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Exploring the dynamics of agricultural climatic resource utilization of spring maize over the past 50 years in Northeast China

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ABSTRACT

Exploring the dynamics of the utilization of agricultural climatic resources (i.e., environmental factors that affect crop productivity such as light, temperature, and water) can provide a theoretical basis for modifying agricultural practices and distributions of agricultural production in the future. Northeast China is one of the major agricultural production areas in China and also an obvious region of climatic warming. We were motivated to analyze the utilization dynamics of agricultural climatic resource during spring maize cultivation from 1961 to 2010 in Northeast China. To understand these dynamics, we used the daily data from 101 meteorological stations in Northeast China between 1961 and 2010. The demands on agricultural climatic resources in Northeast China imposed by the cultivation of spring maize were combined and agricultural climatic suitability theory was applied. The growth period of spring maize was further detailedly divided into four stages: germination to emergence, emergence to jointing, jointing to tasseling, and tasseling to maturity. The average resource utilization index was established to evaluate the effects. Over the past five decades, Northeast China experienced increases in daily average temperature of 0.246 °C every decade during the growing season (May–September). At the same time, strong fluctuating decreases were observed in average total precipitation of 8.936 mm every decade and an average sunshine hour of 0.122 h every decade. Significant temporal and spatial changes occurred in K from 1961 to 2010. The K showed decreasing trends in Liaoning province and increasing trends in Jilin and especially in Heilongjiang province, which increased by 0.11. Spatial differences were visible in different periods, and the most obvious increase was found in the period 2001–2010. The areas with high values of K shifted northeastward over the past 50 years, indicating more efficient use of agricultural climatic resources in Northeast China.

1. Introduction

Climate change and its impacts on agriculture are projected to dramatically affect crop production across broad regions of the world during the twenty-first century (IPCC, 2013; Godfray et al., 2010; Abraha and Savage, 2006), with significant impacts on crop yield and food security worldwide (FAO, 2009). Projections suggest that the number of people at risk of hunger could increase by between 5 million and 200 million by 2100 (Guo et al., 2013; Schmidhuber and Tubiello, 2007). Consequently, more attentions are given to the impact of global warming on agriculture (Gregory and Ingram, 2000; Sanchez, 2000; Fuhrer, 2003; Guo et al., 2013; Zhao et al., 2015).

Northeast China is vulnerable to climate change and an important region for spring maize production, accounting for over 30% of China's total maize production (NBSC, 2010). This region has experienced high temperature increases over the past 50 years, with a rate of 0.38 °C per decade (Liu et al., 2009). These large increases in temperature are thought to have considerable impacts on the agricultural climatic resources (Yuan et al., 2012; Guo et al., 2013), and maize growth and harvest (Tao et al., 2008). Previous studies have applied crop models and climate change scenarios to address the impact of climate change on agricultural climatic resources (Walker and Schulze, 2008), crop yield (Wolf and Van Diepen, 1995; Jones and Thornton, 2003; Tao and Zhang, 2010; Zhao et al., 2011; Guo et al., 2014), cropping systems (Kadiyala et al., 2015), crop diversity (Yuan et al., 2012), and northern

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planting limits (Liu et al., 2013; Zhao and Guo, 2013; Zhao et al., 2015). Liu et al. (2013) reported that climate warming led to a northward expansion of the northern limits of maize between 1961 and 2007 in Northeast China. These studies represent an important contribution toward understanding the effects of climate change on agricultural production. Guo et al. (2013) investigated the utilization of future agricultural climatic for spring maize production in Northeast China under the Intergovernmental Panel on Climate Change (IPCC) scenario A1B using daily data from the high-resolution RegCM3 ($0.25° \times 0.25°$). However, few studies have so far been conducted to quantitatively assess the impact of past climate change on agricultural climatic resource utilization of crops on both a small geographical scale and a large timescale. It is crucial to understand the change in utilization of past climatic resources during the period of crop growth in order to Effectively adapt the crops to changing climate.

The objectives of the present study were to: (1) evaluate the growth period of spring maize which is further detailedly divided into four stages based on the result of Guo et al. (2013): germination to emergence, emergence to jointing, jointing to tasseling, and tasseling to maturity; (2) quantitatively evaluate the temporal and spatial changes of the average resource utilization index from 1961 to 2010; (3) investigate the coordination and utilization of past agricultural climatic resources during spring maize growth on both a small geographical scale (Northeast China) and a large timescale (50 years); and (4) provide a scientific basis for planning the efficient use of agricultural climatic resources for sustainable maize production in Northeast China to adapt to future climate change.

