Evaluation of Agricultural Climatic Resource Utilization During Spring Maize Cultivation in Northeast China Under Climate Change

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ABSTRACT

Agricultural climatic resources (such as light, temperature, and water) are environmental factors that affect crop productivity. Predicting the effects of climate change on agricultural climatic resource utilization can provide a theoretical basis for adapting agricultural practices and distributions of agricultural production. This study investigates these effects under the IPCC (Intergovernmental Panel on Climate Change) scenario A1B using daily data from the high-resolution RegCM3 (0.25°×0.25°) during 1951–2100. Model outputs are adjusted using corrections derived from daily observational data taken at 101 meteorological stations in Northeast China between 1971 and 2000. Agricultural climatic suitability theory is used to assess demand for agricultural climatic resources in Northeast China during the cultivation of spring maize. Three indices, i.e., an average resource suitability index ($I_{\rm sr}$), an average efficacy suitability index ($I_{\rm se}$), and an average resource utilization index (K), are defined to quantitatively evaluate the effects of climate change on climatic resource utilization between 1951 and 2100. These indices change significantly in both temporal and spatial dimensions in Northeast China under global warming. All three indices are projected to decrease in Liaoning Province from 1951 to 2100, with particularly sharp declines in $I_{\rm sr}$, $I_{\rm se}$, and K after 2030, 2021, and 2011, respectively. In Jilin and Heilongjiang provinces, $I_{\rm sr}$ is projected to increase slightly after 2011, while $I_{\rm se}$ increases slightly and K decreases slightly after 2030. The spatial maxima of all three indices are projected to shift northeastward. Overall, warming of the climate in Northeast China is expected to negatively impact spring maize production, especially in Liaoning Province. Spring maize cultivation will likely need to shift northward and expand eastward to make efficient use of future agricultural climatic resources.

Key words: climate change, Northeast China, spring maize, climatic suitability, agricultural climatic resource utilization

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1. Introduction

Climate change introduces new dynamics and uncertainties into agricultural production (IPCC, 2007; Godfray et al., 2010; Abraha and Savage, 2006). General circulation model simulations indicate that global mean temperatures may increase by as much as 5.8℃ by the end of this century (IPCC, 2007), and warming in some regions may be even greater (Giorgi and Bi, 2005). The changes in climate projected for the 21st century are expected to substantially affect crop production (FAO, 2009), with significant impacts on crop yield and food security worldwide. Projections suggest that the number of people at risk of hunger could increase by between 5 million and 200 million in 2100 (Schmidhuber and Tubiello, 2007). The impact of global warming on agriculture is an important issue for both policymakers and scientists (Gregory and

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Ingram, 2000; Sanchez, 2000; Fuhrer, 2003).

Agricultural climatic resources (such as light, temperature, and water) are environmental factors that affect crop productivity. The growth, development, and yield of spring maize (one of the most important crops in China) depend on variability in agricultural climatic resources. Maize is a short-day crop that requires strong light to produce nutrients throughout the growth period. Lengthening the daily illumination time of maize increases the amount of vegetative growth, prolongs the growing time, and postpones tassel differentiation. Maize is thermophilic and sensitive to temperature. The temperature sensitivity of maize is strongest during the flowering stage, with an optimum temperature of 25–28℃. Water loss causes pollen grains to lose vitality when temperature exceeds 32–35℃ and relative humidity is less than 30%. These conditions can inhibit pollination and fertilization. Maize has a strong demand for water, which must be met after the seedling stage to obtain a high yield. Water consumption by maize varies during different growth stages, with peak water demand during the stage from tasseling to filling. This moisture critical period plays an important role in maize flowering, pollination, and grain formation.

Northeast China is both vulnerable to climate change and an important region for spring maize production, accounting for 26.6% of the total maize hectarage in China. Global warming is likely to strongly affect agricultural climatic resources in Northeast China, with potentially serious consequences for sustainable spring maize production and efficient use of these resources. Previous studies have applied climate change scenarios in crop models to address the potential impacts of climate change on agricultural climatic resources (Zhao et al., 2010), crop yield (Zhao et al., 2011; Tao et al., 2008), and crop diversity (Yuan et al., 2012). These studies have helped to better understand the effects of climate change on agricultural production. However, few studies have quantitatively assessed the potential effects of climate change on utilization of agricultural climatic resources (such as that for production of spring maize in northeastern China) on regional scales. Agricultural climatic resources will change constantly as climate changes (IPCC, 2007). Effective agricultural adaptation to changing climate conditions requires a good understanding of how climate change may affect the utilization of climatic resources.

We quantitatively evaluate climatic resource utilization using an average resource suitability index ($I_{\rm sr}$), an average efficacy suitability index ($I_{\rm se}$), and an average resource utilization index (K). We then investigate potential changes in the utilization of agricultural climatic resources for spring maize production in Northeast China under climate change. Our results provide a scientific basis for planning efficient use of agricultural climatic resources for sustainable maize production in Northeast China under future climate change.

