Atmospheric Science

February 2012 Vol.57 No.4: 395–403
doi: 10.1007/s11434-011-4807-2

# The climatic suitability for maize cultivation in China

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Received June 27, 2011; accepted September 9, 2011; published online October 17, 2011

To provide scientific support for planning maize production and designing countermeasures against the effects of climate change on the national maize crop, we analyzed the climatic suitability for cultivating maize across China. These analyses were based on annual climate indices at the Chinese national level; these indices influence the geographical distribution of maize cultivation. The annual climate indices, together with geographical information on the current cultivation sites of maize, the maximum entropy (MaxEnt) model, and the ArcGIS spatial analysis technique were used to analyze and predict maize distribution. The results show that the MaxEnt model can be used to study the climatic suitability for maize cultivation. The eight key climatic factors affecting maize cultivation areas were the frost-free period, annual average temperature, ⩾0°C accumulated temperature, ⩾10°C accumulated temperature continuous days, ⩾10°C accumulated temperature, annual precipitation, warmest month average temperature, and humidity index. We classified climatic zones in terms of their suitability for maize cultivation, based on the existence probability determined using the MaxEnt model. Furthermore, climatic thresholds for a potential maize cultivation zone were determined based on the relationship between the dominant climatic factors and the potential maize cultivation area. The results indicated that the importance and thresholds of main climate controls differ for different maize species and maturities, and their specific climatic suitability should be studied further to identify the best cultivation zones. The MaxEnt model is a useful tool to study climatic suitability for maize cultivation.

**maize, planting distribution, dominant climatic factor, climatic suitability, maximum entropy (MaxEnt) model**

**Citation:** He Q J, Zhou G S. The climatic suitability for maize cultivation in China. Chin Sci Bull, 2012, 57: 395–403, doi: 10.1007/s11434-011-4807-2

The interaction between vegetation and climate can be divided into the adaptability of vegetation to climate, and the feedback of vegetation on the climate. Usually, major vegetation types respond to major climate types, and each climate type or division is associated with a set of corresponding vegetation types. Thus, the study of climate-vegetation classification has drawn increasing attention from botanists, ecologists, climatologists, and geographers [1,2]. There have been many studies on the relationships among the crop cultivation system, the distribution of the cultivation area, and climate; and the growth of maize in different climatic divisions of China and the response of maize crops to climate change have attracted particular attention [3–6]. However, most of these studies have focused on a local area, and few have been conducted at the Chinese national scale. Moreover, the research results vary widely at present, because they are based on data with different temporal scales and dissimilar major factors affecting crop growth. Therefore, planning of crop production and countermeasures to cope with the effects of climate change on the maize crop in China are seriously restricted by the lack of a robust method to analyze the climatic suitability for maize cultivation across China.

Maize is one of the most widely planted crops in the world. Statistics from the Food and Agriculture Organization (FAO) indicated that in 2003, the maize cultivation area worldwide was approx. $1.4268 \times 10^8$ hm$^2$, with a total yield of approx. $6.3804 \times 10^8$ t. The cultivation area of maize is

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usually less than that of rice and wheat; however, its yield is greater than both. Moreover, it is the field crop with the greatest area of expansion and the most rapid increase in crop yield. China has one of the greatest areas of maize cultivation. The maize cultivation area in China has been approx. 2.453 × 10 $hm^2$ per year since the end of the 20th century, with an annual yield of up to $1.2318 \times 10^8$ t, second only to that of the United States of America. Maize is an important source of raw materials for food, feed, products for the fermentation industry, and products for chemical production. It plays a critical role in global food security and national economic development.

The climate is a very important factor in maize production. Global warming is now a reality, and will continue to be so for the foreseeable future [7]. Climate change has resulted in a northward shift and an eastward expansion of the planting boundaries for various maize varieties maturing at different times; early maturing varieties are being replaced by mid- or later-maturing varieties, the plantable area for mid- and later-maturing maize varieties is increasing [8], and the growth period is lengthening in the northwest region [9]. In 2000, the Intergovernmental Panel on Climate Change (IPCC) published a set of scenarios in the Third Assessment Report (Special Report on Emissions Scenarios-SRES). The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. Among these scenarios, the A2 storyline and scenario family indicate a very heterogeneous world with a continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than those in other storylines, and a 3.5°C increase in the global surface air temperature by the end of the 21st century. The B2 storyline and scenario family indicate a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with a continuously increasing population (but lower than that of A2) and intermediate economic development, and a 2.0°C increase in the global surface air temperature by the end of the 21st century. The results suggested that the maize yield in five major maize production regions of China would decrease under the conditions of the A2 and B2 scenarios [10]. To ensure a sustainably high yield of maize in China under the conditions of climate change, there is an urgent need to understand the effects of global change on maize production and to establish where maize could be planted. The key scientific issue to solve this problem is to identify the major climatic factors affecting maize cultivation regions in China and to classify the areas where the climate is suitable for maize cultivation.

