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Climate-associated distribution of summer maize in China from 1961 to 2010

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ABSTRACT

A quantitative description of the change in the cultivation distribution of summer maize under climate change can provide a scientific basis for optimizing the distribution of maize production in China and making countermeasures to cope with climate change. In this paper, we studied the relationship between the cultivation distribution of summer maize and climate in China and investigated the decadal change of cultivation distribution of summer maize and the change in climatic suitability from 1961 to 2010. The results indicate that there has been significant decadal change in the cultivation distribution and climatic suitability of summer maize in China. The most climate-suitable planting area for summer maize exhibited an obvious trend of eastward expansion, reaching its maximum area (3.4×10^7 hm^2) in the 1990s; the climate-suitable planting area exhibited a trend of southward expansion, the magnitude of which was relatively large in the last 20 years, approaching about 1.6×10^8 hm^2 in the last 10 years. The least climate-suitable planting area was the largest and generally exhibited a fluctuating change with a decrease-increase-decrease-increase pattern, with the largest magnitude of fluctuation reaching 2.9×10^7hm^2; the climate-unsuitable area generally exhibited a downward trend, except for a slight increase in the 1970s. In the past 50 years, the arable area of summer maize clearly moved northward. Before the 1990s, expansion in a northwestern direction dominated; since the 1990s, expansion was mainly to the northeast. It indicated that there remains a very large potential of yield increase for summer maize in China against the background of climate change, which primarily concentrates in Northern China.

1. Introduction

Along with continued population growth, mankind is confronted with increasing food needs. Only 12% of the world's land can be cultivated, and many areas cannot grow crops because of the constraints of farming conditions. Although mankind can increase planted areas to a certain extent by adopting various measures such as irrigation and fertilization, climatic conditions are the primary factors that determine crop cultivation. To expand cultivated areas, it is necessary to clarify the relationship between climate and crops' cultivation distribution (Ramankutty and Foley, 1998; Ramankutty et al., 2002). Under current climate conditions, the world's arable land area increased by approximately 120% compared to 1992, reaching 4.1×10^9 hm^2. Global warming will promote the increase in arable land, but it also could cause reduction in actual yields (Ramankutty et al., 2002). Changing agricultural climate resources that affect crop growth, such as sunshine, temperature and rainfall, constitute the main factors that determine crop yield and lead to uncertainty in agricultural production. Therefore, both governments and scientists in various countries have strongly concerned about the influence of climate change on agricultural-production capability and the safety of the food supply. The climate change characterized by warming causes the temperature zone to shift toward the poles, causing changes in the pattern of agricultural geographical distribution (Rosenzweig and Hillel, 1998; Easterling et al., 2007; Ureta et al., 2012). Studies have found that if the annual average temperature increases by 1 °C, the crop zone in the mid-latitude area of the Northern hemisphere will move northward by 150–200 km (Newman, 1980), increasing the arable range of crops. However, uncertainty

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about the influence of global warming on water conditions will significantly constrain the expansion of crop-planting areas. Studies have shown that because the atmosphere's ability to maintain water vapor increases with the temperature, global warming very likely causes global wetting (Rosenberg, 1987). However, a relatively high atmospheric and surface temperature not only enhances plant transpiration and soil evaporation but also increases tension in areas where the soil moisture has already been tense (Parry, 1990). Therefore, there is an urgent need for scientific planning of production layout for crops against the background of climate change to clarify the relationship between climate and the cultivation distribution of regional crops.

Climate change has significantly affected the cultivation distribution of Chinese crops. Studies have indicated that heat enhancement caused by climate warming prompted a significant northward shift in China's boundary for planting its main crops: the rice-cultivation boundary crossed into a previously forbidden area and expanded northward to Yichun municipality and Heihe municipality in Northeast China (Fang and Sheng, 2000; Yun et al., 2005). Similarly, the northern boundary of winter-wheat planting in Liaoning Province moved northward by 1–2 latitude degrees in comparison with the 1950s (Hao et al., 2002); the northernmost boundary of winter-wheat planting in Heilongjiang Province extended to Kedong and Luobei counties. This boundary moved northward by nearly 10 ° of latitude from where the boundary was located in the 1950s (Zu et al., 2001; Yun et al., 2007). Compared to the early 1980s, the northern boundary of maize planting in Heilongjiang Province in the middle and late 1990s moved northward by approximately 4 ° of latitude, and extended to Daxing'an Mountain range and Yichun municipality. Moreover, the maize-planting area expanded to high-elevation areas. In Tibet, the maize-planting area expanded from its traditional elevation of 1700–3200 m in the 1980s to an elevation of 3840 m (Yu and Ou, 1999). Therefore, we urgently need to study variations in the suitable area for all types of crops in China, responding to the new situation of changing arable ranges for crops against the background of global warming, providing the basis for the optimization of food production layout in China, scientifically addressing the influence of climate change, and providing a method of reference for the optimization of crop-planting layout in various regions of the world.

