Physics and Chemistry of the Earth 87–88 (2015) 87–96

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Effects of adjusting cropping systems on utilization efficiency of climatic resources in Northeast China under future climate scenarios

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ARTICLE INFO

Article history:
Received 14 April 2015
Received in revised form 10 July 2015
Accepted 24 July 2015
Available online 5 August 2015

Keywords:
Adjusting cropping systems
Utilization efficiency of climatic resources
Effect
Northeast China
Future climate scenario

ABSTRACT

Quantitatively evaluating the effects of adjusting cropping systems on the utilization efficiency of climatic resources under climate change is an important task for assessing food security in China. To understand these effects, we used daily climate variables obtained from the regional climate model RegCM3 from 1981 to 2100 under the A1B scenario and crop observations from 53 agro-meteorological experimental stations from 1981 to 2010 in Northeast China. Three one-grade zones of cropping systems were divided by heat, water, topography and crop-type, including the semi-arid areas of the northeast and northwest (III), the one crop area of warm–cool plants in semi-humid plain or hilly regions of the northeast (IV), and the two crop area in irrigated farmland in the Huanghuaihai Plain (VI). An agro-ecological zone model was used to calculate climatic potential productivities. The effects of adjusting cropping systems on climate resource utilization in Northeast China under the A1B scenario were assessed. The results indicated that from 1981 to 2100 in the III, IV and VI areas, the planting boundaries of different cropping systems in Northeast China obviously shifted toward the north and the east based on comprehensively considering the heat and precipitation resources. However, due to high temperature stress, the climatic potential productivity of spring maize was reduced in the future. Therefore, adjusting the cropping system is an effective way to improve the climatic potential productivity and climate resource utilization. Replacing the one crop in one year model (spring maize) by the two crops in one year model (winter wheat and summer maize) significantly increased the total climatic potential productivity and average utilization efficiencies. During the periods of 2011–2040, 2041–2070 and 2071–2100, the average total climatic potential productivities of winter wheat and summer maize increased by 9.36%, 11.88% and 12.13% compared to that of spring maize, respectively. Additionally, compared with spring maize, the average utilization efficiencies of thermal resources of winter wheat and summer maize dramatically increased by 9.2%, 12.1% and 12.0%, respectively. The increases in the average utilization efficiencies of precipitation resources of winter wheat and summer maize were 1.78 kg hm^{-2} mm^{-1}, 2.07 kg hm^{-2} mm^{-1} and 1.92 kg hm^{-2} mm^{-1} during 2011–2040, 2041–2070 and 2071–2100, respectively. Our findings highlight that adjusting cropping systems can dominantly contribute to utilization efficiency increases of agricultural climatic resources in Northeast China in the future.

1. Introduction

Global warming as the primary feature of climate change has become one of the major environmental problems in the world today. In recent decades, the issue of climate change has been the focus of academic research (Alexandrov and Hoogenboom, 2000; Walther et al., 2002; Zhao et al., 2011, 2015; Wang and Yan, 2013; Zhang and Yan, 2014). The global land surface temperature (LST) increased by 0.74 °C during the past 100 years (IPCC, 2007). The fifth assessment report of the IPCC (AR5) indicated that climate change was more serious than originally thought. In the past three decades, the decadal average LST was higher than that of any records with the highest LST in ten years since 2000, and the adverse effects of climate change on food production were more significant than any favorable impacts (IPCC, 2014).

Climate change and agriculture are interrelated processes, both of which occur on a global scale (Zhao and Guo, 2013). Under climate change, plant phenology can adapt to the environment through micro-adjusting (Francesco et al., 2000). Since 1960, the activities of animals and plants in spring have gradually advanced

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http://dx.doi.org/10.1016/j.pce.2015.07.012
1474-7065/

(Walther et al., 2002). Observations at different scales demonstrated that the flowering stages of plants shifted to an earlier date (Cleland et al., 2007). In European countries, the increase in spring temperature resulted in an advance in the average growing period of 8 days (Chmielewski and Rötzer, 2001).

A cropping system may be defined as a community of plants which is managed by a farm unit to achieve various human goals. The latter include food, fiber and other raw materials, wealth and satisfaction. Conway (1985) encompassed these multiple goals in the phrase 'increased social value'. Farmers are part of the system. They are able to set, or modify, their own goals, so two farms with identical climates and soils may be managed with different aims to achieve a different mix of outputs. In agriculture, multiple cropping is the practice of growing two or more crops in the same space during a single growing season. It is a form of polyculture. In sub-Saharan Africa, farmers adapted to climate change through adjusting cropping systems and sowing dates, such as choosing long-growing season crop cultivars in the single cropping system or short-growing season crop cultivars in multiple cropping systems (Waha et al., 2013). In China, studies on the responses of cropping systems to climate change have been highlighted and have made great progress (Wang, 1997; Deng et al., 2008; Yang et al., 2010; Zhao and Guo, 2013; Zuo et al., 2014). Wang (1997) simulated the potential impacts of climate change on cropping systems in China based on the regional climate change scenario for China estimated by a composite GCM. This researcher determined that the northern boundary of a triple cropping area would shift from its current border at the Changjiang River to the Huanghe River with more than 5 degrees of latitude in the year 2050; meanwhile, the current double cropping area would shift toward the central part of the present single cropping area. Yang et al. (2010) analyzed the possible effects of climate warming on the countrywide northern limits of cropping systems, the northern limits of winter wheat and double rice, and the stable-yield northern limits of rain-fed winter wheat–summer maize rotation in China from 1981 to 2007. Zhao and Guo (2013) predicted the possible trajectories of different cropping systems in China from 2011 to 2050, based on daily output from the regional climate model PRECIS (~50 km grid interval). Zhao et al. (2015) indicated that from 1961 to 2010, the northern planting boundaries of different maturities (late, medium-late, medium, medium-early and early) of spring maize varieties in Northeast China were all markedly extended northward and eastward. Adjusting cropping systems is one of the feasible ways in rationally using local agricultural climate resources and improving crop yields (Deng et al., 2008; Wang, 1997).