The objectives of this study were (1) to identify the major climatic factors and their thresholds affecting maize cultivation regions in China; and (2) to provide a climate suitability classification for maize cultivation, based on annual climate indices at the Chinese national level. These indices affect the distribution of maize cultivation, and together with information on the geographical distribution of the maize cultivation zone in China, the MaxEnt model, and the ArcGIS spatial analysis technique, they can be used to analyze maize distribution now and in the future.

## 1 Materials and methods

### 1.1 Materials

Information on the geographic distribution of maize cultivation sites in China was obtained from 366 Agricultural Meteorological Observation Stations, and provided by the China Meteorological Administration (Figure 1). Climatic data were provided by the National Meteorological Information Center, China Meteorological Administration.

Climate data are from the Chinese daily climate data set (1971–2000), and include site longitude, latitude, daily mean, maximum, and minimum air temperature, and precipitation. These daily data were interpolated to obtain spatial grid data with 10 km × 10 km resolution based on methods reported elsewhere [11,12] and a digital elevation model (DEM).

### 1.2 Potential climatic factors

For each crop, its cultivation depends on interactions between thermal and water resources. Annual climate indices from both maize and natural vegetation divisions at the Chinese national level were included in these analyses. These indices influence the distribution of maize cultivation. For this study, 10 potential climatic factors with identical biological significance were selected from these indices to determine major climatic factors affecting the distribution of maize cultivation in China. The potential climatic factors

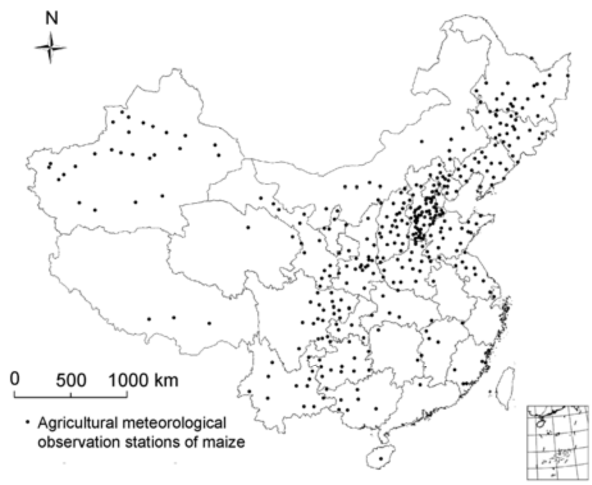


**Figure 1** Distribution of maize cultivation sites from Agricultural Meteorological Observation Stations, China Meteorological Administration.

selected were annual average temperature, ⩾0°C accumulated temperature, ⩾10°C accumulated temperature, ⩾10°C accumulated temperature continuous days, frost-free period, coldest month average temperature, warmest month average temperature, annual range of monthly mean temperature, annual precipitation, and humidity index (Table 1) [13–26].

The frost-free period and ⩾10°C accumulated temperature continuous days indicate the thermal resources in a continuous period. Annual average temperature, coldest month average temperature, warmest month average temperature, and annual range of monthly mean temperature indicate the thermal intensity. The extent of thermal accumulation is reflected by the ⩾0°C accumulated temperature and ⩾10°C accumulated temperature. Annual precipitation and humidity indices are used to evaluate the extent of dry or humid conditions. The higher the moisture index, the more humid the climate.

### 1.3 MaxEnt model

Recently, many kinds of models have been used to simulate the potential distribution of plant species. These models included the ecological models BIOCLIM, BLOMAPPER, DIVA, and DOMAIN, the dynamic simulation model CLIMEX, a generalized additive model (GAM), a generalized linear model (GLM), a genetic algorithm for rule-set prediction (GARP), and MaxEnt [27–31]. Of these, MaxEnt showed the best predictive capacity and was the most precise [32–38], giving the most accurate distribution function based on best entropy. First, the characteristic space, i.e. the known distribution domain of specific plant species, is determined. Next, the restrictive conditions (environmental factors) are identified, and the assemblage of restrictive factors developed. Finally, the relationship between the potential distribution and environmental factors is established [31].

