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Crop yield responses to climate change in the Huang-Huai-Hai Plain of China

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A B S T R A C T

Global climate change may impact grain production as atmospheric conditions and water supply change, particularly intensive cropping, such as double wheat–maize systems. The effects of climate change on grain production of a winter wheat–summer maize cropping system were investigated, corresponding to the temperature rising 2 and 5 °C, precipitation increasing and decreasing by 15% and 30%, and atmospheric CO_2 enriching to 500 and 700 ppmv. The study focused on two typical counties in the Huang-Huai-Hai (3H) Plain (covering most of the North China Plain), Botou in the north and Huaiyuan in the south, considering irrigated and rain-fed conditions, respectively. Climate change scenarios, derived from available ensemble outputs from general circulation models and the historical trend from 1996 to 2004, were used as atmospheric forcing to a bio-geo-physically process-based dynamic crop model, Vegetation Interface Processes (VIP). VIP simulates full coupling between photosynthesis and stomatal conductance, and other energy and water transfer processes. The projected crop yields are significantly different from the baseline yield, with the minimum, mean (±standardized deviation, SD) and maximum changes being −46%, −10.3 ± 20.3%, and 49%, respectively. The overall yield reduction of −18.5 ± 22.8% for a 5 °C increase is significantly greater than −2.3 ± 13.2% for a 2 °C increase. The negative effect of temperature rise on crop yield is partially mitigated by CO_2 fertilization. The response of a C3 crop (wheat) to the temperature rise is significantly more sensitive to CO_2 fertilization and less negative than the response of C4 (maize), implying a challenge to the present double wheat–maize systems. Increased precipitation significantly mitigated the loss and increased the projected gain of crop yield. Conversely, decreased precipitation significantly exacerbated the loss and reduced the projected gain of crop yield. Irrigation helps to mitigate the decreased crop yield, but CO_2 enrichment blurs the role of irrigation. The crops in the wetter southern 3H Plain (Huaiyuan) are significantly more sensitive to climate change than crops in the drier north (Botou). Thus CO_2 fertilization effects might be greater under drier conditions. The study provides suggestions for climate change adaptation and sound water resources management in the 3H Plain.

1. Introduction

Throughout the last 150 years, atmospheric CO_2 concentration has increased from ~280 ppmv to ~385 ppmv in 2008 (http://www.esrl.noaa.gov/gmd/ccgg/trends/) due to widespread human activities such as fossil fuel burning, cement production, and modified land-use patterns (IPCC, 1996; Fan et al., 2007). At the current rate of increase the concentration of atmospheric CO_2 will double before 2100, which will likely have dramatic effects on global and regional-scale climate. Globally, many climatic variables are already changing. For example, since 1950 the Huang-Huai-Hai (3H) Plain in China, which comprises most of the North China Plain (Fig. 1), has experienced a reduction in precipitation at an average rate of 2.92 mm year^{-1}, and a temperature increase at an average rate of 0.20 °C decade^{-1} with minimum temperature increasing more rapidly than maximum temperature (Mo et al., 2006; Tian, 2006). Tao et al. (2006) showed that at Zhengzhou, a typical station in the 3H Plain, maximum and minimum temperatures in winter, spring and summer increased by 0.39–0.95 °C decade^{-1} since 1980. Although change in climate is represented by changes in several climatic variables (i.e., air pressure, humidity, solar irradiance, atmospheric CO_2 concentration, ozone, and air quality, among others mentioned in Brown and Rosenberg, 1997; Mera et al., 2006; Robock and Li, 2006), the changes in precipitation, temperature, and atmospheric CO_2 concentration have been the main focus to date. Other climate variables previously assumed to be station-