Northeast China, located in the mid-and high-latitude zones, is a typical region sensitive to climatic changes (Zhao et al., 2015). The concept of eco-fencing is important for the grain production base of the nation (Zhao et al., 2012; Dong et al., 2013). The cropping system in Northeast China has changed with increasing heat resources and a shortened growing season of crops under climate change. However, accurately predicting the impacts of adjusting cropping systems on the utilization efficiency of climatic resources in Northeast China remains a critical and unsolved issue at the regional scale so far, because of the complicated Chinese farming patterns, great scientific uncertainties in the prediction of climate change, and differences in the climate scenarios produced by different global climate models (Zhao and Guo, 2013).

The objectives of the present study are to (1) quantitatively evaluate the possible trajectories in planting boundaries of different cropping systems in the one thermophilic crop in the semi-arid area of the northeast and northwest (III), the one crop area of warm-cool plants in the semi-humid plain or hilly regions of the northeast (IV), and the two crop area in irrigated farmland in the Huanghuaihai Plain (VI) of the one-grade zone in Northeast China based on high-resolution regional climate model RegCM3 output (0.25 °C × 0.25 °C) from 1981 to 2100 under the future A1B scenario; (2) compare the total climatic potential productivities between 2011 and 2100 after replacing the one crop in one year model (spring maize) with the two crops in one year model (winter wheat and summer maize); (3) determine the contributions of adjusting cropping systems to increase in the climate resource utilization from 2011 to 2100 in Northeast China; and (4) provide a better understanding of the potential implications of climate change for agricultural sustainability in China.

2. Materials and methods

2.1. Data

Daily climate variables were obtained from high-resolution regional climate model RegCM3 output (0.25 °C × 0.25 °C) for the years of 1981 to 2100, including maximum, minimum and mean air temperature, precipitation, solar radiation, relative humidity, and wind speed. These model results were provided by the National Climate Centre of China. Due to the restrictions by collected data, we used data from a RegCM3 model simulation based on the A1B scenario (an A1 scenario that assumes a balanced distribution of energy sources). RegCM3 was widely used in regional climate simulation and prediction in China. The use of such high-resolution regional models could greatly improve simulations of contemporary climate and provide more reliable forecasts (Gao et al., 2011). Detailed descriptions of RegCM3 data correction methods and validation in Northeast China could be found in Yuan et al. (2012). This current study presents our first attempt to use corrected data from the RegCM3 climate model to evaluate quantitatively the spatial–temporal dynamics of cropping systems, potential productivity and agricultural climatic resource utilization in Northeast China under future climate scenarios.

The observation data on the phenology, growth and development of maize and wheat from 1981 to 2010 were requested from 53 agro-meteorological experiment stations in Northeast China. These stations cover the majority of these growing areas. The yearly dates of major events are documented by agro-technicians, including the sowing, seedling, heading and maturity stages for each maize and wheat growth cycle at each station (Zhao et al., 2015).

2.2. Agro-climatic indicators for different cropping systems

A cropping system refers to the structure, configuration, cropping and planting mode in a region or crop production unit. In China, cropping systems are divided into three bands, according to the method of progressive partitioning and type zoning (Liu and Han, 1987). The zero-grade band of cropping systems is mainly divided by accumulated temperature. The one-grade band is divided by heat, water, topography and crop. As for one crop in one year, the one-grade band can be divided into five one-grade zones (I, II, II, IV, V). As for two crops in one year, the one-grade band can be divided into four one-grade zones (VI, VII, VIII, IX). As for three crops in one year, the one-grade band can be divided into two one-grade zones (X, XI).

In this study, the indicators for cropping system division reported by Liu and Han (1987) were used (Table.1). Three one-grade zones were considered, including one thermophilic crop in the semi-arid area of the northeast and northwest (III), the one crop area of warm–cool plants in the semi-humid plain or hilly regions of the northeast (IV), and the two crop area in irrigated farmland in the Huanghuaihai Plain (VI).

Correspondingly, the active accumulated temperature stably passing the daily average temperature of 0 °C (⩾0 °C accumulated