 108 agricultural meteorological observation stations for summer maize cultivation in China.

1971–2000 daily dataset of China's basic and reference surface meteorological observation stations at the National Meteorological Information Centre. Then, 10 km × 10 km dataset was developed based on a spatial interpolation algorithm with the weighted distance method of truncated Gaussian filter [25,26].

2.2. Climate scenario data

The future climate data include monthly surface temperatures, daily mean temperatures, daily maximum temperatures and precipitation from historical experiments and representative concentration pathways (RCPs) exported by the CMIP5 coupled models. The number of models used in different RCP scenarios and their details are summarized in Table 1.

We selected 1861–1890 as the reference period for global warming in the 21st century [27]. Concerning the prominent inter-annual characteristics of climate change, we implemented a 9-year running average treatment on the global temperature series to eliminate the impact of inter-annual climate variability, and the time at which it exceeded the average by 1.5 °C (2.0 °C) for the first time was taken as the occurrence time of GW1.5 (GW2.0). Based on the year in which the corresponding global warming threshold was reached, we selected four years before and four years after it. We calculated the 9-year running average and analysed the multi-model ensemble mean results under the equal weight coefficient [28]. Given the inconsistent horizontal resolutions of different models, we uniformly interpolated the results of all models to grid points with a spatial resolution of 10 km × 10 km through bilinear interpolation to facilitate comparison.

2.3. Maximum entropy (MaxEnt) method

The MaxEnt method (Version 3.4.1 http://biodiversityinformatics.amnh.org/open_source/maxent/) was used, which is based on the niche principle. It evaluates the habitat suitability for species using the species occurrence point data and environmental variable data [29,30] and provides the probability of species existence under multifactorial synergy. This MaxEnt method has demonstrated the best predictive capacity and precision in many studies [31–34]. By using the MaxEnt method, He and Zhou [9,24], Duan and Zhou [35] and Sun et al. [36] constructed models of the relationship of CSR distribution of main crop (summer maize, rice and winter wheat) with climate in China. These studies have presented the crop climatic suitability and provided references for the allocation of cultivation and climatic zoning of China's main food crops (maize, rice and wheat).

2.4. The centre-of-gravity model

The spatial shifts of CSR for summer maize cultivation were evaluated by the centre-of-gravity model [9,37,38], which help to understand its spatial variation trends in China. The centre-of-gravity model can then be expressed as

$$\bar{x} = \sum_{i=1}^{n} M_i X_i / \sum_{i=1}^{n} M_i,$$

$$\bar{y} = \sum_{i=1}^{n} M_i Y_i / \sum_{i=1}^{n} M_i,$$

where (X_i, Y_i) is the central coordinate of the i-th cell unit, M_i is the weight of this cell, here it is the area of this cell.

2.5. Climatic factors controlling crop cultivation distribution

To develop the relationship of crop CSR with climate, the climatic factors should be identified firstly. The climatic factors controlling crop cultivation distribution mainly include physiological temperature tolerance, the heat and water demand for crop growing duration [39]. Thus, He and Zhou [8] identified the climatic factors listed in Table 2 from the references and the jackknife module in the MaxEnt method, including average temperature in the coldest month (indicating crop physiological temperature tolerance), annual average temperature, continuous days with daily average

Table 1
Basic information on global climate models in CMIP5 [17].[a]