## 2 Results and analyses

### 2.1 Applicability of the MaxEnt model

To validate the applicability of the MaxEnt model to predict the maize cultivation zone in China, 75% of the total data were selected as the training data subset to construct the MaxEnt model, which is then used to obtain the model parameters. Then, 25% of the total data set was used to evaluate the applicability of the constructed MaxEnt model. The model required two data sets: the geographic distribution data set of the selected plant species, i.e. the geographic distribution information of maize cultivation sites in China obtained from 366 Agricultural Meteorological Observation Stations; and the national environmental data set, i.e. 10 climatic factors selected from the references of the maize climate division and natural vegetation division at the national Chinese level that influence the distribution of maize cultivation (Table 1).

A receiver operating characteristic (ROC) curve is generally used to evaluate the simulation accuracy of the model [39]. The area below the ROC curve, i.e. the value of the area under the curve (AUC) indicates the predictive accuracy of the model. The value of AUC ranges from 0.5 and 1, indicating the following degrees of predictive accuracy [40]: 0.50–0.60 (fail), 0.60–0.70 (poor), 0.70–0.80 (fair), 0.80–0.90 (good), and 0.90–1.0 (excellent). When the values of

**Table 1** Potential climatic factors affecting the distribution of maize cultivation in China

| Climate factor | Calculation method | Explanation | Reference |
|---|---|---|---|
| ⩾ 0°C accumulated temperature | Five-day sliding average | Thermal resources suitable for crop farming period | [13,14] |
| ⩾ 10°C accumulated temperature | Five-day sliding average | Temperature intensity and durative time during growing period of warm mate plant or during peak growing period of cool mate plant | [15–25] |
| ⩾ 10°C accumulated temperature continuous days | Five-day sliding average | Growing period of warm mate plant or peak growing period of cool mate plant | [19] |
| Frost-free period | Durations of daily minimum temperature ⩾2°C | Length of growing period for field crop | [13,17,20,21] |
| Annual average temperature | $\sum_{i=1}^{n} t_i / n$ | Annual thermal resources | [20] |
| Annual precipitation | $\sum_{i=1}^{n} p_i$ | Annual water resources | [14] |
| The coldest month average temperature ($t_c$) | Average temperature of January | The overwinter condition for crop | [14] |
| The warmest month average temperature ($t_w$) | Average temperature of July | The high temperature condition for warm mate plant | [14] |
| Annual range of monthly mean temperature | Temperature difference ($t_w$–$t_c$) | Variation range of monthly mean temperature during one year | [14] |
| Humidity index | The ratio of precipitation and potential evapotranspiration | Dry or humid climate condition | [14,26] |

AUC are more than 0.75, the constructed model is applicable. The higher the AUC value, the more accurate the predictions of the constructed model [41].

The AUC of the constructed model based on the potential climatic factors affecting the distribution of the maize cultivation zone was 0.818. This value indicated that the constructed model had "good" predictive accuracy, and therefore, that it was suitable for predicting the geographic distribution of maize cultivation in China.

### 2.2 Major climatic factors affecting the geographic distribution of maize cultivation in China

The 10 potential climatic factors were derived from the literature; however, their contributions to the geographic distribution of maize cultivation have not been evaluated. To construct the MaxEnt model with the greatest AUC, the contributions made by the potential climatic factors to the geographic distribution of maize cultivation were quantitatively evaluated at the Chinese national level. As a result, quantitative contributions of the major climatic factors to distribution were determined. Figure 2 shows the contribution ratio of the potential climatic factors to the geographic distribution of maize cultivation from the Jackknife module, based on the constructed MaxEnt model. In terms of their quantitative contribution to distribution, the climatic factors were ranked in the following order: frost-free period > annual average temperature ⩾ 0°C accumulated temperature ⩾10°C accumulated temperature continuous days ⩾10°C accumulated temperature > annual precipitation > warmest month average temperature > humidity index > coldest month average temperature > annual range of monthly mean temperature.

Eight major climatic factors were identified based on their ratio of contribution to the geographic distribution of maize cultivation in China. This ratio was calculated from the Jackknife module, based on the constructed MaxEnt model. The eight major climate factors were frost-free period, annual average temperature, ⩾0°C accumulated temperature, ⩾10°C accumulated temperature continuous days, ⩾10°C accumulated temperature, annual precipitation, the warmest month average temperature, and the humidity index. The contribution from these eight major climatic factors is approx. 91.5%.