2. Materials and methods

2.1 Climate data

Daily climate variables (maximum and minimum air temperatures, mean air temperature, precipitation, solar radiation, relative humidity, and wind speed) are taken from high-resolution RegCM3 ($0.25°\times0.25°$) output during 1951–2100. These model results have been provided by the National Climate Center of China. Daily meteorological observations from 101 meteorological stations in Northeast China during the period 1971–2000 have been provided by the National Meteorological Information Center of China. RegCM3 is widely used in regional climate simulation and prediction in China. The use of such high-resolution regional models can greatly improve simulations of contemporary climate and provide more reliable forecasts (Gao et al., 2011).

2.2 Selection of climate change scenario

Climate change scenarios are used to estimate the global climatic and socioeconomic effects of changes in greenhouse gases or other climate forcings. The Intergovernmental Panel on Climate Change (IPCC) has constructed global greenhouse gas emission scenarios for the next 100 years based on analysis of a large number of models published in the Special Report on

Emissions Scenarios (SRES) (Nakićenović et al., 2000). The IPCC SRES scenarios consider a variety of potential drivers of climate change, including population growth and socioeconomic development. Future changes that may influence the sources and sinks of greenhouse gases (such as changes in energy systems or land use) have also been accounted for. The future evolution of the forces that drive climate change is highly uncertain, so the SRES scenarios are constructed to cover a wide range of possible scenarios for how greenhouse gas emissions will change over time. The scenarios can be described within two-dimensional spaces. The first dimension designates a preference toward economic development (A) or environmental sustainability (B), while the second dimension designates whether emissions are more globally homogenous (1) or more regionally diverse (2). Scenarios are then designated using the identifiers A1, A2, B1, or B2. Here, we use data from a RegCM3 model simulation based on the A1B scenario (an A1 scenario that assumes a balanced distribution of energy sources).

2.3 Research methods

2.3.1 Correction of model data

Differences between simulation data and observational data indicate that error corrections should be applied to the simulation data before the data analysis. In this study, error corrections are made to daily mean temperature, daily maximum and minimum temperatures, cumulative precipitation at 10-day intervals, daily mean relative humidity, and daily mean wind speed. The correction is performed using data from 70 of 101 meteorological stations in Northeast China. The corrected model output is then validated using data from the remaining 31 meteorological stations. Both steps use a bilinear interpolation method. Gridded data are interpolated to the known stations, and the results are adjusted to match the observations. Yuan et al. (2012) provided a detailed description of the method used to correct the RegCM3 climate model data and validation of the corrected data. This study represents our first attempt to use corrected data from the RegCM3 climate model to quantitatively evaluate the effects of climate changes on utilization of agricultural climatic resources for spring maize production in Northeast China.

2.3.2 Evaluation indices

The growth, development, and yield of spring maize depend on agricultural climatic resources (i.e., environmental factors that affect crop productivity such as light, temperature, and water). Here, we mainly consider three climatic factors, namely, light, temperature, and water, that play decisive roles in crop growth. The growth period is divided into three stages: germination to emergence, emergence to tasseling, and tasseling to maturity. The subordinate functions of light, temperature, and water during different growth periods for spring maize in Northeast China are established and comprehensively evaluated. Three indices are used as indicators of suitability and utilization of agricultural climatic resources for maize production: an average resource suitability index ($I_{\rm sr}$), an average efficacy suitability index ($I_{\rm se}$), and an average resource utilization index (K). These indices are defined as:

$$I_{\rm sr} = \frac{1}{3n}\sum_{t=1}^{n}\left[S_{\rm T}(T) + S_{\rm W}(W) + S_{\rm R}(r)\right], \tag{1}$$

$$I_{\rm se} = \frac{1}{n}\sum_{t=1}^{n}\left[S_{\rm T}(T) \wedge S_{\rm W}(W) \wedge S_{\rm R}(r)\right], \tag{2}$$

$$K = I_{\rm se}/I_{\rm sr}, \tag{3}$$

where n is the number of development stages during the growth period (in this case $n = 3$ for the three growth stages defined above) and $S_{\rm T}(T)$, $S_{\rm W}(W)$, and $S_{\rm R}(R)$ are the subordinate functions of temperature, water, and solar radiation, respectively. Higher values of $I_{\rm sr}$ indicate a higher degree of climatic resource suitability. Higher values of $I_{\rm se}$ indicate a more favorable combination of light, heat, and water resources for crop growth. Higher values of K correspond to a more efficient utilization of agricultural climatic resources.

