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Climate-smart management can further improve winter wheat yield in China

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ABSTRACT

Climate change, genotype, and agronomic management have profound impacts on crop yield. Our goal in this study is to untangle the interrelated contributions of climate change, genetic improvements, and agronomic management on winter wheat yield in China to develop management strategies that address future nutritional needs. The Agricultural Production System Simulator (APSIM) farming systems model was used to simulated long-term (1981–2010) wheat yield for four wheat production regions under different Genotype by Environment by Management (GxExM) scenarios. Using detailed field experimental data from 1981 to 2005 in conjunction with the APSIM-wheat model, the potential for climate-smart management to improve yield on a regional scale is investigated. Results showed that when all climatic variables were considered together, winter wheat relative yield change decreased from 0.62% to 7.16% over the period 1981 to 2010, depending on cultivar and growing region. The impact of individual climatic variables varied by region. In general, winter wheat yields showed the least decline in the Northern China Plain (NC) due to climate change. Cultivar renewal combined with improvements in agronomic management boosted yields but to a different extent in each region. For cultivar renewal, yields increased 6.93%, 17.69%, 24.87%, and 52.72% in the NC, Yellow and Huai River Valleys (YH), SW and YV, respectively over the period 1981 to 2010. Agronomic management improved yields by 22.91%, 5.27%, 58.77%, and 59.20% in these regions, respectively. Overall, the observed yield improvements with agronomic management were higher than those resulting from cultivar renewal for most of China's wheat growing regions. The exception was found in YH, where improvements in winter wheat yield from cultivar renewal were greater than those from agronomic management. Regardless, there is still ample room for yield improvement in winter wheat by implementing climate-smart management. SW would benefit significantly, with a potential increase of 99% because of improved agronomic management. More moderate, but still significant increases were predicted for NC and YH (49% and 42%, respectively) while only moderate improvements were anticipated for YV (17%). Our findings highlight the extent that improvements in cultivar renewal and agronomic management have compensated for the negative impacts of climate change for different wheat growing regions of China over the past three decades. The results also indicate that advances in agronomic management outweighed the effects of cultivar renewal in most regions. Climate-smart management is still needed to further improve yields in wheat-growing regions of China.

1. Introduction

Improvements in crop yields have slowed since the 1990s (Evenson and Gollin, 2003; Rosegrant and Cline, 2003) and even stagnated in much of the world since the last century (Finger, 2010; Fischer and Edmeades, 2010; Grassini et al., 2013; Hafner, 2003; Ray et al., 2012). The stagnation or collapse of crop yields has profound implications for global food systems (Ray et al., 2012). Indeed, continued crop yield improvements are required to feed the world in the 21st century (Cassman, 1999; Rosegrant and Cline, 2003; Tester and Langridge, 2010). Accordingly, substantial research efforts have been directed towards quantifying the contributions of the drivers (e.g. climate change, genotype, and agronomic management) to crop productivity and their subsequent effects on yield improvements for both China (Bai et al., 2015; Xiao and Tao, 2014) and internationally (Fischer et al., 2009; Kirkegaard and Hunt, 2010).

Climate is the major uncontrollable factor that influences crop yield and has been accepted as one of the factors contributing to yield stagnation globally (Godfray et al., 2010; Hochman et al., 2017; You et al., 2009). Several studies documented that temperature increases since the

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1980s have reduced crop yields by accelerating phenological development, shortening the duration of crop growth and grain filling period, aggravating heat-related water stress, and exacerbating pest and disease losses (Lobell et al., 2013; Xiao et al., 2013). Improvements in crop cultivars and agronomic management practices had somewhat alleviated the negative impacts of climate change and helped to maintain continued increases in crop yields (Wang et al., 2012b). The interactions between climate change, genotype, and agronomic management are quite complicated and vary substantially between regions and cropping systems. To improve our understanding of climate change impacts and develop adaptation options, it is necessary to isolate the contributions of climate change, the impacts of each climate variable, genotypic improvements, and modern agronomic management to the observed changes in crop yield (Bai et al., 2015).

Information technology has the potential to improve agricultural production through the integration of knowledge to deliver improved management options to producers (Sassenrath et al., 2008). Climate-smart management can favorably increase yield and improve food security, which could be defined as an optimal management practice.