### 2.3 Classification of climatic zones in terms of suitability for maize cultivation in China

The climatic zones were classified in terms of their suitability for maize cultivation in China based on the existence probability ($p$) derived from the MaxEnt model. The MaxEnt model was constructed from the eight major climatic factors selected. The existence probability from the MaxEnt model ranges from 0 to 1. Based on statistical principles, low probability events take place when the existence probability is less than 0.05. Therefore, a region with an existence probability less than 0.05 would not be suitable for maize cultivation. Together with the description of probability from the Fourth Assessment Report of the IPCC, the standard values of existence probability ($p$) for the climate suitability classification are: $p<0.05$ (unsuitable area), $0.05\leqslant p<0.33$ (less suitable area), $0.33\leqslant p<0.66$ (suitable area), and $p\geqslant 0.66$ (optimum area).

Figure 3 shows climate suitability classification of maize cultivation zones in China. Approx. 4% of the total land area is "optimum", approx. 25% is "suitable", approx. 40% is "less suitable", and approx. 31% is "unsuitable". Thirty-one provinces show strong suitability for growing maize. However, the effects of climate on the maize cultivation zone result in a narrow belt from the northeast to southwest

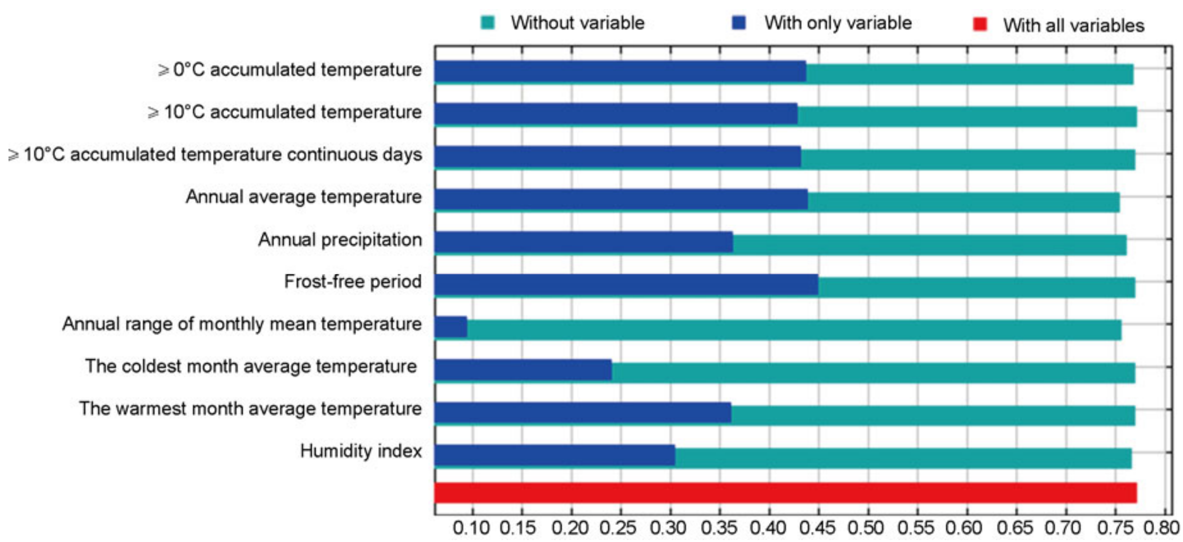


**Figure 2** Contribution ratio of potential climatic factors indicating their contribution to distribution of maize cultivation in China. Ratio was calculated from the Jackknife module based on the constructed MaxEnt model.