No.	Model	Country	Resolution (Grids)	RCP2.6	RCP4.5	RCP8.5
1	ACCESS1-0	Australia	192 × 145		✓	✓
2	ACCESS1-3	Australia	192 × 145		✓	✓
3	BCC-CSM1-1	China	128 × 64	✓	✓	✓
4	BNU-ESM	China	128 × 64		✓	
5	CanESM2	Canada	128 × 64	✓	✓	✓
6	CCSM4	USA	288 × 192	✓	✓	✓
7	CESM1-BGC	USA	288 × 192		✓	
8	CMCC-CMS	Italy	192 × 96		✓	✓
9	CMCC-CM	Italy	192 × 96		✓	
10	CNRM-CM5	France	256 × 128		✓	✓
11	CSIRO-MK3-6-0	Australia	192 × 96	✓	✓	✓
12	GFDL-CM3	USA	144 × 90	✓	✓	✓
13	GFDL-ESM2G	USA	144 × 90	✓	✓	
14	GFDL-ESM2M	USA	144 × 90	✓	✓	✓
15	HadGEM2-CC	UK	192 × 145		✓	
16	HadGEM2-ES	UK	192 × 145	✓	✓	✓
17	INM-CM4	Russia	180 × 120		✓	✓
18	IPSL-CM5A-LR	France	96 × 96		✓	
19	IPSL-CM5A-MR	France	144 × 143	✓	✓	✓
20	IPSL-CM5B-LR	France	96 × 96		✓	✓
21	MIROC5	Japan	256 × 128	✓	✓	✓
22	MIROC-ESM	Japan	128 × 64	✓	✓	✓
23	MIROC-ESM-CHEM	Japan	128 × 64	✓	✓	✓
24	MPI-ESM-LR	Germany	192 × 96	✓	✓	✓
25	MPI-ESM-MR	Germany	192 × 96	✓	✓	✓
26	MRI-CGCM3	Japan	320 × 160	✓	✓	✓
27	NorESM1-M	Norway	144 × 96	✓	✓	✓

[a] "✓" indicates the model used under each scenario.

Table 2
Potential climatic factors affecting the maize cultivation distribution in China.

Principle of selection	Potential climatic factors	Method of calculation	Meaning
Length of growing season and heat supply	≥10 °C accumulated temperature (°C d)	Method of 5-d moving average	Temperature magnitude and growing season duration for thermophilic plants or vigorous growing season for plants that like coolness
	Continuous days with daily average temperature ≥10 °C (d)	Method of 5-d moving average	Growing season for thermophilic plants and vigorous growing season for plants that like coolness
	Annual average temperature (°C)	$\sum_{i=1}^{n} t_i/n$	Annual overall heat resource situation
	Average temperature in the warmest month (°C)	Average temperature in July	High-temperature condition required by thermophilic crops
	Annual temperature range (°C)	Monthly average temperature in July-monthly average temperature in January	Magnitude of the variation in the monthly average temperature throughout the year
Water supply	Annual precipitation (mm)	$\sum_{i=1}^{n} p_i$	Annual overall water condition
	Humidity index	Ratio between rainfall and potential evapotranspiration	Index of dry and moist degree of the climate in a certain area
The lowest temperature the maize can withstand	Average temperature in the coldest month (°C)	Average temperature in January	Overwintering conditions for crops

temperature ≥10 °C, ≥10 °C accumulated temperature, average temperature in the warmest month (indicating heat demand for crop growing duration), annual precipitation, and humidity index (indicating water demand for crop growing duration) [9]. The seven climatic factors would be used to develop the relationship of summer maize CSR with climate.

3. Results

3.1. Distribution of summer maize cultivation in China at GW1.5 and GW2.0

We obtained the relationship between distribution of summer maize CSR and climate through training of the MaxEnt method according to the geographical distribution information of the 108 AMOS, in combination with the environmental variable layers formed by the 30-year averages of seven dominant climatic factors during 1971–2000 (climate reference years). Then, the CSR of summer maize cultivation was simulated at GW1.5 and GW2.0 using the dominant climatic factors under different RCP scenarios at GW1.5 and GW2.0. The climatic suitability is given by the relationship of CSR and climate, namely, the probability of existence, p. According to the study of He and Zhou [8], summer maize cultivation area is unsuitable with $p < 0.05$, less suitable with $0.05 \le p < 0.33$, suitable with $0.33 \le p < 0.66$ and optimum with $p \ge 0.66$.