2.3.2.1 Subordinate function for temperature

The effects of temperature on maize growth and development are quantitatively evaluated by separately considering temperatures above the maximum temperature threshold, temperatures below the minimum temperature threshold, and temperatures within the optimum temperature interval. The subordinate function for temperature is based on fuzzy mathematics:

$$S_{\mathrm{T}}(T)=\begin{cases}0, & T<t_{\mathrm{L}} \text{ or } T>t_{\mathrm{H}};\\ \dfrac{1}{2}-\dfrac{1}{2}\sin\dfrac{\pi}{t_{\mathrm{T}}-t_{\mathrm{s1}}}\Big(T-\dfrac{t_{\mathrm{s1}}+t_{\mathrm{L}}}{2}\Big), & t_{\mathrm{L}}\leqslant T\leqslant t_{\mathrm{s1}};\\ \dfrac{1}{2}-\dfrac{1}{2}\sin\dfrac{\pi}{t_{\mathrm{H}}-t_{\mathrm{s2}}}\Big(T-\dfrac{t_{\mathrm{s2}}+t_{\mathrm{H}}}{2}\Big), & t_{\mathrm{s2}}\leqslant T\leqslant t_{\mathrm{H}};\\ 1, & t_{\mathrm{s1}}\leqslant T\leqslant t_{\mathrm{s2}},\end{cases} \tag{4}$$

where T is the average temperature during the growing season, t_{L} is the minimum temperature threshold, t_{H} is the maximum temperature threshold, and t_{s1} and t_{s2} are the lower and upper boundaries of the optimum temperature interval. The variable S_{T} takes values between 0 and 1 (0 and 1 reflect unsuitable resource conditions and ideal resource conditions, respectively). The partitioning of temperature is based on the cardinal temperatures for spring maize growth and development in Northeast China (Table 1).

Table 1. Values for the minimum temperature threshold, maximum temperature threshold, and optimum temperature interval for each stage of spring maize production in Northeast China

Development stage	t_{L} (℃)	t_{H} (℃)	t_{s1} (℃)	t_{s2} (℃)
Germination to emergence	10.0	35.0	20.0	28.0
Emergence to tasseling	12.0	35.0	24.0	31.0
Tasseling to maturity	15.0	30.0	22.0	27.0

2.3.2.2 Subordinate function for water

Maize crops in Northeast China are rain-fed. Excess rainfall does not occur frequently enough to cause waterlogging, so we consider only two conditions: rainfall shortage and optimum rainfall. The subordinate function for water is calculated as follows:

$$S_{\mathrm{W}}(W)=\begin{cases}P/\mathrm{ET}_m, & P<\mathrm{ET}_m;\\ 1, & P\geqslant \mathrm{ET}_m,\end{cases} \tag{5}$$

where P is the cumulative precipitation during the growth period and ET_m is the water demand. ET_m is defined as $\alpha\times\mathrm{ET}_0$, where ET_0 is the reference crop evapotranspiration rate calculated using the FAO (Food and Agriculture Organization) Penman-Monteith method and α is a coefficient that depends on the growth period (Table 2). In this case, we divide the period from emergence to tasseling into two sub-stages: emergence to jointing and jointing to tasseling. In Northeast China, maize requires 30 days of growth after emergence to reach the jointing stage and additional 30 days to reach the tasseling stage.

Table 2. Crop coefficients α for spring maize in Northeast China during different development stages

Germination to emergence	Emergence to jointing	Jointing to tasseling	Tasseling to maturity
0.4	0.8	1.15	0.85

2.3.2.3 Subordinate function for solar radiation

The amount of solar radiation reaching the ground is also important for crop growth, with a critical threshold that varies during different growth stages. The subordinate function for solar radiation is calculated as follows:

$$S_{\mathrm{R}}(R)=\begin{cases}1, & R\geqslant R_0;\\ \mathrm{e}^{-\left(\frac{R-R_0}{b}\right)^2}, & R<R_0,\end{cases} \tag{6}$$

where R_0 is the critical amount of radiation for crop growth, R is the mean amount of radiation during the development stage, and b is a constant that can be determined by fitting.

3. Results

3.1 Temporal changes in the evaluation indices

Figure 1a shows temporal variations of I_{sr} in Northeast China between 1951 and 2100. The average value of I_{sr} in Liaoning Province is approximately 0.72 through 2030, greater than the mean values in Jilin Province (~0.65) and Heilongjiang Province (~0.63). The average value of I_{sr} in Liaoning decreases after 2030, while the values in Jilin and Heilongjiang increase slowly after 2011. These trends suggest that climatic conditions in Liaoning will gradually become more unsuitable for spring maize cultivation, while conditions in Jilin and Heilongjiang will become progressively more favorable for spring maize.

Figure 1b shows the temporal variability of I_{se} in Northeast China between 1951 and 2100. The average value of I_{se} in Liaoning is approximately 0.47 before 2020, with a gradual decrease after 2021. The values are essentially stable in Jilin (about 0.4) and Heilongjiang (about 0.38) before 2030, and then increase slightly after 2031. The value of I_{se} in Liaoning is projected to become less than that in Jilin in 2071 and less than that in Heilongjiang in 2081. This result indicates that changes in the combination of light, temperature, and water resources during the growing season induced by climate change will create enormous challenges for maize production in Liaoning, particularly after 2021. By contrast, conditions in Jilin and Heilongjiang are projected to become gradually more favorable for spring maize.