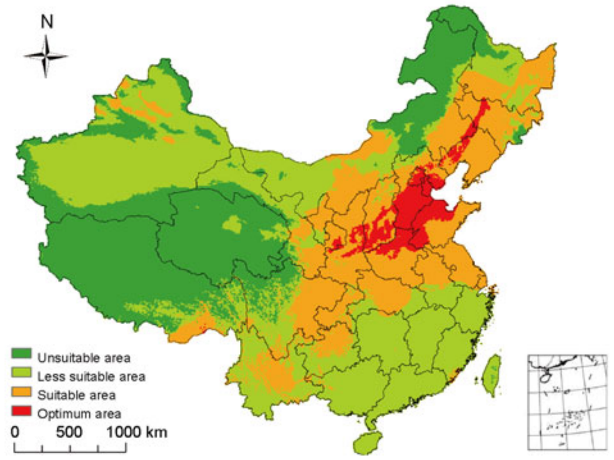


**Figure 3** Climate suitability classifications of maize cultivation zones in China.

(Figure 3). The major maize production regions are in Heilongjiang, Jilin, Liaoning, Hebei, Henan, Shanxi, Shandong, Shaanxi, Hubei, Sichuan, and Yunnan provinces, although different provinces have different climates (Table 2). The optimum area for maize cultivation, which includes Jilin, Liaoning, Hebei, Shanxi, Shaanxi, Gansu and Henan provinces, has mainly a middle- and cold-temperate semiarid, subhumid climate, with appropriate thermal and precipitation conditions that meet the growth demands of maize without causing high temperature damage. The suitable area, which includes Heilongjiang Province; the Inner Mongolia Autonomous Region (Inner Mongolia for short); the southern Tibetan Plateau; Shandong, Jiangsu, Henan, Anhui, Hubei, Sichuan, Yunnan provinces, and Chongqing, belongs to the warm temperate subhumid climate, and has appropriate temperature and irrigation facilities. The less suitable area includes the Xinjiang Uygur Autonomous Region (Xinjiang for short); Inner Mongolia; most of Gansu Province; Zhejiang, Jiangxi, Guizhou, Hunan, Guangdong, Fujian, Hainan, Taiwan provinces, and Guangxi Zhuang Autonomous Region (Guangxi for short). There is sufficient sunshine, a large day/night temperature difference, and less precipitation in Xinjiang, Inner Mongolia, and most parts of Gansu Province, where maize could not be grown without irrigation. The other less suitable area has excessive rainfall and very high temperatures; here the main production crop is paddy rice followed by maize. The unsuitable area, which includes Qinghai Province; most of the Xizang (Tibet) Autonomous Region (Xizang for short); northern and southern parts of Xinjiang; the northern part of Heilongjiang Province; the northern part of Inner Mongolia; and the northwestern part of Sichuan Province, has a cold, dry climate.

The geographical ranges of the “optimum”, “suitable”, “less suitable”, and “unsuitable” areas presented in this study almost correspond with the results from the maize climate division of China [42]. However, the optimum area in this study shifts slightly southward, and it includes most parts of Henan and Shandong provinces. In addition, most of the inland regions in northwest China change from “optimum” to “suitable” or “less suitable” areas; and the western part of Inner Mongolia changes from an “unsuitable” to a “less suitable” or “suitable” area. The reason for these changes is that the current maize division is based on growth season, precipitation, and yield, while global warming and improvement of maize varieties will result in a prolonged growth season and enhanced drought resistance. As

**Table 2** General view of climate suitability of the maize planting zone in China

| Item | Optimum area | Suitable area | Less suitable area | Unsuitable area |
|---|---|---|---|---|
| Frost-free period (d) | 176–316 | 147–366 | 62–366 | 61–366 |
| Annual average temperature (°C) | 4.7–19.2 | 2.9–22.1 | –0.5–24.9 | –10.2–21.0 |
| ⩾0°C accumulated temperature (°C d) | 3336.9–6507.3 | 2047.0–7179.9 | 1419.4–7980.7 | 45.0–6915.5 |
| ⩾10°C accumulated temperature continuous days (d) | 166–270 | 125–309 | 82–310 | 11–299 |
| ⩾10°C accumulated temperature (°C d) | 2913.9–6146.0 | 1320.3–7164.3 | 291.6–7980.7 | 1.5–6772.0 |
| Annual precipitation (mm) | 508.7–812.7 | 125.3–1708.3 | 53.3–2203.3 | 52.0–2198.6 |
| The warmest month average temperature (°C) | 22.1–28.6 | 13.5–30.8 | 8.7–29.3 | –0.4–26.8 |
| Humidity index | 0.05–0.14 | 0.02–0.27 | 0.01–0.50 | 0.01–3.67 |
| Main distribution | most parts of Hebei, Shanxi, Shandong and Henan provinces; Beijing and Tianjin; small parts of Jilin, Liaoning, Shaanxi and Gansu provinces | Northeast Plain located in the east of Da Hinggan Mountains, North China Plain, Loess Plateau, Sichuan basin, middle and lower reaches of Yangtze River; parts of Yunan-Guizhou Plateau, Junggar basin and South Tibetan Plateau | north Heilongjiang Province; West Inner Mongolia; most of Xinjiang, Gansu and Yunnan provinces; south Sichuan Province; South Yangtze River | northern part of 50°N; East Inner Mongolia; most parts of Qinghai-Tibet Plateau and western Sichuan Plateau; northern and southern part of Xinjiang |

a result, the optimum maize cultivation zone shifts southward. Gao et al. [43] pointed out that annual precipitation in the arid and semiarid transitional region of northwestern China has significantly decreased over the last 50 years, especially in the last decade. Aridification might increase in the future as temperature and soil evaporation rates increase. Thus, a warm-dry climate would result in the "optimum" areas in most of the inland region of northwest China changing to "suitable" or "less suitable" areas. With global warming, the western part of Inner Mongolia would change from being an "unsuitable'' to a "suitable" or "less suitable" area.