Empirical analysis is recognized as a widely-used approach for quantifying environmental and managerial contributions to yield gains, using historical data on crop yields, investments, and environments to train specific regression equations (Lobell and Asner, 2003; Xiong et al., 2014; You et al., 2009). In spite of limited reliance on detailed field data for statistical methods to detect the effects of different drivers (Lobell and Burke, 2010), empirical analysis still showed a limited ability to mechanistically interpret and explain the observed yield stagnation (Xiong et al., 2014). Additional methods to delineate the causes of yield trends are needed. Process-based crop growth models are commonly used to quantify the impacts of environment and agronomic management on crop yields (Li et al., 2015; Liu et al., 2010; Xiao and Tao, 2014; Zhang et al., 2013). Because of the ability to repeat and simulate a range of management scenarios, crop models are capable of evaluating the effectiveness of different agricultural management (or adaptation) strategies (Xiong et al., 2014). The Agricultural Production System Simulator (APSIM) model is now being used in over 110 countries around the world (Gaydon et al., 2017; Hochman et al., 2017; Keating et al., 2003) and has been widely tested and applied to crop studies in China (Chen et al., 2010; Li et al., 2015; Liu et al., 2010; Sun et al., 2015; Xiao et al., 2017). It is a component-driven model with several simulation modules including crop growth and development, soil water and nitrogen dynamics developed by the Agricultural Production Systems Research Unit of Australia (Holzworth et al., 2014). APSIM has evolved towards a new generation of agricultural systems simulation since its inception and the enhanced APSIM model can be used to simulate a wide range of combinations of Genotype by Environment by Management (GxExM) scenarios to assess the effect of changed cultivars and so on (Holzworth et al., 2014; Ridoutt et al., 2013).

Wheat is a vital cereal crop in China, which is grown on 24.7% of the cultivated land accounting for 21.2% of total Chinese grain production (National Bureau of Statistics of China, 2015). Winter wheat accounts for 91.0% of the total wheat yield and 87.5% of the area planted to wheat (National Bureau of Statistics of China, 2015). In the past several decades, actual wheat yield in China has improved due to the combined effects of climate change, cultivar renewal, improved agronomic management practices, and technological advancement (Qin et al., 2015). However, it is challenging to maintain a rapid and consistent rate of yield improvement all the time. Identifying the causal factors contributing to yield improvements in winter wheat in China has become increasingly important in the development of realistic management protocols to maintain and improve future yield goals. Many studies have investigated the roles of climate, cultivar, and management on winter wheat yield changes (Bai et al., 2015; Xiao and Tao, 2014), but primarily at a station level with few studies addressing regional yield shifts.

In this study, our goal is to untangle the contributions of climate change, cultivar renewal, and agronomic management on past winter wheat yield growth for the four primary wheat production regions of China under different Genotype by Environment by Management (GxExM) scenarios during the period from 1981 to 2010. We use detailed experimental data from 1981 to 2005 together with the evaluated APSIM-wheat model at a regional scale to delineate causal relationships between environment, cultivar, management and wheat yield. These results are then used to investigate the potential improvements in yield that would be possible through implementation of climate-smart management on a regional scale.

2. Materials and methods

2.1. Study areas

Winter wheat is planted under diverse geographic and climatic conditions across China. A previous study (Jin, 1991) classified the winter wheat-growing areas of China into six physiogeographic regions: the Northern China Plain (NC); the Yellow and Huai River Valleys (YH); the Middle and Lower Yangtze Valleys (YV); Southwestern China (SW); Xinjiang (XJ); and Southern China (SC) (Fig. 1). In this study, research was concentrated on the four major winter wheat regions (NC, YH, YV and SW) that produce > 90% of China's wheat.

2.2. Sources of data

The climate data set for this study was obtained from 205 weather stations from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/), selected based on the length of time series and data integrity (Fig. 1). The weather station data include the daily minimum and maximum temperatures, sunshine hours, average relative humidity, wind speed, and rainfall from 1981 to 2010. The data quality control practices for these climate variables were implemented by the China Meteorological Administration. Actual solar radiation measurements were not available at most of the stations, thus sunshine hours were converted to daily solar radiation using the Angstrom formula (Black et al., 1954; Jones, 1992).

Crop data on winter wheat phenology were obtained from field trials at the Agro-meteorological Experimental Stations operated by the China Meteorological Administration. The experimental station data on winter wheat phenology (sowing, emergence, flowering, and maturity dates), cultivar type, yield, biomass, and management practices (planting density, irrigation, and fertilizer) used in this study were

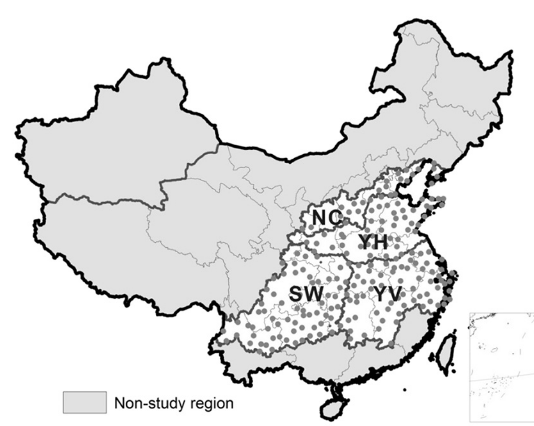

Fig. 1. Physiogeographic wheat production regions and weather recording stations in China. The four winter wheat producing regions of China are identified with labels: NC, Northern China Plain; YH, Yellow and Huai River Valleys; YV, Middle and Lower Yangtze Valleys; SW, Southwestern China. The grey solid points in the figure indicate the location of the weather stations used in this study.