Figure 1c shows the temporal variability of K in Northeast China between 1951 and 2100. The value of K in Liaoning is projected to decrease dramatically after 2011. The values of K in Jilin and Heilongjiang also decrease, but the magnitude of these reductions is less than that in Liaoning. The decrease in the value of K in Liaoning indicates that increases in temperature and solar radiation disrupt the efficient utilization of light, temperature, and water resources. The values of K in Jilin and Heilongjiang are approximately 0.6, with the value in Heilongjiang slightly less than that in Jilin (primarily because Heilongjiang is located at a higher latitude with a slightly lower mean temperature). Although global warming is projected to bring increases in temperature in both provinces, changes in the combination of light, temperature, and water resources result in a less efficient utilization of the available resources. The simulated impact of global warming on the value of K is much smaller in Jilin and Heilongjiang provinces than that in Liaoning Province.

Climate change is likely to adversely impact spring maize production in Liaoning, where temperatures are currently sufficient for maize production. By contrast, a warming climate would enhance spring maize production in Jilin and Heilongjiang, where temperatures are currently relatively low. Considering the potential changes in suitability and coordination of agricultural climatic resources as a whole, climate change is likely to have negative effects on spring maize production in Northeast China. Effective adaptation to climate change should include strategies to effectively utilize changing agricultural climatic resources in Northeast China and ensure a stable yield of spring maize.

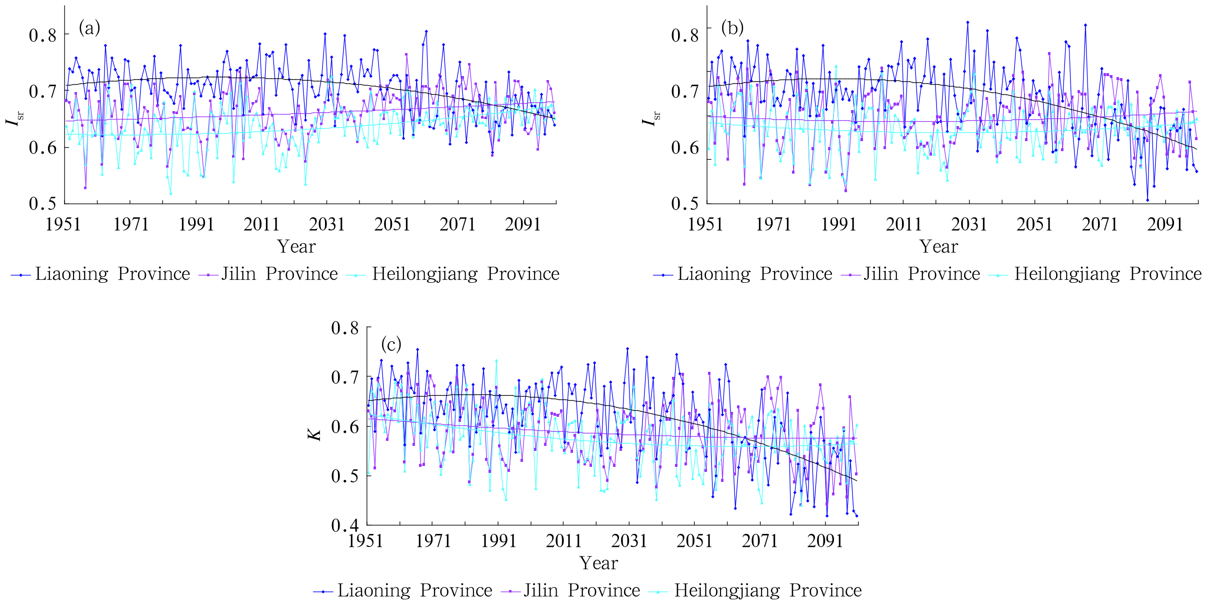

Fig. 1. Temporal variability in (a) the average resource suitability index (I_{sr}), (b) the average efficacy suitability index (I_{se}), and (c) the average resource utilization index (K) in three provinces in Northeast China between 1951 and 2100.

3.2 Changes in spatial distributions of evaluation indices over time

Figure 2 shows spatial distributions of I_{sr}, I_{se}, and K in Northeast China averaged over several 30-yr intervals from 1951 to 2100. The period 1981–2010 is taken as the baseline climate. The highest values of I_{sr} are located in the Liaodong Peninsula and western Liaoning corridor during the period 1951–2040. The magnitudes of the values in Heilongjiang Province are not projected to change substantially between 1951 and 2040. By contrast, values of I_{sr} in Jilin Province are projected to increase sharply during the latter part of this period, from 0.5–0.6 during 1981–2010 to 0.6–0.7 during 2011–2040. The locations of the highest values of I_{sr} shift northeastward after 2041. Values of I_{sr} are as high as 0.7 in large regions of Northeast China during the period 2071–2100.