The distribution of CSR during the reference period (1971–2000) is shown in Fig. 2. The optimum area is mainly distributed in northwest Shandong, southeast Hebei and north Henan provinces and the southeast Tibet Autonomous Region; together, the optimum and suitable areas cover China's main producing areas of summer maize. The distribution of summer maize CSR at GW1.5 and GW2.0 is shown in Fig. 3. Compared with the reference period, the range of optimum area markedly decreases at GW1.5 and GW2.0 under all three scenarios (RCP2.6, RCP4.5 and RCP8.5); it shows a prominent trend of eastward retreat and is mainly concentrated on the east coast of Shandong. Southeast Tibet also changes from an optimum to an unsuitable area. At GW2.0 compared with GW1.5, the range of suitable area substantially decreases and shows a trend of northward migration and eastward retreat, which is mainly reflected in southeast Hebei, north Henan and north Shandong provinces. However, the range of suitable area increases in local areas of the Xinjiang Uygur Autonomous Region in northwest China. Meanwhile, the less suitable area also markedly shifts northwards. The original less suitable area in Anhui and east Henan provinces at GW1.5 has changed into an unsuitable area, while the climatic suitability in the west Inner Mongolia Autonomous Region shows an increasing trend. In general, the global warming, especially with an increased threshold, leads to a considerable decrease in the acreage of China's main producing area of summer maize; however, there is a certain potential for adaptation in local areas of Xinjiang and Inner Mongolia.

3.2. Summer maize cultivation climatically suitable acreages at GW1.5 and GW2.0

Under all three scenarios, there are significant decreases in the acreages of cultivable ($P \ge 0.05$), optimum and suitable areas for summer maize in China at GW1.5 and GW2.0 compared with the reference period (1971–2000; Table 3); the decreases in cultivable area acreage are approximately 10.71%–18.78% and 14.67%–17.13%, respectively. The most prominent decreases are found in the acreages of optimum area. At GW1.5, the acreages of optimum area corresponding to all three scenarios are 3.68×10^6, 5.28×10^6 and 4.99×10^6 hm^2, which decrease (relative to the acreage of optimum area of 1971–2000) of 89.85%, 85.43% and 86.23%, respectively. At GW2.0, there are approximately 90.98% and 92.55% decreases (relative to the acreage of optimum area of 1971–2000) in the acreages of potential optimum area corresponding to RCP4.5 and RCP8.5 (the global surface temperature did not reach the threshold of GW2.0 under RCP2.6), respectively. The decreases in the acreage of optimum area are more at GW2.0 than at GW1.5 by approximately 38% (RCP4.5) and 46% (RCP8.5). Moreover, the CSR decreases (relative to the acreage of suitable area of 1971–2000) by approximately 40.17%–55.48% at GW1.5 and GW2.0 under different scenarios. Except for RCP2.6, the decrease in suitable area acreage is more prominent than at GW2.0; its acreage decreases by 11% (RCP4.5)–26% (RCP8.5) at GW2.0 compared with GW1.5, with the largest decrease under RCP8.5.

In general, the less suitable and unsuitable areas for summer maize cultivation in China show a weak increasing trend, and only under RCP2.6 does the unsuitable area show a weak decreasing trend. The acreage of less suitable area increases by approximately 0.42%–14.27%; compared with that at GW1.5, there are approximately 5% (RCP4.5) and 4% (RCP8.5) increments at GW2.0, and the maximum value appears under RCP2.6. Under RCP4.5 or RCP8.5, the optimum, suitable and less suitable regions all appear to be more sensitive to global warming, and the magnitude of changes in the acreages of optimum and suitable areas is considerably greater at GW2.0 than that at GW1.5. The adverse impacts on summer maize cultivation become increasingly serious as the global warming threshold increases.

