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# Spatio-temporal patterns of winter wheat yield potential and yield gap during the past three decades in North China

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ABSTRACT

To develop strategies for sustainable intensification of agricultural production, it is necessary to obtain precise and spatially explicit knowledge of crop potential and yield gap at a large scale. In this study, we estimated the yield potential for winter wheat by county during the period of 1981–2008 in North China using an ensemble simulation of a well validated large-scale crop model, MCWLA-Wheat, for each $0.5^{\circ} \times 0.5^{\circ}$ grid. An ensemble simulation was used to better represent the heterogeneous conditions in climate, soil and cultivars over a large area. The spatio-temporal patterns of winter wheat actual yield, yield potential and yield gap were evaluated according to the simulation results. We found that more than 90% of counties had experienced an overall increase in wheat yield. However, 30.1% of counties have already experienced yield stagnation. The mean yield potential ranged generally from approximately 5000 to 8000 kg/ha. The yield potential under water-limited conditions showed considerably smaller values, ranging from about 2000 to 5000 kg/ha. Yield gaps in about 62% of counties were generally lower than 40% of potential yields, indicating a relatively small potential for yield improvement. During the study period, yield potential decreased in most counties because of a significant increase in temperature and decrease in solar radiation. In contrast, the increase of yield potential in the west and southeast areas could be attributed to the increase of solar radiation during the growing season. Overall, yield gap in the past decades showed a substantial decrease due to the changing pattern of yield potential and the rapid increase of actual yield, especially in the North China Plain, with a rate of 1–3% per year. These patterns imply a shrinking of space for further yield improvement. Our results highlight the necessity of applying advanced management technologies to realize a high yield, as well as adopting technical progress and policy support to overcome the yield bottleneck. Moreover, breeding climate-resilient cultivars to further increase yield potential should be of equal importance.



## 1. Introduction

It is widely accepted that the increasing world population will require substantially greater food production (Bruinsma, 2009; Van Wart et al., 2013). The rate of population increase by 2050 is projected to be 35%. However, an approximate doubling of food demand seems unavoidable when considering the changing dietary habits, higher income and consequent higher consumption of food (Godfray et al., 2010; Licker et al., 2010; Tilman et al., 2011). People are trying to improve crop production without significantly expanding cropland to meet the goals of both ensuring the low food price and preserving the natural environment (Cassman, 1999; Cassman et al., 2003; Searchinger et al., 2008). Therefore, crop yield improvement on existing cultivated land should be of high priority (Licker et al., 2010; Van Wart et al., 2013). However, yield stagnation has been observed in many places across the world (Brisson et al., 2010; Cassman et al., 2010; Ray et al., 2012; Grassini et al., 2013), which implies poor prospects for achieving the goal of yield rapid increase (Lobell et al., 2009). In China, this issue is critical because of the large population and relatively insufficient area of cultivated land. Since the area of China's farmland has decreased during the past decade and is expected to continuously decrease in the future in response to economic and environmental development (Lu and Fan, 2013), raising crop productivity will become

*Abbreviations:* NCP, North China Plain; MLRYR, the middle and lower reaches of the Yangtze River; Ya, actual yield; Yp, potential yield; Ypw, water-limited potential yield; Ygp, yield gaps; Ygpp, percentage of Ygp; Yp_we, weighted potential yield; IR, irrigated ratio; RFR, rain fed ratio.

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**Table 1**
Weather conditions in the study area of each province. The growing season is from November to May of the following year.

| Province | Annual | | Growing season | |
|---|---|---|---|---|
| | Average temperature (°C) | Total precipitation (mm) | Average temperature (°C) | Total precipitation (mm) |
| Anhui | 15.84 | 1139.56 | 9.90 | 417.71 |
| Hebei | 12.78 | 575.19 | 6.14 | 115.80 |
| Henan | 14.60 | 836.94 | 8.37 | 237.38 |
| Hubei | 16.41 | 1267.80 | 10.82 | 525.65 |
| Jiangsu | 15.75 | 1110.56 | 9.75 | 386.32 |
| Shaanxi | 11.39 | 728.70 | 5.79 | 186.67 |
| Shandong | 13.77 | 734.25 | 7.33 | 167.87 |
| Shanxi | 10.08 | 599.72 | 3.96 | 139.06 |

critical for meeting the food demand (Liu et al., 2011). In addition, crop yield stagnation has also been recently observed in some areas of China (Iizumi et al., 2014; Li et al., 2014; Zhang et al., 2014), stressing the necessity of evaluating the potential of agricultural production. To evaluate the potential of yield improvement and the possible food supply under sustainable intensification of agriculture production, it is essential to estimate the yield potential (Yp) and the yield gap (Ygp) at a regional scale (van Ittersum et al., 2013).