The climate suitability classifications of the spring and summer maize cultivation zones are shown in Tables 3 and 4, respectively. These classifications are based on geographic distribution information from 216 spring maize cultivation sites and 188 summer maize cultivation sites from the Agricultural Meteorological Observation Stations, China Meteorological Administration, and the Chinese daily climate data set (1971–2000) with 10 km × 10 km spatial resolution.

There are variations in the importance of major climatic factors affecting different maize varieties and their thresholds (Tables 2–4). By comparison, the climate suitability classification of the maize cultivation zones determined in this study almost match the current distribution of maize cultivation [42], and the northern border of the spring maize cultivation zone is consistent with the result reported by Zhang et al. [44]. These findings indicate that climate suitability should be studied for different maize varieties and maturities to obtain accurate crop distribution information. Our studies on the climate suitability of spring and summer maize show that the MaxEnt model can be used to simulate the climate suitability of the maize cultivation zone in China.

### 2.4 Analyses of thresholds of major climatic factors affecting the maize cultivation zone in China

Climatic differences restrict crop growth and development, and affect the distribution of the crop cultivation area [45]. Eight major climatic factors affecting the distribution of cultivated maize were identified in this study, based on the MaxEnt model (see 2.2). The thresholds of major climatic factors affecting the maize cultivation zone can be given in terms of climate suitability classifications and the relationship between the distribution of the maize cultivation area (indicated by the number of grids) and the major climatic factors. The thresholds of major climatic factors affecting the distribution of maize cultivation areas are as follows (Figure 4(a)–(h)): frost-free period ⩾62 d, annual average temperature −0.51 to 24.9°C, ⩾0°C accumulated temperature 1419.4 to 7980.7°C·d, ⩾10°C accumulated temperature continuous days 82 to 310 d, ⩾10°C accumulated temperature 291.57 to 7980.7°C·d, annual precipitation 53.3 to 2203.3 mm, warmest month average temperature 8.7 to 30.8°C, and humidity index 0.01 to 0.50.

## 3 Discussion and conclusion

In this study, 10 potential climatic factors affecting the maize cultivation zone in China were examined. These factors, which were based on annual climate indices from references at the Chinese national level, together with information about the distribution of maize cultivation, were

**Table 3** General view of climate suitability of the spring maize cultivation zone in China

| Item | Optimum area | Suitable area | Less suitable area | Unsuitable area |
|---|---|---|---|---|
| ⩾0°C accumulated temperature (°C d) | 3035.9–4244.1 | 2214.0–7179.8 | 1500.4–7980.7 | 44.85–7247.7 |
| ⩾10°C accumulated temperature (°C d) | 2559.2–3814.3 | 1403.0–7164.3 | 321.8–7980.7 | 1.54–7150.8 |
| ⩾10°C accumulated temperature continuous days (d) | 259–211 | 125–308 | 91–310 | 11–302 |
| Frost-free period (d) | 164–248 | 157–366 | 62–366 | 61–366 |
| The warmest month average temperature (°C) | 20.6–25.1 | 13.5–30.8 | 8.7–29.6 | −0.42–28.3 |
| Annual average temperature (°C) | 3.8–11.5 | 2.9–22.1 | −1.5–24.9 | −10.2–22.0 |
| Annual precipitation (mm) | 383.0–811.1 | 126.6–1749.7 | 53.3–2203.3 | 52.0–2076.3 |
| Humidity index | 0.08–0.20 | 0.02–0.28 | 0.01–0.49 | 0.01–3.67 |
| Main distribution | western part of Jilin and Liaoning provinces; parts of Inner Mongolia; Beijing; Hebei, Shanxi, Shaanxi and Gansu provinces | Liaoning, Hebei, Shandong provinces and Ningxia Hui Auonomous Region (Ningxia for short); Beijing, Tianjin, most parts of Heilongjiang, Jilin, Shanxi, Henan and Shaanxi provinces; south Gansu Province; small parts of Inner Mongolia, Xinjiang, Sichuan basin, Chongqing, Yunnan, Jiangsu, Hubei, Hunan provinces and southern Tibetan Plateau | Northeast China except north Heilongjiang and east Jilin provinces; North China except east Inner Mongolia; East China, Middle China and South China; east Sichuan Province, most part of Xinjiang and southern Tibetan Plateau | north part of 50°N, east Inner Mongolia, Qinghai-Tibet Plateau, western Sichuan Plateau; part of Xinjiang |