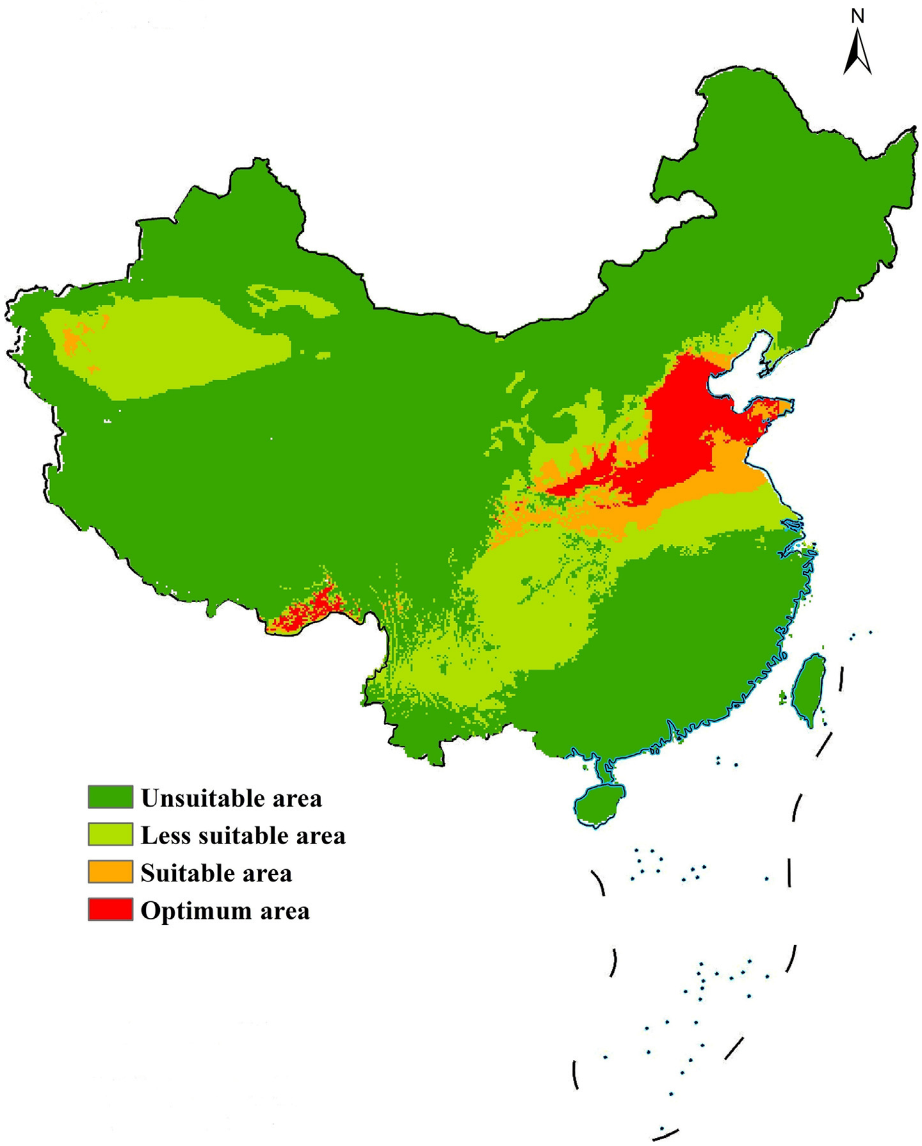

Fig. 2. Spatial pattern of summer maize cultivation in China simulated by the reference period (1971–2000).

3.3. Spatial shifts in the centres-of-gravity of CSR for summer maize cultivation at GW1.5 and GW2.0

Fig. 4 illustrates the changes in the centres-of-gravity of CSR at GW1.5 and GW2.0. The centres-of-gravity of different climatically suitable areas show a relatively consistent trend of shifts under RCP4.5 and RCP8.5. Specifically, the optimum area centre-of-gravity shifts to the northeast, the centres-of-gravity of both suitable and less suitable areas shift to the northwest, although the northward trend is more prominent for the less suitable area, and the unsuitable area centre-of-gravity shifts to the southeast. The largest distance of centre-of-gravity shifts is for the suitable area, mainly due to an increased range of suitable climate in local areas of the northwest region. The less suitable area shows a smaller centre-of-gravity shift distance compared with the suitable area, while the unsuitable area shows the smallest distance of shifts. In summary, half-a-degree more global warming drives northward shifts in the summer maize cultivable area in China under RCP4.5 and RCP8.5.

