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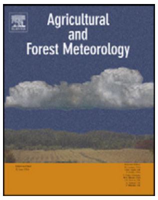

Climate change impacts on regional winter wheat production in main wheat production regions of China

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ABSTRACT

Wheat is the second primary crop in China. Wheat production in China is an important component for national food security. The combination of high-resolution Global Climate Model (GCM) and WheatGrow model was used to assess the effects of climate change on wheat yields in the main wheat production regions of China. With the application of many techniques including the downscaling of meteorological data, rasterizing of sowing date, parameterization of region cultivar and vectorization of soil data, the spatial data in study area is divided into homogeneous grids with the resolution of $0.1^\circ \times 0.1^\circ$. The grid is taken as the basic simulation unit, and each grid has a complete set of input data (meteorological, soil, management and varieties). Regional productivities are simulated with WheatGrow for each grid cell under scenarios of climate-change. There is an advance in flowering date in future climate compare to 2000s, but with a more homogeneous pattern for the whole producing region. The changes in grain filling period are relatively stable. Under rain-fed conditions, wheat yield is reduced in the north regions of China in three future periods, while wheat yield increases in the south regions of China. Under full-irrigation conditions, irrigated wheat yields will increase in almost all regions of whole producing region. The spatial pattern of evapotranspiration change is quite similar to that of yield change under rain-fed and full-irrigation conditions. The correlation between wheat yield and evapotranspiration (ET) increases to 0.96 and 0.51 ($p < 0.01$) under rain-fed and full-irrigation conditions, respectively. The irrigation water use efficiency (IWUE) will decrease under three time slices in 2030s, 2050s and 2070s in western Shandong, southern Sichuan, as well as northern Henan, Shanxi and Shaanxi, while IWUE will increase under scenarios of climate-change in other areas. The results revealed that the increase in effective irrigation in the future would help to increase the ET and further improve the wheat yield in the northern regions of China, and the limited water should be mad full use of in the regions with relatively high IWUE under scenarios of climate-change.

1. Introduction

The impact of future climate change on crop production has been widely studied by using crop models and climate change scenarios (Cantelaube and Terres, 2005; Challinor and Wheeler, 2008; Guo et al., 2010; Tao et al., 2008). Future climate scenarios may be beneficial for wheat in some regions, but could reduce productivity in zones where optimal temperatures already exist (Ortiz et al., 2008). The tendency of wheat yield in American Northern Plains will increase 25% in 2030 and 36% in 2095 (Izaurralde et al., 2003). Zhang et al. (2004) indicated that the average wheat production will increase by 9.8% in the North China Plain in the 2090s' B2A scenarios (local sustainability) (Nakicenovic and Swart, 2000). Zhang and Liu (2005) indicated that the future wheat yields will increase 7–58% in the Loess Plateau of China. Winter wheat production in southern Sweden was predicted to increase by 10–20% in 2050 (Eckersten et al., 2001). England wheat production is likely to increase 15–23% in 2050 (Richter and Semenov, 2005). However, wheat yield in southern Australia will decrease about from 13.5% to 32% under most climate change scenarios (Luo et al., 2005).

Evaluation of future climate change research is divided into two groups. The first one is the research for the crop response to the historical climate change (Egli, 2008; Malone et al., 2009; Tao et al., 2006) and the results derived from this group can be used as the basis for making a prediction for crop yields in the future. While the second is, the use of atmospheric circulation model output to drive crop models and can be further subdivided as follows: (1) direct use outputs of GCM or RCM (regional climate model) as the crop model input data (Lin et al., 2005); (2) adjust historical daily meteorological data according to the GCM or RCM outputs results (Daccachea et al., 2011; Liu et al., 2010); (3) adjust the weather generator

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parameters downscaling of GCM or RCM data to generate daily meteorological data (Semenov and Stratonovitch, 2010; Tao and Zhang, 2011; Trnka et al., 2004; Zhang et al., 2004). 221 papers that used crop simulation models to examine diverse aspects of how climate change might affect agricultural systems were reviewed by White et al. (2011). Only six direct GCM or RCM output was taken as the input of the crop model. 141 papers adjusted historical daily data with outputs of the circulation models. 68 papers adjusted parameters of weather generators such as WGEN or LARS-WG to provide daily weather data which could represent future climates.

The first method has some limitations. Global and regional climate model results cannot directly be used as input for crop models because the output is typically available as monthly means or changes in monthly means of climatic variables (Semenov and Stratonovitch, 2010), but daily time series are needed as input in most crop models. Even if daily output is available, the coarse spatial resolution and large biases, in particular for precipitation is unsuitable for direct use in crop models (Supit et al., 2012). The second method only considers the mean for temperature, rainfall, and radiation, but the standard deviation of these meteorological elements in the future cannot be incorporated. In recent years, the third method has become the most important method for the evaluation of future climate change research. In addition, although GCMs can effectively assess climate change caused by increasing of greenhouse gas emissions, coarse spatial resolution does not reflect reliable regional details. Therefore, downscaled GCMs (Cantelaube and Terres, 2005; Wang et al., 2011) or RCM (Xiong et al., 2007) combined with crop models was used to study the impact of future climate change on crop production in many efforts.

