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Abstract

We analyzed a provincial-scale data set of observed winter wheat yield, together with fine-scale daily weather outcomes from 1979 to 2011, to assess the responses of winter wheat yield in China to changes in the daytime temperature (Tmax) and the nighttime temperature (Tmin). Contrasting with the literature's emphasis on a negative correlation between Tmin and wheat yield, we showed that winter wheat yield in China responded positively to higher Tmin, with the positive yield responses varying across wheat growing seasons. In line with the previous studies, we found that winter wheat yield exhibited negative responses to higher Tmax. These findings are useful for the development of China's wheat-breeding programs and the design of efficient adaptation strategies in China's grain sector to cope with future warming.

Key Words: agriculture, China, warming, temperature, winter wheat yield

JEL Codes: Q10, Q54

Contents

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Xiaoguang Chen and Guoping Tian*

1. Introduction

Global observed temperature data over the past half century indicate that the daily minimum temperature (T_{min}) has been rising faster than the daily maximum temperature (T_{max}) in many parts of the world (Easterling et al. 1997). The asymmetric increases in T_{min} and T_{max} are expected to affect crop yields, because plant physiological processes such as photosynthesis and transpiration occur during daytime and are sensitive to changes in T_{max}, whereas other physiological processes such as respiration occur throughout the day and are sensitive to changes in both T_{min} and T_{max} (Lobell and Ortiz-Monasterio 2007; Peng et al. 2013). Several studies focusing on rice production in Asia have provided statistical evidence that changes in T_{min} and T_{max} had large and significant impacts on rice yield (Chen et al. 2016; Peng et al. 2004; Welch et al. 2010). Although agronomic studies have long suggested that wheat yield exhibits different responses to changes in T_{min} and T_{max} (Lobell and Ortiz-Monasterio 2007; see Porter and Gawith 1999), studies analyzing the temperature effects on wheat yield have primarily focused on examining the effects of rising daily average temperature (T_{ave}) on yield (Liu et al. 2016; for example, see Nicholls 1997). Hence, the impacts of higher T_{min} and T_{max} on wheat yield have not been well understood (Prasad et al. 2008).

The purpose of this paper is to assess the effects of changes in T_{min} and T_{max} on winter wheat yield in China. As the world's largest wheat-producing country, China produced around 126.3 million metric tons of wheat in 2011, which accounted for about 17% of the global wheat production (http://faostat3.fao.org/browse/Q/QC/E). Wheat is also China's second most-prevalent field crop; the first position is held by rice. China grows both spring wheat and winter wheat. We focused on winter wheat, because it is widely produced across China's agricultural heartland (see Figure S1 in the Supplementary Material) and accounts for about 90% of the total wheat production in China. Therefore, understanding how winter wheat yield has responded to rising T_{min} and T_{max} provides useful information for the development of China's wheat-breeding

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programs and efficient adaptation strategies in China's grain sector to cope with future warming.

Many studies have investigated the effects of temperature on wheat yield using the agronomic approach and the regression approach, at the global scale (Asseng et al. 2015; Lobell and Field 2007; Lobell et al. 2011) and at a regional scale (Lobell et al. 2005; Nicholls 1997; Tack et al. 2015). The agronomic approach uses crop simulation models to predict how wheat yield will change under different warming scenarios. As compared to the regression approach, the agronomic approach considers the main physiological processes inherent to crop growth (Liu et al. 2016). However, parameters used to calibrate these crop simulation models are typically based on field trials (Boote et al. 1996), and do not consider the effects of non-climate factors, such as prices of fertilizers, labor and chemicals, on yield. As a result, findings based on the agronomic approach cannot represent outcomes that may occur in real agricultural settings (Welch et al. 2010).

Only a few studies have used observed data and the regression approach to assess the responses of wheat yield to the simultaneous variations in T_{min} and T_{max} (see a reivew in Liu et al. 2016). Based on the data collected from a field trial at Kansas State University, Prasad et al. (2008) found a negative correlation between spring wheat yield and T_{min}. Using historically observed yield and weather data, Lobell et al. (2005) and Lobell and Ortiz-Monasterio (2007) also showed that higher T_{min} has negatively affected spring wheat yield in Mexico. Several studies discovered that wheat yield exhibited negative responses to higher T_{max} (Gibson and Paulsen 1999; Lobell and Ortiz-Monasterio 2007; Tashiro and Wardlaw 1989).