4. Discussions

According to the temperature control targets proposed by the *Paris Agreement*, this study uses the simulation results of the CMIP5 models under three different RCPs to analyse the spatial pattern of climatic suitability and changes in its centre-of-gravity for summer maize cultivation in China at GW1.5 and GW2.0. The ranges of cultivable area always show decreasing trends at GW1.5 and GW2.0 under the different RCPs. The spatial ranges of optimum and suitable areas show the most prominent decreases, which are mainly concentrated in east Shandong and may be associated with the slight changes in future warming and precipitation in that region [40]. With regard to suitable area acreage, the largest values appear under RCP2.6, and a decreasing trend is shown with increased temperature under the different scenarios; however, local areas of the northwest region exhibit some potential for expansion of summer maize cultivation, which may be related to the future trend of warming and humidification in northwest China [18]. Therefore, in the future, particular emission reduction measures should be

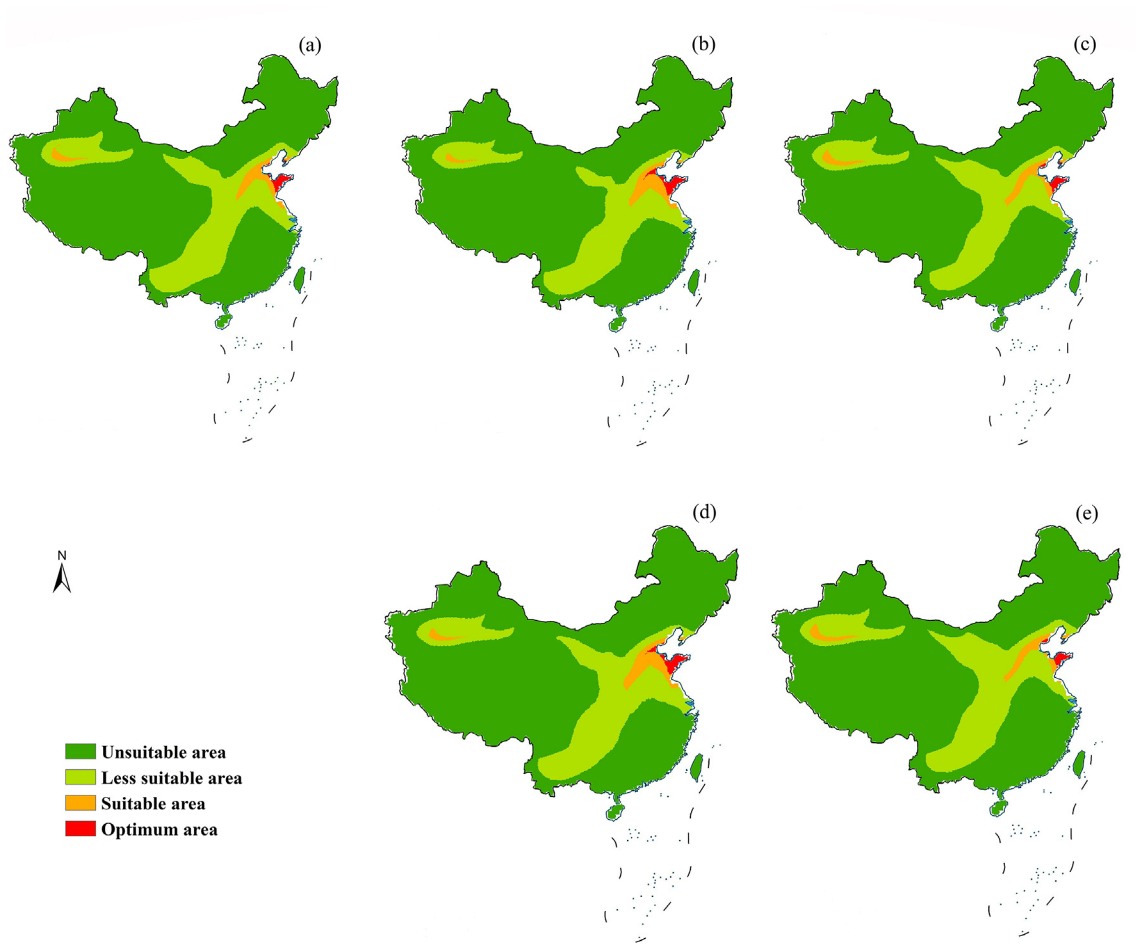

Fig. 3. Changes in the spatial distribution of summer maize cultivation in China projected by multi-model ensemble means at GW1.5 and GW2.0 under the scenarios for three typical concentration pathways (RCP2.6, RCP4.5 and RCP8.5). (a) RCP2.6 scenario with GW 1.5; (b) RCP4.5 scenario with GW 1.5; (c) RCP4.5 scenario with GW 2.0; (d) RCP8.5 scenario with GW 1.5; (e) RCP8.5 scenario with GW 2.0.

Table 3
The acreages of changes in climatically suitable areas for summer maize cultivation in China at 1.5 and 2.0 °C global warming.[a]

Climate suitability	Classification	Reference period (1971–2000)	1.5 °C			2.0 °C	