Figure 3 shows the spatial distributions of I_{se} in Northeast China averaged over the same five 30-yr time intervals. Values of I_{se} decrease sharply in all three provinces, particularly in the western Liaoning corridor, the Liaodong Peninsula, and the southeastern Jilin Province. The minimum values of I_{se} during 2011–2040 and 2071–2100 are as low as 0.2–0.3. Between 1951 and 2040, the largest values of I_{se} (0.5–0.6) are located in the Liaodong Peninsula and western Liaoning corridor. The maximum values shift to the northeast of Liaoning Province between 2041 and 2070, away from the Liaodong Peninsula and western Liaoning corridor. Values of I_{se} in the Liaodong Peninsula and western Liaoning corridor are the lowest in Northeast China (0.2–0.3) by 2071–2100.

The largest values of I_{se} shift to the border between Liaoning and Jilin provinces by 2071–2100. Values of I_{se} are generally predicted to decrease in Northeast China under climate change, while the areas with large values of I_{se} are expected to shift northeastward and diminish in size. These results suggest that the combination of light, temperature, and water resources in Northeast China in the future will be less favorable for spring maize production than that in the past, especially at the border between Liaoning and Jilin provinces. This change will likely have negative

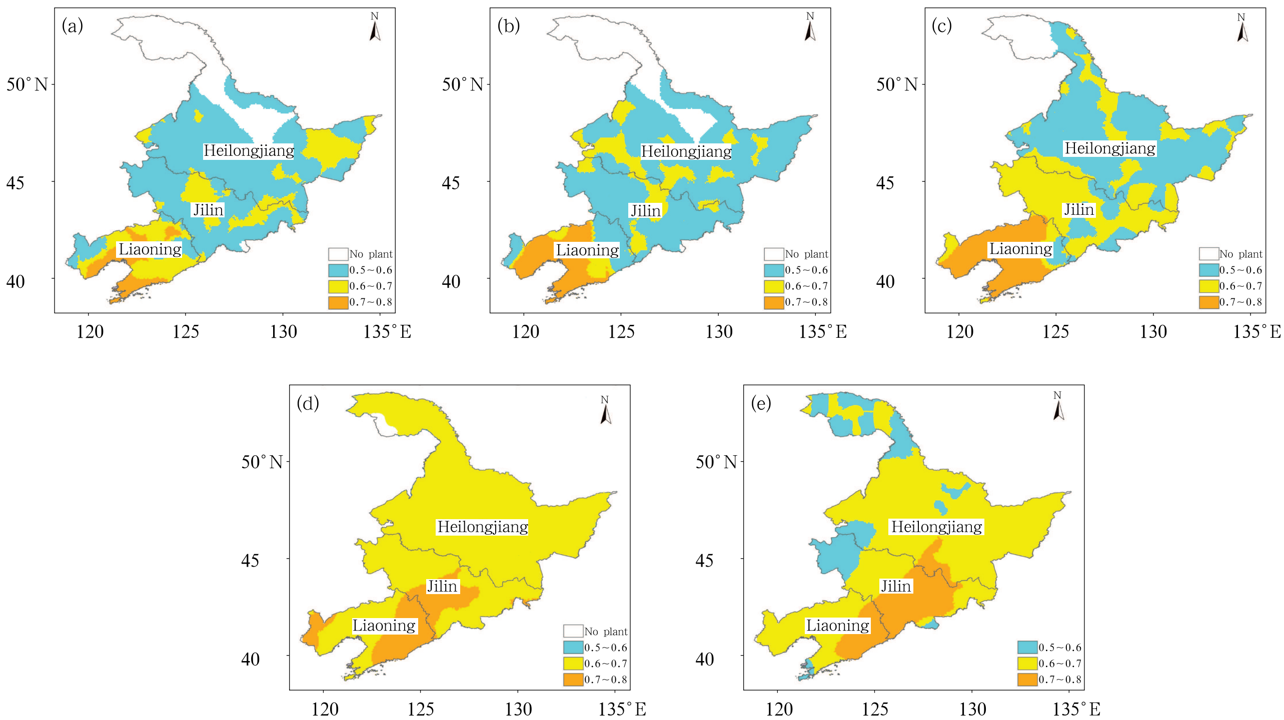

Fig. 2. Spatial distributions of the average resource suitability index (I_{sr}) in Northeast China averaged over the periods (a) 1951–1980, (b) 1981–2010, (c) 2011–2040, (d) 2041–2070, and (e) 2071–2100.