2. Materials and methods

2.1. Study area

The region of interest extends from 38.9°N to 53.0°N and includes the entire Heilongjiang, Jilin, and Liaoning Provinces (Fig. 1). The climate in this study area is characterized by warm summers, cold winters, abundant precipitation, and short growing seasons, largely controlled by the East Asian monsoon, changing from a warm temperate zone to a cool temperate zone from south to north, and from a humid zone to a semiarid zone from east to west (Zhao et al., 2012). The mean annual air temperature ranges from −4.2 to 10.9 °C, decreasing from south to north. The annual precipitation decreases from the southeast (1070 mm) to the northwest (450 mm) (Liu et al., 2013). Precipitation is generally concentrated in the summer and autumn seasons, coinciding with the crop growing season (May–September). The annual total sunshine hours ranges from 2220 to 2930 h, and has tended to decrease by 40.6 h per decade ($p < 0.01$) (Liu et al., 2013).

2.2. Data

Daily climate variables gathered from 101 meteorological stations in Northeast China for 1961–2010, were provided by the National Meteorological Information Center. These daily data were organized in a database containing the following variables: maximal and minimal air temperature (°C), average air temperature (°C), precipitation (mm), solar radiation ($MJ/(m^2 d)$), relative humidity (%), and wind velocity (m/s). The observation data from 1981 to 2010 on the phonological, growth and development of maize were also requested from 53 agro-meteorological observation stations in Northeast China. These stations cover the majority of these maize-growing areas. Agro-technicians documented the yearly dates of major events, including the sowing, seedling, heading and maturity stages for each maize growth cycle at each station.

2.3. Utilization of agricultural climatic resources

The agricultural climatic resources (i.e., environmental factors that affect crop productivity such as light, temperature, and water) affect growth, development, and the yield of spring maize. Here, we mainly consider three climatic factors (light, temperature, and water) that play decisive roles in spring maize growth in Northeast China. The growth period of spring maize is further detailedly divided into four stages based on the result of Guo et al. (2013): germination to emergence, emergence to jointing, jointing to tasseling, and tasseling to maturity. The subordinate functions of light, temperature, and water based on fuzzy mathematics during the different growth periods for spring maize in Northeast China are established and comprehensively evaluated. Fuzzy mathematics forms a branch of mathematics related to fuzzy set theory and fuzzy logic. It started in 1965 after the publication of Lotfi Asker Zadeh's seminal work *Fuzzy sets* (Zadeh, 1965). A fuzzy subset A of a set X is a function $A{:}X \rightarrow L$, where L is the interval $[0,1]$. This function is also called a membership function. A membership function is a generalization of a characteristic function or an indicator function of a subset defined for $L = \{0,1\}$. More generally, one can use a complete lattice L in a definition of a fuzzy subset A. Three indices are used as indicators of agricultural climatic resource suitability and utilization for maize production: an average resource suitability index (I_{sr}), an average efficacy suitability index (I_{se}), and an average resource utilization index (K). These indices are defined as follows (Yuan et al., 2012; Guo et al., 2013; Zhao et al., 2015):

$$I_{sr} = \frac{1}{3n}\sum_{t=1}^{n}[S_T(T) + S_W(W) + S_R(R)] \tag{1}$$

$$I_{se} = \frac{1}{n}\sum_{t=1}^{n}[S_T(T) \times S_W(W) \times S_R(R)] \tag{2}$$

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

where I_{sr} is average resource suitability index. Higher values of I_{sr} indicate a higher degree of climatic resource suitability; I_{se} is average efficacy suitability index. Higher values of I_{se} indicate a more favorable combination of light, heat, and water resources for crop growth; K is average resource utilization index. Higher values of K correspond to a more efficient utilization of agricultural climatic resources; n is the number of developmental stages during the growth period (in this case $n = 4$ for the four growth stages defined above); $S_T(T)$, $S_W(W)$, and $S_R(R)$ are the subordinate functions of temperature, water, and solar radiation, respectively.

2.3.1. Subordinate function of 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 (Zhao et al., 2015):

$$S_T(T) = \begin{cases} 0 & T > t_L \text{ or } T > t_H \\ \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{t_L - t_{s1}}\left(T - \frac{t_{s1}+t_L}{2}\right) & t_L \leqslant T \leqslant t_{s1} \\ \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{t_H - t_{s2}}\left(T - \frac{t_{s2}+t_H}{2}\right) & t_{s2} \leqslant T \leqslant t_H \\ 1 & t_{s1} \leqslant T \leqslant t_{s2} \end{cases} \tag{4}$$

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 value of S_T takes values