			RCP2.6	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Optimum area	Acreage (10^6 hm^2)	36.24	3.68	5.28	4.99	3.27	2.70
	Relative change (%)	NA	−89.85	−85.43	−86.23	−90.98	−92.55
Suitable area	Acreage (10^6 hm^2)	34.30	16.39	19.00	20.52	16.90	15.27
	Relative change (%)	NA	−52.22	−44.61	−40.17	−50.73	−55.48
Less suitable area	Acreage (10^6 hm^2)	171.84	196.36	172.57	181.18	180.69	188.86
	Relative change (%)	NA	14.27	0.42	5.44	5.15	9.90
Unsuitable area	Acreage (10^6 hm^2)	729.10	724.72	744.30	734.46	740.29	734.32
	Relative change (%)	NA	−0.60	2.08	0.74	1.53	0.72
Cultivable area	Acreage (10^6 hm^2)	242.38	216.43	196.85	206.69	200.86	206.83
	Relative change (%)	NA	−10.71	−18.78	−14.72	−17.13	−14.67

[a] NA, not applicable.

taken, while the allocation of cultivation needs to be adjusted to maintain the CSR, further ensuring the stability of total maize yields. At GW2.0, the acreage of the main producing region (including optimum and suitable regions) is significantly smaller compared with that at GW1.5 under RCP4.5 and RCP8.5. This result implies that summer maize cultivation is extremely sensitive to climate warming and that limiting the temperature rise to within 2.0 °C will be more conducive to maize production.

In this study, the summer maize CSR is projected under the scenarios of future global warming, which improves the understanding of the study results [41]. It is worth noting that there exist uncertainties in the simulation results of each model because of the differences in the model driving datasets as well as the differences in the structures and coupling modes of atmospheric, oceanic and terrestrial modules [42]. Uncertainties in the simulation of climatic factors may directly lead to uncertainties in the