Several studies have used the regression approach to assess the effects of variations in temperature on wheat yield in China (Li et al. 2010; for example, see Tao et al. 2008; Xiong et al. 2014; You et al. 2009; Zhang et al. 2016). However, these studies all have apparent methodological issues. Although wheat yield was found to exhibit different responses to changes in T_{min} and T_{max}, most of these studies used T_{ave} as the temperature variable to explain yield variations (Li et al. 2010; Xiong et al. 2014; You et al. 2009; Zhang et al. 2016). Based on a provincial-scale data set from 1979 to 2002, Tao et al. (2008) analyzed the effects of T_{min}, T_{max} and precipitation on wheat yield. They showed that wheat yield was negatively correlated with T_{max} and that the effects of higher T_{min} on wheat yield varied across regions. However, the regression approach used by Tao et al. (2008) consisted of simple linear regressions. That is, when examining the effect of T_{min} (or T_{max}) on wheat yield, they regressed wheat yield only on T_{min} (or T_{max}), without controlling for other relevant weather variables. Weather variables, such as $T_{\min}$, $T_{\max}$, precipitation and solar radiation, are typically correlated. If $T_{\max}$, precipitation and radiation were not considered when estimating the relationship between $T_{\min}$ and yield, it would cause biased parameter estimates of the $T_{\min}$ variable. Because of the methodological issues discussed above, empirical findings reported in these earlier studies are questionable.

In this paper, we developed a simple regression model to assess the responses of winter wheat yield to changes in $T_{\min}$ and $T_{\max}$. The regression model we developed incorporated a comprehensive set of weather variables, including $T_{\min}$, $T_{\max}$, precipitation and solar radiation, which enabled us to obtain the net impacts of temperature changes on yield. Following Tack et al. (2015), we divided the growing cycle of winter wheat into three seasons: Fall (from planting in late September or early October to November), Winter (from December to February) and Spring (from March to grain maturity). We constructed these weather variables for each of the three seasons. We also incorporated input use in one model specification to investigate how winter wheat yield has responded to changes in input use. Moreover, we included various fixed effects to account for the unobserved factors that may have affected winter wheat yield. Specifically, we included region fixed effects to account for the time-invariant unobserved factors that are specific to a given region, such as geographical location. We have also incorporated year fixed effects to account for the unobserved factors that had the same yield effects for all regions in a given year, such as global CO_2 concentrations. The regression analysis was conducted by using a provincial-scale data set of winter wheat yield, combined with daily weather outcomes during the period 1979-2011.

This paper makes two major contributions to the related literature. First, we add to the sparse literature examining the effects of rising $T_{\min}$ and $T_{\max}$ on winter wheat yield by employing a detailed provincial-scale data set for the world's largest wheat-producing country. Second, contrasting with the previous studies assessing the effects of variations in temperature on winter wheat yield in China (Li et al. 2010; Tao et al. 2008; Xiong et al. 2014; You et al. 2009; Zhang et al. 2016), we recognized that wheat yield is sensitive to changes in $T_{\min}$ and $T_{\max}$ and that this sensitivity differs across phenological growth stages of wheat. We also constructed weather variables accordingly, which enabled us to detect whether there existed differential effects of temperature on yield across the three growing seasons of wheat.

2. Regression Model

We assessed the weather effects on winter wheat yield using the following regression model:

$$Y_{i,t} = W_{i,t}\alpha + E_{i,t}\beta + \theta_i + \lambda_t + \varepsilon_{i,t} \qquad (1)$$

where i indexes province and t indexes year. Thus, $Y_{i,t}$ represents the average yield of winter wheat in province i and year t. $W_{i,t}$ is the vector of weather variables, including the means of $T_{\min}$ and $T_{\max}$ and the sums of radiation and precipitation for each of the three growing seasons of winter wheat. $E_{i,t}$ is a vector of economic variables denoting input use per hectare (ha) for winter wheat production. Province fixed effects (θ_i) were incorporated to account for the unobserved variables that were time invariant and unique to province i during the sample period, such as soil quality. Year fixed effects (λ_t) were also included to account for the unobserved variables that had the same effects on yield in all provinces in a given year, such as changes in global CO_2 concentrations. $\varepsilon_{i,t}$ are the error terms denoting other unobserved factors that are not included in Equation (1). We allowed $\varepsilon_{i,t}$ to be spatially correlated, due to the concern that some of the variables, such as production practices used by neighboring provinces and possible pest problems experienced in neighboring provinces in a particular growing season, may be spatially correlated; however, these variables are omitted as explanatory variables in Equation (1). Our baseline regression analysis first considered a distance matrix, under which the spatial correlation between two provinces is determined based on the inverse of the geographical distance, to account for this spatial correlation. We used a spatial weights matrix to test the sensitivity of our results as a robustness check. α is a vector of the parameters of interest, and measures the marginal effects on winter wheat yield of each unit change in weather variables, holding other variables constant.