**Table 4** General view of climate suitability of the summer maize cultivation zone in China

| Item | Optimum area | Suitable area | Less suitable area | Unsuitable area |
|---|---|---|---|---|
| Frost-free period (d) | 212–313 | 195–359 | 116–366 | 61–366 |
| Annual average temperature (°C) | 10.5–17.9 | 8.8–22.1 | –0.7–23.3 | –10.2–24.9 |
| ⩾10°C accumulated temperature continuous days (d) | 196–263 | 183–309 | 77–309 | 11–310 |
| ⩾0°C accumulated temperature (°C d) | 4229.4–6080.3 | 3506.3–7179.8 | 1254.5–7480.4 | 44.9–7980.7 |
| ⩾10°C accumulated temperature (°C d) | 3755.5–5667.2 | 2822.6–7164.3 | 154.0–7472.6 | 1.54–7980.7 |
| The coldest month average temperature (°C) | –6.4–7.0 | –10.4–15.1 | –24.9–18.5 | –29.8–20.0 |
| The warmest month average temperature (°C) | 22.0–27.1 | 17.7–30.8 | 8.5–30.7 | –0.4–29.3 |
| Annual precipitation (mm) | 514.1–901.7 | 90.2–1407.6 | 53.5–2038.5 | 52.0–2203.3 |
| Main distribution | most part of Shandong and Henan provinces; Tianjin, most part of Beijing; south Shanxi Province, middle Shaanxi Province, north Henan Province | Shandong Province, most part of Henan Province; south Shanxi and Shaanxi provinces, north Jiangsu, Hubei and Anhui provinces; east Sichuan Province, small part of Gansu Province; Chongqing, Xinjiang and southern Tibetan Plateau | northern China except north Heilongjiang Province, east Jilin Province and east Inner Mongolia, northwest China except north Gansu Province, small part of Xinjiang and west Inner Mongolia; southern China except Guangdong Province, northwest Jiangxi Province, Guangxi, small part of Fujian Province, most part of Hainan Province | north Heilongjiang Province, southeast Jilin Province, western and northeastern parts of Inner Mongolia, north Gansu Province; most part of Guangdong and Hainan provinces; small part of Guangxi, Jiangxi and Fujian provinces; Qinghai-Tibetan Plateau |

used to evaluate the applicability of the MaxEnt model for simulating the maize cultivation zone. The results indicated that the MaxEnt model had "good" predictive accuracy (AUC = 0.818) in terms of the relationship between the distribution of maize cultivation and climate. This indicated that the MaxEnt model can be used to predict geographic distribution, to reveal major climatic factors, and to classify various climates in terms of their suitability as maize cultivation zones in China.

The thresholds of eight major climatic factors affecting the distribution of maize cultivation in China were calculated as follows: frost-free period ⩾62 d, annual average temperature −0.51 to 24.9°C, ⩾0°C accumulated temperature 1419.4 to 7980.7°C·d, ⩾10°C accumulated temperature continuous days 82 to 310 d, ⩾10°C accumulated temperature 291.6 to 7980.7°C·d, annual precipitation 53.3 to 2203.3 mm, warmest month average temperature 8.7 to 30.8°C, and humidity index, 0.01 to 0.50.

Based on the major climatic factors and the existence probability from the MaxEnt model, we classified climate zones in terms of their suitability for maize cultivation. The geographical ranges of optimum area, suitable area, less suitable area, and unsuitable area shown in this study almost match the current distribution of maize cultivation in China [42]. The optimum area was approx. 4% of the total land area in China; the suitable area approx. 25%; the less suitable area approx. 40%; and the unsuitable area approx. 31%. Because of global warming and improvement in maize varieties, the optimum area in this study shifts slightly southward and includes most of Henan and Shandong provinces. Most of the inland regions in the northwest of China change from being optimum areas into being suitable or less suitable, and the western part of Inner Mongolia changes from being an unsuitable area into a less suitable or suitable area. These data could provide scientific support for planning maize production and countermeasures to cope with climate change in China.

Moreover, the results of this study indicate that there are variations in the importance and the thresholds of major climatic factors affecting different maize varieties. These findings suggest that the climate suitability of different maize varieties and maturities should be studied to obtain accurate information on the areas of crop cultivation. Our studies on the climate suitability of spring maize and summer maize show that the MaxEnt model can be used to classify climatic zones according to their suitability for cultivation of spring and summer maize in China.

It should be noted that the distribution of maize cultivation in China depends not only on climate, socio-economic conditions, and local production technologies, but also on soil type, geographic characteristics, crop varieties, human activity, and so on [46]. Therefore, for maize cultivation, one should consider the overall impact, especially in relation to its yield and economic value. In this study, we have not considered the effects of agro-meteorological disasters, or differences in maize varieties and maturity. These aspects should be further studied in future research.