Impact assessment of climate change using crop models can be conducted at either the site or regional scale. At present, evaluation studies at site scale and regional scale are mainly based on the results of several representative agricultural experimental eco-sites (Guo et al., 2010; Zhang et al., 2004). Although it is easy to implement and less time consuming to couple the growing process with environmental variables, the method of using a representative site for a large area or area that has complex spatial heterogeneity can lead to significant simulation errors (Wang et al., 2011). Therefore, the evaluation results with only a few eco-sites cannot represent the characteristics of the region. Comparatively little investigation is based on high-resolution raster data for regional scale evaluation studies (Cantelaube and Terres, 2005; Ramirez-Villegasa et al., 2011; Supit et al., 2012), and mainly for foreign areas.

Many studies have assessed wheat phenology, yield and water use in response to climatic changes in China. Guo et al. (2010) explored the responses of wheat yield and water use efficiency to climate change in the North China Plain, and indicated that wheat yield will increase 9.8% without CO_2 fertilization in 2090s. Liu and Tao (2012) made a probabilistic assessment of changes in wheat yield (based on 5 different climate scenarios) and found that wheat yield would decrease with a probability of more than 69% and 54% under rain-fed and full-irrigation condition with the temperature rising 3°C without CO_2 fertilization. Ju et al. (2005) found that wheat yield would decrease 20% in ten agro-ecological zones of China without CO_2 fertilization in 2070. Tao et al. (2006) explored trends in phenology and yields of wheat in China from 1981 to 2000. Wang et al. (2008) investigated phenological trends in winter wheat in response to climatic changes from 1981 to 2004 in northwest China. Zhang et al. (2011) evaluated changes in evapotranspiration over irrigated winter wheat in North China Plain from 1979 to 2009 and provide references for assessing future ET change. Studies of climate change impacts on wheat in China showed conflicting results and uncertainties primarily relating to differences of sites, crop models, GCM scenarios and managements (Xiong et al., 2009), and above studied mainly explored the responses of wheat yield and water use efficiency to climate change based on site-specific conclusions. A systematic analysis of the relationship between climate change and wheat phenology, yield and water use is essential to assess wheat production risks and water resource allocation at regional scale in the future.

The aim of this paper is to explore the responses of winter wheat phenology, spatial variation of potential and rain-fed production, actual evapotranspiration and IWUE to climate change with the WheatGrow model in China's main wheat production regions and further analyze the reason affecting wheat yield under climate change projections of A2, A1 and B1 in each province, which provides a scientific basis of the future production strategy formulation and the redistribution of agricultural water resources in the wheat producing provinces.

2. Materials and methods

2.1. Study region

Based on the wheat sowing area in 2005 of each county in China obtained from the statistical yearbook, the sowing-area-weighted method (Jagtap and Jones, 2002) was used to aggregate the data of county-level wheat sowing area in 2005 to $0.5^\circ \times 0.5^\circ$ resolution grid-level wheat sowing area, then the ratio of wheat sowing area to total area in each grid was calculated and exhibited in Fig. 1 with ARCGIS 9.2. Ten major production provinces, Jiangsu, Hebei, Henan, Shandong, Shanxi, Shaanxi, Gansu, Hubei, Sichuan and Anhui provinces inside the blue line in Fig. 1A, which have the relatively largest wheat sowing fraction were chosen as study provinces.

The black line in Fig. 1A is the dividing line between winter and spring wheat in Chinese wheat producing regions (Jin, 1996). The regions above the black line are planted to spring wheat, while areas below the black line are planted to winter wheat and were the primary regions for this study. Fig. 1B shows average wheat sowing date (Day of Year, DOY) for the 1998–2003 study regions.

2.2. Data

2.2.1. Generating daily weather

Three GCM models providing the necessary weather variables for WheatGrow model were used in this study. There are the CSIRO-Mk3.5 (Commonwealth Scientific and Industrial Research Organisation Atmospheric Research, Australia, $1.9^\circ \times 1.9^\circ$), ECHam5 (Max Planck Institute for Meteorology, Germany, $1.9^\circ \times 1.9^\circ$) and MIROC3.2 (Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change, University of Tokyo, Japan, $2.8^\circ \times 2.8^\circ$). GCM generally has a lower spatial resolution. Such a coarse spatial resolution cannot reflect reliable regional detail (Cantelaube and Terres, 2005), therefore it is required to be downscaled in spatial scale for assessing regionally site-specific climatic impacts of climate change on winter wheat. The high-resolution monthly average meteorological data of three GCMs in this study were come from the CIAT database (http://www.ccafs-climate.org/data/) (Ramirez and Jarvis, 2008). The time slices 1990–2010, 2020–2040, 2040–2060 and 2060–2080 were chosen from the GCM data. Three scenarios of A2 (a high-greenhouse-gas-emission scenario), A1 (a low-emissions scenario) and B1 (a medium-emission scenario) are chosen as climate change projections (Nakicenovic and Swart, 2000).

Jones and Thornton (2013) describe a generalized downscaling and data generation method that takes the outputs of a GCM and allows the stochastic generation of daily weather data that are to some extent characteristic of future climatologies. Future