3. Data Sources

Data used for this analysis were compiled from several sources. We obtained province average yields of winter wheat from the National Bureau of Statistics of China for the period 1979-2011. Of the 34 provinces and province-equivalent municipal cities in China, about 22 provinces produce winter wheat (see Figure S1 in the Supplementary Material). Growing cycles of winter wheat in these 22 provinces were taken from the Ministry of Agriculture of the People’s Republic of China, which reports planting and harvest dates of major crops produced in China. As summarized in Table S1 in the Supplementary Material, winter wheat is typically planted in late fall or early winter and harvested before summer. From the same data source, we collected information on machinery (RMB•ha^{-1}), pesticide (RMB•ha^{-1}) and labor (day•ha^{-1}) used for winter wheat production. Our sample is a balanced panel with 726 observations covering 22 provinces.

We obtained daily records of $T_{\min}$, $T_{\max}$, precipitation and radiation for about 800 weather stations located in mainland China from the China Meteorological Data Sharing Service System. The daily weather data were merged with the yield data using the latitudes and longitudes of weather stations and province boundaries. We used two approaches to construct weather variables for each winter wheat growing province. We first constructed area-weighted weather variables using weather information from weather stations in a province, with county-level availability of cropland in that province in 2010 as the weighting function. County-level cropland availability in 2010 was also compiled from the National Bureau of Statistics of China. In the robustness check section, we used the averages of the weather variables across all weather stations in a province as the weather variables for that province to examine the robustness of our main findings.

Table S2 in the Supplementary Material reports summary statistics for winter wheat yield, weather variables and input use. We found that winter wheat yield varied substantially across provinces and years, ranging between 537 kg per ha and 6277 kg per ha. The average yield of winter wheat was 3024 kg per ha during the sample period. Weather variables, including temperature, precipitation and solar radiation, also exhibited considerable variability during the sample period.

4. Regression Results

We considered three regression models. Model 1 incorporated only $T_{\min}$, $T_{\max}$, and precipitation. Model 2 added the radiation variables. Model 3 incorporated three economic variables to assess the yield responses to changes in input use.

Table 1 reports estimated effects of weather on winter wheat yield. We found that winter wheat yield responded positively to higher $T_{\min}$ across the three growing seasons. Each 1°C increase in $T_{\min}$ in the fall was associated with a yield increase of 133-168 kg per ha, depending on model specifications. Relative to the yield increase in the fall, the positive effects on yield stemming from higher $T_{\min}$ in the winter and spring were significantly larger. Specifically, each 1°C increase in $T_{\min}$ in the winter and spring raised winter wheat yield by 165-235 kg per ha and 290-520 kg per ha, respectively, which are 13-40% and 72-257% larger than the corresponding yield increase in the fall.

Winter wheat yield responded negatively to elevated $T_{\max}$, with the negative yield impacts varying across model specifications. In Model 1, with temperature and precipitation as weather variables, higher $T_{\max}$ had large and negative impacts on winter wheat yield during the three growing seasons. For each 1°C increase in $T_{\max}$, the negative $T_{\max}$ effect ranged between -102 kg per ha in the fall and -192 kg per ha in the spring. In Models 2 and 3, with the inclusion of the three radiation variables, the negative effects of $T_{\max}$ on yield are statistically significant only in the fall and spring. Specifically, each 1°C increase in $T_{\max}$ in the fall and spring reduced winter wheat yield by 95-102 kg per ha and 393-460 kg per ha, respectively. Precipitation had negligible impacts on winter wheat yield.

The addition of the radiation variables in Models 2 and 3 affected both magnitudes and significance levels of the coefficient estimates of temperature variables. Specifically, inclusion of radiation decreased the parameter estimates of the $T_{\min}$ variables in the fall and winter by 13-21% and 27-30%, respectively, while increasing the parameter estimates of $T_{\min}$ in the spring by 43-79%. Higher $T_{\max}$ was found to have significant, negative effects on winter wheat yield across the three growing seasons in Model 1. The negative responses are only significant in the fall and spring in Models 2 and 3. The inclusion of the radiation variables also increased the absolute value of the parameter estimate of $T_{\max}$ in the spring by 105-140% relative to the corresponding parameter estimate in Model 1. These findings are expected, given the large correlations between temperature and radiation during the wheat growing period (see Table S3 in the Supplementary Material). Increased radiation in the spring had a significant and positive effect on winter wheat yield, while the radiation impacts on winter wheat yield are insignificant in the fall and winter.

Estimated weather effects on winter wheat yield remained broadly consistent when the three input-use variables were added in Model 3. Coefficient estimates of the labor and machinery variables are statistically significant and positive, indicating that increased use of labor and machinery has effectively boosted winter wheat yield. The coefficient estimate of the pesticide variable is insignificant.