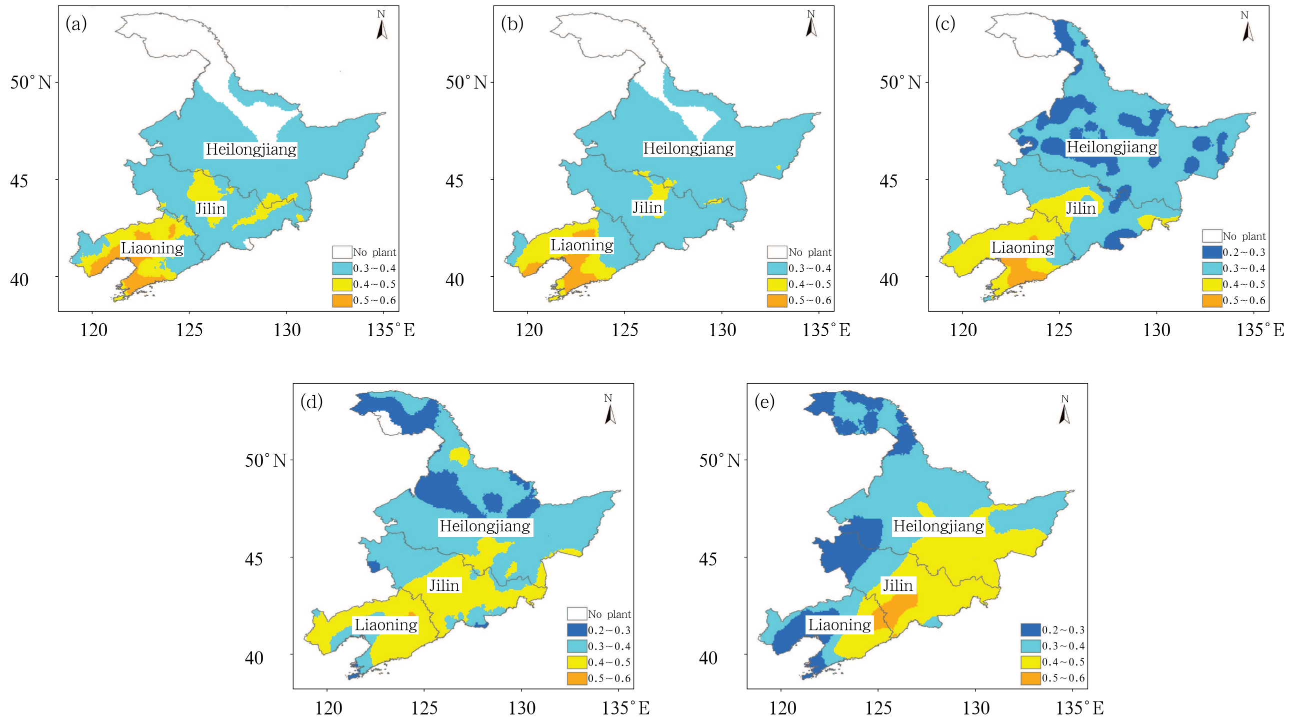

Fig. 3. As in Fig. 2, but for the average efficacy suitability index (I_{se}).

effects on spring maize production in Northeast China.

Figure 4 shows spatial variations of K over the same time periods. The distribution of K in Northeast China differs substantially during different time periods. Values of K decrease throughout Northeast China from 1951–1980 to 1981–2010. The largest values during the entire 1951–2100 period (0.7–0.8) are located in the Liaodong Peninsula and western Liaoning corridor during 1951–1980. Values of K in Jilin Province change substantially from 1981–2010 to 2011–2040, with increases from 0.4–0.5 to 0.5–0.6 (as high as 0.6–0.7 in some areas). Meanwhile, values of K in the northern Northeast Plain decrease by 0.1 over the same periods. Values of K in Liaoning Province decrease after 2041, when areas with high values of K shift northward and eastward to Jilin Province and eastern Liaoning Province. The lowest values of K (0.3–0.4) during the period 1951–2100 are located in the Liaodong Peninsula, the western Liaoning corridor, and the midwestern Northeast Plain during 2071–2100. Values of K are projected to decrease in southwestern Northeast China and increase in northeastern Northeast China under global warming.

4. Discussion

4.1 Impact of climate change on agricultural climatic resources for maize production in Northeast China

Agriculture is a fundamental activity of human societies that may be affected significantly by climate change (IPCC, 2007). Agricultural climatic resources are the main factors that determine crop yields and crop suitability for specific geographic regions, and have accordingly become an important focus area in agricultural research. Traditional methods of evaluating agricultural climatic resources have relied mainly on meteorological data without accounting for changing demands during different stages of crop growth. Different crops (or the same crop at different growth stages) may have very different demands for climatic resources. Above, we have considered actual and potential future climatic conditions in Northeast China and evaluated how these conditions affect agricultural