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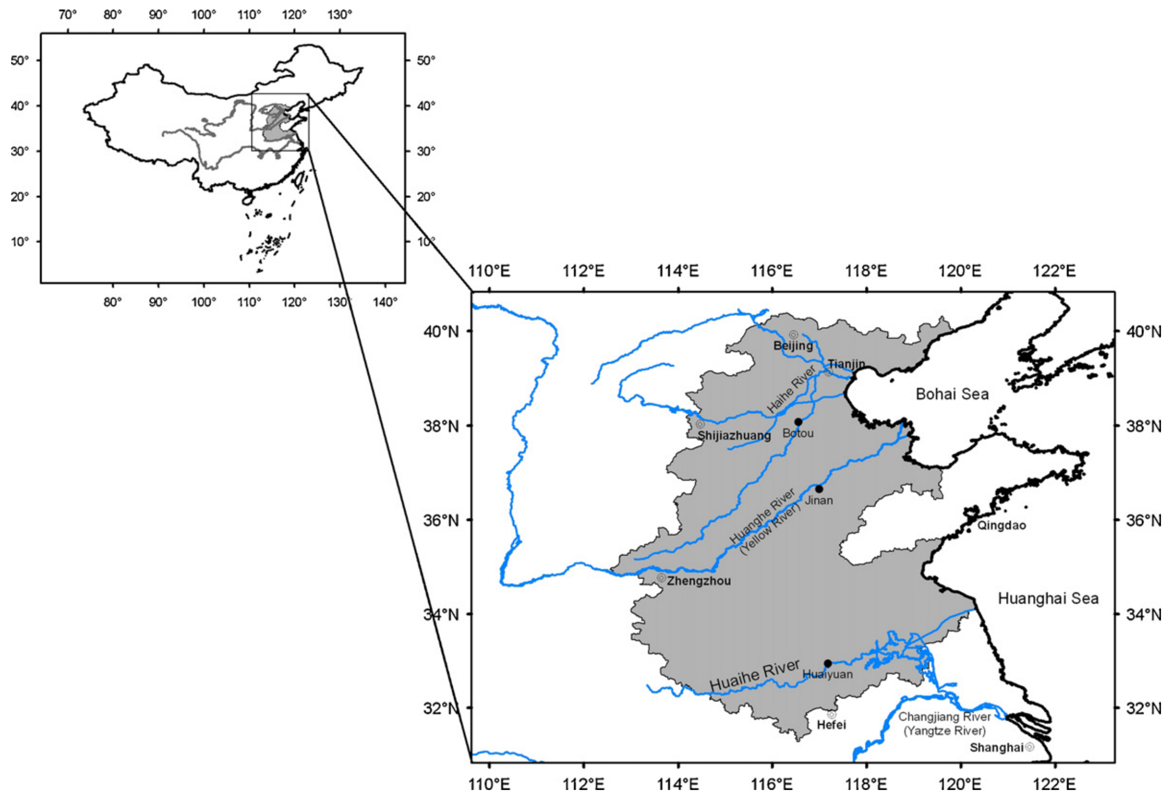

Fig. 1. The location of the two typical counties in the 3H Plain (Shaded area) within China (The Haihe, Huanghe and Huaihe Rivers are on the China map from north to south, from which the Huang-Huai-Hai Plain was formed).

ary (no trend) are now being investigated. For example, Roderick et al. (2007) and McVicar et al. (2008) found negative trends in near-surface terrestrial wind-speeds, which will influence both the actual and potential evapotranspiration estimation.

Observations on the 3H Plain show that crops are significantly affected by climate variation. The increase in temperature shortens the phenological phases, reducing the time for light/water uptake and carbon assimilation, while changes in rainfall affect water availability. In addition, accelerated crop development and a shortened grain filling period reduce grain yield. Although it is difficult to assess the role of technological advances in farming practices on yield, Tao et al. (2006) reported a strong negative correlation between maize yield and increasing summer temperatures on the 3H Plain. There is also a correlation between climate variation and the planting, anthesis, and maturity dates for maize throughout the last two decades.

How crop yield responds to climate change will affect food security of a nation. For example, if we can understand the role of climate forcing on yield in the past, present, and projected future changes, it will be helpful for establishing a warning system so that adaptations can be made at an early stage. This knowledge is especially critical to the 3H Plain, which is a very important agricultural region, accounting for about 69.2% of wheat and 35.3% of maize yield in China based on the yield data (http://www.stats.gov.cn/tjsj/ndsj/2005/indexch.htm) averaged over 1996–2007. The 3H Plain is particularly sensitive because it is situated on the transition between semi-humid and semi-arid zones, where rainfall distribution is irregular during a year with more than 70% falling in summer. Intensive double-cropping systems may also be particularly vulnerable to climate change as it affects water availability and crop water use. The spring crops (such as wheat) commonly need supplemental irrigation to obtain favorable production. In this way, farmers can mitigate the response caused by one driving factor with the response caused by another factor. For example, less precipitation in winter may reduce grain yield, and the reduced yield may be mitigated by adding irrigation. Of course the two effects may be not able to be exactly offset to zero. This same explanation will be used below when we use the word "offset". As surface water cannot meet the intensive demand for industrial and agricultural development, the water resources supply in this region is vulnerable (Liu and Wei, 1989; McVicar et al., 2002). To meet the irrigation requirement, groundwater has been over-pumped (Xu et al., 2005). As a consequence, the water table has continuously fallen over the last several decades, creating the so-called "groundwater funnel" in some northern parts which has considerably deteriorated the agricultural sustainability and environmental conditions.

With rising concerns over food security and water resources limitations, the responses of agricultural systems to climate change of the 3H Plain have garnered much attention by domestic and international research scientists as well as managers, stakeholders and farmers over the last decades. Using the regional climate change and crop models, Lin et al. (2005) demonstrated that future climate change without CO_2 fertilization could reduce the crop yields in China. Tao et al. (2006) synthesized crop and climate data from representative stations across China during 1981–2000 and showed that temperature was negatively correlated with crop yield at all stations except Harbin in northeastern China. Some studies (Thomson et al., 2006) showed that winter wheat yields in 3H would increase on average due to warmer nighttime temperatures and higher precipitation. Zhang and Liu (2005) documented at the Loess Plateau, where wheat yield increased 7–58% and maize yield increased 32–64% under three Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). They explained that the overall increase in yield for the three scenarios was attributed to the considerable increase in precipitation, which is the important limiting factor for agricultural production in that region. Generally, if moisture demand is met, productivity