China is one of the world's three maize-cultivation zones. As of 2012, China's maize acreage reached $3.50 \times 10^7\,hm^2$ and total production reached 2.06×10^8t. China has the most summer maize — and the most concentrated cultivation of that crop — in the world, with perennial acreage accounting for more than 40% of the nation's maize-cultivation land. Total production accounts for approximately 34% of the national maize yield and plays an important role in China's maize industry (Liu et al., 2012). However, the existing studies are primarily focused on maize and spring maize (He and Zhou, 2012). Although the perennial cultivation area for summer maize accounts for more than 40% of China's maize crop, studies on summer maize's response to climate change are insufficient. To ensure a high, stable yield of summer maize in China impacted by climate change, there is an urgent need both to clarify the influence of climate change on the cultivation distribution of summer maize and to investigate scientific measures to enable summer maize to cope with climate change. In recent years, remote-sensing information technology, geographic information technology, and species-distribution models have arisen and thrived, providing technical support for the study of climatic suitability of crop planting, including ecological niche models (e.g., BIOCLIM, BLOMAPPER, DIVA, and DOMAIN), a dynamic simulation model (CLIMEX), a generalized additive model (GAM), a generalized linear model (GLM), a distribution prediction model based on hypothesis testing (GARP, the genetic algorithm for rule-set prediction), and the maximum entropy(MaxEnt) model (Phillips et al., 2004; Guisan and Thuiller, 2005; Elith et al., 2006; Sun and Liu, 2010; Kriticos and Randall, 2011), which have been used to study the potential distribution of species. Of the existing models of species potential-distribution simulation, the MaxEnt model has the best predictive capability and accuracy (Phillips et al., 2006; Giovanelli et al., 2008; Saatchi et al., 2008; Cao et al., 2010; Estes et al., 2013; Halvorsen et al., 2015). This model is based on the principle of maximum entropy and selects the distribution with the largest entropy from the distributions that satisfy the conditions as the optimum distribution, deriving the probability distribution of species. It is able to model species geographic distributions with presence-only data (Phillips et al., 2006; Merow et al., 2013), and it was successfully applied for predicting species invasion, plant diseases and insect pests, species conservation and so on (Phillips et al., 2006; Evans et al., 2010; Peavey, 2010). He and Zhou (2012) and Sun et al. (2012) used the maximum-entropy method to construct the relationship of the cultivation distribution of maize and winter wheat with climate in China. They also derived the division of climate suitability for maize and winter wheat, providing the reference for the production layout and climatic division of maize and winter wheat.

We considered the published literature and the development of different summer maize cultivars in different regions, and gathered the potential climatic indices affecting the distribution of the summer maize at regional and annual scales. Our objectives in this paper were: (1) to reveal the major climatic indices of summer maize distribution using a MaxEnt model and obtain the MaxEnt probability distribution of summer maize in China; (2) to investigate decadal changes in potential cultivation distribution of China's summer maize from 1961 to 2010; and (3) to evaluate the influence of climate change on the cultivation distribution of summer maize in China.

2. Materials and methods

2.1. Data on meteorology and crop distribution

The data used for this study were mainly divided into two categories. The first category was the geographic distribution data for summer maize, which were derived from the dataset for crop growth and development status in China provided by the National Meteorological Information Center, China Meteorological Administration (CMA) including the longitude and latitude of 188 agricultural meteorological-observation stations for summer maize. The second category was meteorological data, which were obtained from the daily dataset in 1961–2010 obtained at basic and benchmark meteorological observation stations by the National Meteorological Information Center, including the elements of station longitude, latitude, daily mean, maximum, and minimum air temperature, and precipitation. The geographic distribution of the agricultural meteorological observation stations for summer maize and the meteorological stations were shown in Fig. 1.

In addition, we combined the daily meteorological data of the station format from1961 to 2010 with data from the digital elevation model (DEM) and adopted the spatial interpolation algorithm of a truncated Gaussian filter operator to interpolate data into daily spatial raster data over the spatial resolution of 10 km × 10 km (Thornton et al., 1997; Liu et al., 2006).

2.2. The method of maximum entropy

We applied the MaxEnt (Maximum Entropy) method to analyze the relationship between the cultivation distribution of summer maize and climatic factors in China. The MaxEnt method is based on the principle of maximum information entropy and can be used