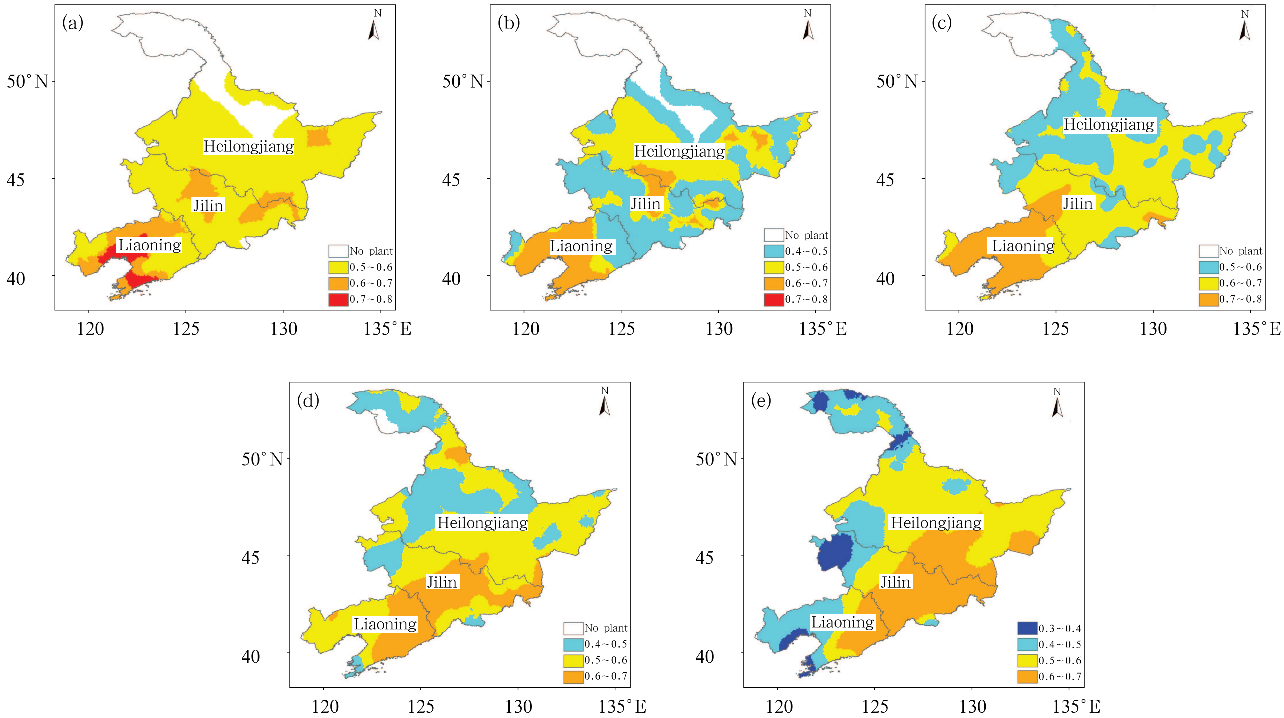

Fig. 4. As in Fig. 2, but for the average resource utilization index (K).

climatic resource availability and utilization during spring maize production. Here, we discuss our results in the context of previous studies.

Crop growth, development, and yield are closely related to agricultural climatic resources such as temperature, precipitation, and light. A high yield of maize requires strong light, appropriate temperature, and sufficient water to produce nutrients throughout the growth period; however, the actual demands for light, temperature, and water differ during different growth stages. These differences lead in turn to differences in utilization of agricultural climatic resources in the cultivation of spring maize. Increasing CO_2 concentrations and the accompanying climate warming could affect crop production in several ways. Environmental changes may strongly affect physiological processes such as photosynthesis, respiration, and the partitioning of photosynthesis products (Guo et al., 2002). Higher temperatures accelerate the growth rate and shorten the time required for maturation of maize. Asseng et al. (2004) showed that warming could accelerate the growth of wheat, with an increase of 1.7℃ in the average temperature shortening the time to anthesis by 11 days and the time to maturity by 3 days. However, plant growth may slow when the temperature is outside of an acceptable range (Bannayan et al., 2004). An increase in the mean temperature may be accompanied by an increase of the frequency of extreme temperatures, which could also affect crop productivity (Wu et al., 2006). The combined effects of higher temperatures, elevated CO_2 concentrations, and changes in precipitation are complex (Walker and Schulze, 2008). In this study, we have divided the spring maize growth period into three stages (germination to emergence, emergence to tasseling, and tasseling to maturity). We have determined the lower and upper thresholds of the acceptable and optimal temperature ranges for spring maize in Northeast China based on actual surveys and existing studies. This information may enable more efficient utilization of agricultural climatic resources for spring maize production in the future.

Previous modeling studies have evaluated maize production at higher latitudes (Davis et al., 1996). These studies have predicted that warming would lead to an expansion of the geographic area suitable for maize production. Predictive models of maize production in the midwestern United States (Southworth et al., 2000) and Europe (Wolf and Van Diepen, 1995) forecast increased yields in northern areas and decreased yields in southern areas, with the latter primarily due to drought (Tao and Zhang, 2010). Odgaard et al. (2011) showed a geographical expansion of the area used for maize cultivation in Denmark from 1999 to 2008. We show in this study that the values of $I_{\rm sr}$, $I_{\rm se}$, and K for spring maize production in Northeast China will change both spatially and temporally with future climate warming. Warming is likely to disrupt the optimal combination of light, temperature, and water that is suitable for maize growth, resulting in a less efficient utilization of agricultural climatic resources. Spring maize cultivation in Northeast China will need to move northward and expand eastward to use future agricultural climatic resources more efficiently. This prediction is consistent with the conclusions of Yuan et al. (2012), Zhao et al. (2010), and Zhang et al. (2008) that maize production in this region will potentially expand northward over time.