Winter wheat (*Triticum aestivum* L.) is one of the major staple food crops in China, accounting for more than 20% of the total sowing area in recent decades (National Bureau of Statistics of China, 2012), which makes China the largest wheat-producing country in the world. Thus, wheat yield and its Yp in China have become a major research focus (Licker et al., 2010; Chen C. et al., 2011; Chen et al., 2013; Ray et al., 2012; Wang et al., 2012; Lu and Fan, 2013; Zhang et al., 2013; Xiao and Tao, 2014). Previous studies agree that wheat yield in China still has potential to increase, and advances in management practices will contribute to yield improvement. For instance, based on experimental data and the CERES-Wheat model, Zhang et al. (2013) indicated that advances in agricultural management have played an important role in increasing yield, while climate changes have reduced crop yield. A similar result has been found by Wang et al. (2012), who tested improved crop varieties and management practices for a wheat–maize cropping system, showing that those would compensate some of the negative impacts of climate changes and significantly improve the yields. As for the Yp and Ygp of winter wheat in China, results of statistical analysis presented by Licker et al. (2010) showed a Ygp percentage (Ygpp) of less than 25% for wheat in the North China Plain (NCP) and the middle and lower reaches of the Yangtze River (MLRYR), whereas the Ygpp was generally larger than 50% in other areas of North China. In contrast, Lu and Fan (2013) stated that the Ygpp was between 7% and 69% according to the simulation results of EPIC model in 43 representative stations across the NCP. In the case of the changes of Yp and Ygp, the simulated results of the APSIM model showed a decreasing Yp in the northern NCP during past decades but no clear change in the southern NCP (Chen et al., 2010). Considering the increasing or stagnating yield pattern in China (Ray et al., 2012), the Ygp is showing a declining trend. The shrinking of the Ygp has also been shown by Li et al. (2014); however, their conclusions were attributed to the increasing Yp and a more notable on-farm yield improvement.

The previous studies have inconsistencies in the magnitude of the Ygp and the trends of Yp. These discrepancies may be caused by the different methods used in estimating the regional Yp. Crop model simulation is considered a more reliable method than statistical methods for estimating crop yield potential (Lobell et al., 2009; van Ittersum et al., 2013). However, when using crop models to estimate the Yp, uncertainties may originate from many sources, one of the most important of which is the study scale. Previous studies tended to conduct site-specific estimations of Yp, and then interpolated the results to a large scale to evaluate regional spatio-temporal patterns of Yp and Ygp. However, up-scaling these location-specific estimates to the regional scale may produce large uncertainties from the spatial heterogeneous conditions of climate, soil and planting practices and consequently result in poor representativeness (Jagtap and Jones, 2002).

Considering that there are very few studies focused on the regional simulation of wheat yield potential in China, we applied the process-based general Model to capture the Crop–weather relationship over a Large Area (MCWLA) for wheat (MCWLA-Wheat) (Tao and Zhang, 2013), which is designed for regional simulations, as a tool to estimate winter wheat yield potentials and the yield gap at county scale across the major wheat production regions in China. The simulation involved a large number of grids across the research region, which would better represent the spatial heterogeneous conditions in the growing environment. In addition, to improve the yield estimation, we built ensemble simulations to account for the uncertainties in the biophysical processes of the model and to better represent the diversities among crop cultivars (Tao et al., 2015). We aimed to (1) better estimate the crop Yp and consequently the Ygp over a large area, and (2) present a spatially explicit pattern of crop Yp and Ygp across the major wheat cultivation areas of China. The improved results will be helpful to accelerate sustainable intensification of cropping systems.

## 2. Material and methods

### 2.1. Study area

Winter wheat is cultivated widely across North China, mainly in the NCP and MLRYR. To analyze the yield pattern of winter wheat in China, our study area covered the NCP, MLRYR and the surrounding areas, including parts of Shanxi and Shaanxi provinces (Fig. 1). Among these regions, the NCP covers the entire area of Tianjin and major parts of Hebei, eastern Henan, western Shandong, southern Beijing, and northern Anhui and Jiangsu. Meanwhile, the majority of Hubei and southern Jiangsu belong to the MLRYR. The entire study area comprises nearly 700 administrative counties, which together account for 84% of the sowing area and about 90% of winter wheat production in China (National Bureau of Statistics of China, 2012). The weather conditions in the study area of each province are shown in Table 1. Differences in weather conditions are apparent among the different areas. The annual average temperature ranged from 10 to 16 °C, and the annual total precipitation ranged from approximately 600 to 1300 mm. The growing season of winter wheat is in the relatively colder and drier months of the year (from November to May of the following year), with temperatures ranging from 4 to 11 °C and precipitation from 100 to 500 mm.

### 2.2. MCWLA-Wheat model

The MCWLA-Wheat model was developed by Tao and Zhang (2013). This model was designed to simulate the crop growth and development in a daily time step, as well as evaluating the