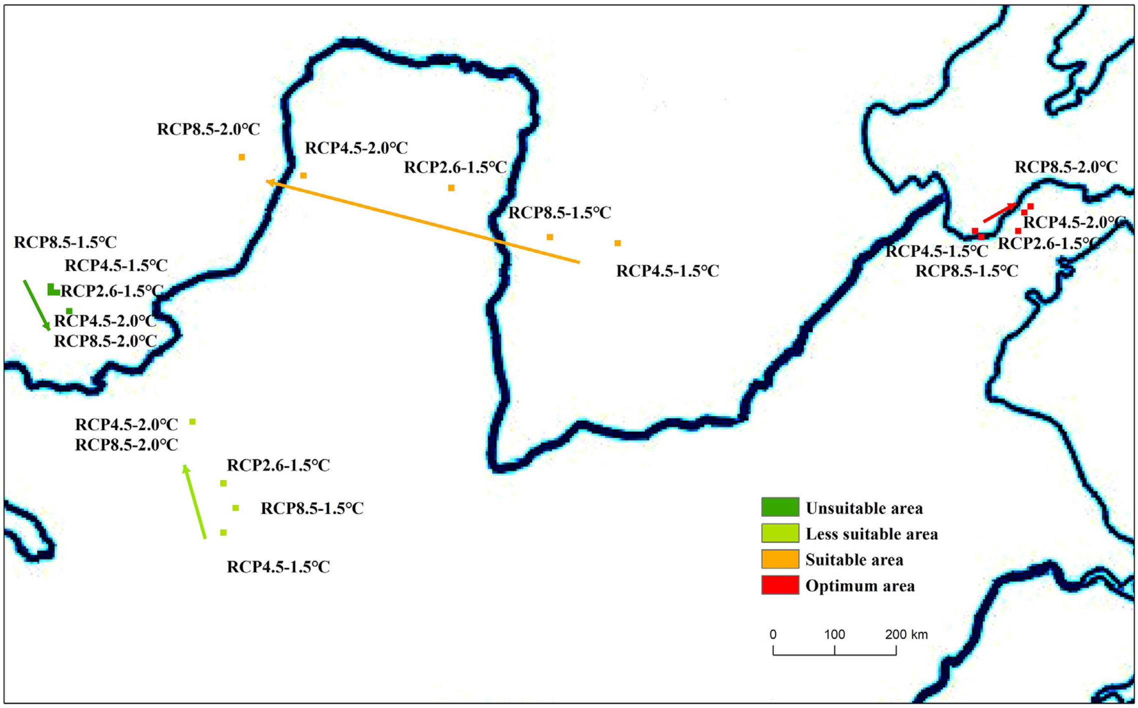

Fig. 4. Changes in the centres-of-gravity of climatically suitable areas for summer maize cultivation in China at GW 1.5 and GW 2.0 under three scenarios with different representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5).

simulation of the distribution of CSR. Therefore, the current analysis is only based on a warming response with transient changes rather than on a steady-state warming. To explore the impacts and mechanisms of future climate change, many model tests specifically designed to study the future impacts and differences for GW1.5 and GW2.0 are needed [43,44].

5. Conclusions

This study has projected the spatial distribution of climatic suitability and changes in its centre-of-gravity for summer maize cultivation in China at GW1.5 and GW2.0 in the future in terms of the simulation results of the CMIP5 coupled climate models under different RCP scenarios. The suitable area acreage decreases by approximately 40.17%–55.48% (relative to 1971–2000), while its spatial distribution mainly shifts eastwards at GW1.5 and GW2.0. Compared with those at GW1.5, the acreages of both optimum and suitable areas are significantly smaller at GW2.0. The decreases in optimum area acreage are approximately 38% (RCP4.5) and 46% (RCP8.5), and those in suitable area acreage are approximately 11% (RCP4.5) and 26% (RCP8.5). By contrast, the acreage of less suitable area increases slightly by approximately 5% (RCP4.5) and 4% (RCP 8.5). The acreages of the optimum, suitable and less suitable areas all appear to be more sensitive to global warming. From GW1.5 to GW2.0, the centres-of-gravity of the optimum, suitable and less suitable areas all show a northward shifting trend. In particular, the CSR shows the largest shifts in centre-of-gravity distance, and the west and north regions exhibit a certain potential for cultivation expansion. If only the impacts of climate conditions are considered, the adverse impacts of GW2.0 will be even more serious. Thus, it is urgent to lay out summer maize cultivation according to climatic conditions.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Qijin He, Guangsheng Zhou and Xiaomin Lü designed jointly research issue and new finding, Qijin He, Xiaomin Lü and Mengzi Zhou analyzed data, Qijin He, Xiaomin Lü and Guangsheng Zhou wrote the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.03.030.

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