4.2 Regional implications

The most intensive maize production in Northeast China is located in the warmer southern parts. The global north–south distribution of maize production is similar. The relative importance of the individual variables that affect the distribution of maize is scale-dependent, both geographically and temporally. On local scales in the near term, factors such as maize varieties and economic and political issues play important roles in determining the geographic distribution of maize production. On longer timescales, climate may become the most important factor in determining the distribution of maize cultivation. Our analysis indicates that values of K for spring maize will decrease with warming in Northeast China, especially in Liaoning Province where temperatures are already sufficient for maize production. These increases in temperature will be difficult to use to the full advantage and will likely have a negative impact on overall maize production in Northeast China. Sustainable maize production and optimal use of agricultural climatic resources in this region will require adaptive countermeasures that compensate for increases in temperatures that are disadvantageous for maize growth. Such countermeasures may include adjusting sowing dates or selecting heat-tolerant varieties for cultivation in some areas of Liaoning Province. Determining how to most effectively adjust sowing dates is a complicated task that must account for a wide range of factors associated with geographic and climatic conditions; however, simply changing maize varieties to constantly adapt to climate warming is not a long-term solution.

4.3 Uncertainties

This study has focused on the possible effects of climate change on agricultural climatic resources in Northeast China. The results provide a scientific basis for more efficient utilization of agricultural climatic resources and sustainable maize production. However, the impacts of climate change on agriculture are complex, with many attendant uncertainties. The accuracy of climate change forecasts is limited by large uncertainties associated with greenhouse gas emission scenarios, errors in the description of the climate system by imperfect climate models, and internal variability in climate model simulations. Daily differences in climate variables and differences between ensemble experiments also affect the overall projections. Different general circulation models (GCMs) each produce different projections of regional climate change. No single model can be taken as correct; each model has strengths and weaknesses that depend on the focus, design, and approach of the model development team. As a result, modelers recommend that outputs from GCMs be used not as predictions, but rather as sensitivity studies or scenarios of possible future climates (Tao et al., 2003). Future climate changes may prove beneficial for a given crop in some regions while simultaneously reducing productivity in regions where temperatures are already nearly optimal (Ortiz et al., 2008). Jones and Thornton (2003) predicted a 10% decrease in maize production in Africa and Latin America by 2055 using climate scenarios generated by a GCM and a crop model. However, regional estimates of future agricultural climatic resources must be considered speculative and uncertain until regional climate models and climate scenarios can be better evaluated. Moreover, substantial uncertainties remain regarding the actual effects of climate conditions on crops (Xu et al., 2010). Tremendous progress is being made in providing the data and establishing the understanding needed to improve yield predictions, but major uncertainties remain despite efforts to control environmental conditions and avoid artifacts in the experimental systems. Further uncertainties arise because of factors we have chosen not to consider in this study, such as the characteristics of different maize varieties, available water levels, and economic conditions.

5. Conclusions

We have evaluated a future climate scenario from 1951 to 2100 using daily data from the high-resolution RegCM3 (0.25°×0.25°), adjusted to minimize errors relative to daily meteorological data from 101 meteorological stations in Northeast China between 1971 and 2000. We have calculated the temporal and spatial distributions of several indices used in agricultural climatic suitability theory (I_{sr}, I_{se}, and K) and used these distributions to quantitatively evaluate how climate change may affect the utilization of climatic resources for spring maize production.

Our results suggest that climate change will indeed affect the utilization of agricultural climatic resources in Northeast China. The distributions of I_{sr}, I_{se}, and K for spring maize production in Northeast China change considerably between 1951 and 2100 under this climate change scenario. All three indices decrease with warming in Liaoning Province, with particularly sharp declines after 2030 for I_{sr}, 2021 for I_{se}, and 2011 for K. The values of I_{sr} increase slightly in Jilin and Heilongjiang provinces after 2011. The values of I_{se} increase slightly in these two provinces after 2030, while the values of K decrease slightly. The areas with high values of all three indices will shift northeastward under global warming. The combined contributions of agricultural climatic resources indicate that spring maize cultivation should move northward and expand eastward to make efficient use of future agricultural climatic resources in Northeast China. Climate warming is likely to adversely impact spring maize production, particularly in Liaoning Province. Adaptive countermeasures should be adopted to make full use of future agricultural climatic resources and ensure a stable and high yield of spring maize in Northeast China.

These results are useful information for policymakers attempting to develop effective and sustainable strategies for agricultural development. However, a complete assessment of future agricultural climatic resources and spring maize production in Northeast China will need to account for additional factors such as crop varieties and water resource availability for irrigation. Future work in this area should include both field-based studies and the development and application of more sophisticated crop models.

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