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Quantifying the spatial variation in the potential productivity and yield gap of winter wheat in China

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Abstract

Despite the improvement in cultivar characters and management practices, large gaps between the attainable and potential yields still exist in winter wheat of China. Quantifying the crop potential yield is essential for estimating the food production capacity and improving agricultural policies to ensure food security. Gradually descending models and geographic information system (GIS) technology were employed to characterize the spatial variability of potential yields and yield gaps in winter wheat across the main production region of China. The results showed that during 2000–2010, the average potential yield limited by thermal resource (YG_T) was 23.2 Mg ha^{-1}, with larger value in the northern area relative to the southern area. The potential yield limited by the water supply (YG_W) generally decreased from north to south, with an average value of 1.9 Mg ha^{-1} across the entire study region. The highest YG_W in the north sub-region (NS) implied that the irrigation and drainage conditions in this sub-region must be improved. The averaged yield loss of winter wheat from nutrient deficiency (YG_N) varied between 2.1 and 3.1 Mg ha^{-1} in the study area, which was greater than the yield loss caused by water limitation. The potential decrease in yield from photo-thermal-water-nutrient-limited production to actual yield (YG_O) was over 6.0 Mg ha^{-1}, ranging from 4.9 to 8.3 Mg ha^{-1} across the entire study region, and it was more obvious in the southern area than in the northern area. These findings suggest that across the main winter wheat production region, the highest yield gap was induced by thermal resources, followed by other factors, such as the level of farming technology, social policy and economic feasibility. Furthermore, there are opportunities to narrow the yield gaps by making full use of climatic resources and developing a reasonable production plan for winter wheat crops. Thus, meeting the challenges of food security and sustainability in the coming decades is possible but will require considerable changes in water and nutrient management and socio-economic policies.

Keywords: spatial variation, potential productivity, yield gap, winter wheat, China

1. Introduction

The world population is projected to increase 35% by 2050, which will require a 70–100% increase in food production (Wart *et al*. 2013). Therefore, there is an urgent need to develop more efficient and sustainable agricultural production systems to feed the growing population. Two options are available for increasing food production: increasing the

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area of cultivated land (Lambin and Meyfroidt 2011; Grassini and Cassman 2012) and enhancing crop productivity on existing farmland (Rudel *et al*. 2009). However, further expansion of the crop area would contribute to climate change (Karl and Trenberth 2003). Therefore, increasing crop productivity on the existing farmland seems to be the best strategy for narrowing the yield gap. To achieve this goal, it is important to explore the potential production of crops, quantify yield gaps and identify limiting factors for improving yield.

Process-based crop simulation models can estimate potential production under conditions with no stress from weeds, pests and diseases, and with sufficient available nutrients and water supply (Asseng *et al*. 2013). Several studies have investigated the potential production and yield gaps in different crops using these simulation models (Wu *et al*. 2006; Bhatia *et al*. 2008; Florian *et al*. 2014). For example, Abeledo *et al*. (2008) used the Crop Environment Resource Synthesis (CERES)-Wheat Model to simulate the potential yield of wheat and analyse the gap between attainable and potential yields. Grassini *et al*. (2011) estimated that the average corn yield potential ranged between 11.4 and 16.1 Mg ha^{-1} across 18 locations in the corn belt of the western U.S. based on the Hybrid-Maize Model. Lü *et al*. (2013) combined High-Resolution Global Climate Model (GCM) and WheatGrow Model to assess the effects of climate change on wheat yields in the main wheat production regions of China and found that the potential yields of wheat decreased from north to south due to lower radiation and shorter growing season caused by higher temperatures in the south. However, crop simulation models generally estimate yield potentials at small spatial scales and require sufficient input information for model calibration and operation (Asseng *et al*. 2013), which can raise the uncertainty of crop models under varied production environments (Bussel *et al*. 2011; Folberth *et al*. 2012; Asseng *et al*. 2013; Dzotsi *et al*. 2015).

In addition, many studies have been carried out to predict the potential crop productivity with reduced form and empirical models, such as the gradually descending model, agro-ecological zones (AEZ) and global agro-ecological zones (GAEZ) (Stehfest *et al*. 2007; Jiang *et al*. 2013). The reduced form and empirical models are established based on experts' knowledge and statistical methods with less consideration of crop growth processes. With simple input data and fewer parameter requirements, these models have been widely applied to evaluate the crop potential productivity at regional or worldwide scales. Xie *et al*. (2003) using the weather data collected from 129 stations to analyze the spatial and temporal variation of climatic potential productions of wheat, rice and maize in eastern China with the gradually descending model. Masutomi *et al*. (2009) combined a GAEZ Model with general circulation models (GCMs) to simulate the potential yield and assess the impact of climate change on rice production in Asia. Jiang *et al*. (2013) employed the gradually descending model to predict the potential photosynthetic, photo-thermal and climatic production of rice in the main production regions of China and found that the yield gap contributed by irrigation was between 5 and 20 Mg ha^{-1} and between 20 and 40 Mg ha^{-1} in most of the single- and double-cropping rice-growing regions, respectively.

Wheat is a major food crop throughout the world, and approximately 35–40% of the world's population uses wheat as the main staple food (Asseng *et al*. 2011). Until 2020, wheat production in developing countries is expected to increase by 1.6% per annum worldwide to meet the growing demand for food resulting from population growth and economic development (Ortiz *et al*. 2008). China is currently the world's largest wheat-producing country, and this crop accounts for approximately 11% of the total planting area and more than 16% of the total crop production (FAO 2012). Therefore, understanding the temporal and spatial variability of wheat production and the limiting factors for yield improvement in China is essential to optimizing agricultural policies and prioritizing research areas to achieve the potential production and ensure food security.

Although previous studies indicated that a large gap exist between the potential yield and the actual yield for wheat, the gap was not distributed uniformly and had great spatial variation in region (Li *et al*. 2014). In addition, most studies about the yield gaps in China were mainly focused on the North China Plain (NCP) (Wu *et al*. 2006; Chen *et al*. 2011; Wang *et al*. 2012; Li *et al*. 2014), none of them considered on the potential production and yield gaps in the whole winter wheat production region of China. Furthermore, most studies either focused on the impact of climate change on crop production (Caldiz *et al*. 2002; Jiang *et al*. 2013) or on the water-limited yield potential in rain-fed production systems (Boogaard *et al*. 2013; Jiang *et al*. 2013; Wart *et al*. 2013). The effects of nutrient deficiency and other factors, such as farming technology level, social factors and economic strategies, have not been fully considered. Therefore, the present study sought to predict the potential wheat yields as influenced by different production factors, such as climate, water, nutrients, technology, and social-economic factors, in the main winter wheat growing regions of China with gradually descending models. This study then aimed to quantify the yield gaps between potential factor productions and actual wheat yields and to analyse the spatial and temporal variations of different potential yields and yield gaps. The results are expected to help characterize the potential yields and yield gaps of winter wheat in China to aid in future improvements.