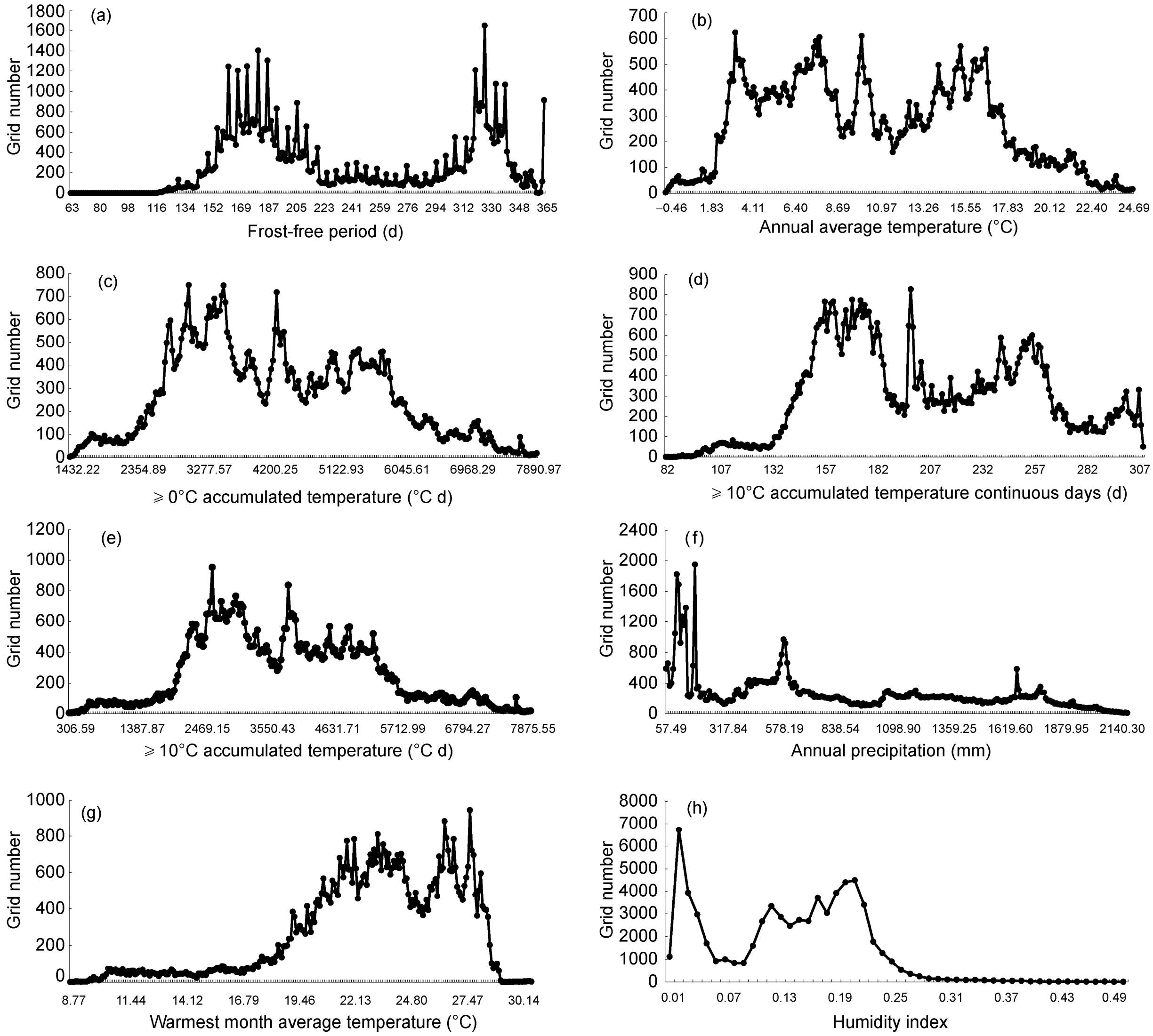


**Figure 4** Relationships between distribution of maize cultivation area in China and major climatic factors. (a) Frost-free period; (b) annual average temperature; (c) ⩾ 0°C accumulated temperature; (d) ⩾ 10°C accumulated temperature continuous days; (e) ⩾ 10°C accumulated temperature; (f) annual precipitation; (g) warmest month average temperature; (h) humidity index.

*This work was supported by the National Basic Research Program of China (2010CB951303), the Special Fund for Agro-scientific Research in the Public Interest (200903003) and the Basic Operation Cost of China Meteorological Administration (CMA).*

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