5. Robustness Checks

We considered three different scenarios to examine the robustness of estimated temperature effects on winter wheat yield. Specifically, in Scenario (1), we considered the spatial correlation of the error terms based on whether two provinces share a common boundary (a spatial contiguity matrix). In Scenario (2), we used the averages of the weather variables across all weather stations in a province as the weather variables for that province. In Scenario (3), we followed the standard agronomic literature and re-defined growing seasons of winter wheat.[1] Specifically, we divided the growing cycle of winter wheat into three growth phases, including the vegetative growth phase from establishment to tillering, the reproductive growth phase from tillering to heading, and the maturation growth phase from heading to mature grain. Based on the three growth stages, we then re-constructed weather variables and replicated the above regression analysis using the newly constructed weather variables. We conducted these sensitivity analyses using Model 3.

Figure 1 displays the results of robustness checks. To facilitate comparisons, Figure 1 also presents our baseline estimates of weather variables. Our key findings of the positive $T_{\min}$ effects and the negative $T_{\max}$ effects on winter wheat yield remained broadly consistent across the three scenarios considered. We noticed that the positive $T_{\min}$ effects are statistically significant during the three growing seasons in the baseline scenario. However, the positive $T_{\min}$ effects on yield are statistically significant only in the winter and spring in Scenario (1), in the spring in Scenario (2), and during the vegetative and reproductive stages in Scenario (3). Across the various scenarios that we considered, we found that the negative effects of higher $T_{\max}$ on winter wheat yield are most significant near the time of grain maturity in the spring (or during the maturation stage). Estimated precipitation and radiation impacts on winter wheat yield in Scenarios (1)-(3) are fairly close to our baseline estimates.

6. Discussion

Prior studies found negative correlations between $T_{\min}$ and spring wheat yield (Lobell et al. 2005; Lobell and Ortiz-Monasterio 2007; Prasad et al. 2008). In this paper, we showed that winter wheat yield in China exhibited positive responses to higher $T_{\min}$. The existing literature emphasizes that higher $T_{\min}$ reduces wheat yield by decreasing spikelet fertility, grains per spike, grain size and grain filling duration (Prasad et al. 2008). The difference in findings between this paper and the prior studies may be because $T_{\min}$ within our sample never touched the critical $T_{\min}$ threshold above which is detrimental for wheat yield. For instance, the optimal $T_{\min}$ for winter wheat growth during the maturation stage typically ranges between 18 and 25°C (see Table 4 in Porter and

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[1] "Wheat growth and physiology," FAO corporate document repository. Available at: http://www.fao.org/docrep/006/Y4011E/y4011e06.htm.

Gawith 1999). In our sample, mean and maximum $T_{\min}$ in the spring were only 11.0°C and 16.2°C, respectively (see Table S2 in the Supplementary Material). Experimental studies based on field trials also suggested that winter wheat yield in North China may increase with higher $T_{\min}$ (Chen et al. 2014; Fang et al. 2015).

Our finding of the negative effects of $T_{\max}$ on winter wheat yield is consistent with the previous assessments (Gibson and Paulsen 1999; Lobell and Ortiz-Monasterio 2007; Tashiro and Wardlaw 1989). Higher $T_{\max}$ can negatively affect winter wheat yield by reducing grain number and grain size (Gibson and Paulsen 1999; Lobell et al. 2012) and shortening the duration of wheat grain filling (Tashiro and Wardlaw 1989). Our key findings of the positive $T_{\min}$ effects and the negative $T_{\max}$ effects on winter wheat yield remained broadly consistent across different model specifications.

7. Conclusions

We investigated the effects of weather on winter wheat yield, using a regression model and a provincial-scale data set of observed winter wheat yield and weather variables in China. To increase the precision of estimated temperature effects and account for the simultaneous variations in weather variables, our regression model included precipitation and radiation as additional weather variables and considered various region and time fixed effects. In contrast to the existing studies, we discovered that winter wheat yield in China responded positively to higher $T_{\min}$, with the positive yield responses varying across wheat growing seasons. In line with the previous assessments, we showed that winter wheat yield in China was negatively correlated with higher $T_{\max}$.

The primary caveat of this work is that estimated weather effects on winter wheat yield were based on an aggregated provincial-scale data set. Because there exists considerable heterogeneity in crop yields across counties within a province, the estimated weather effects reported in this paper may deviate from the actual effects of weather on yield. Using a county-level data set on rice yield, Chen et al. (2016) analyzed the temperature effect on rice yield in China. The main findings reported in Chen et al. (2016) held when a coarse province-level data set was used (Chen and Tian 2016). Therefore, our main findings of the positive $T_{\min}$ effects and the negative $T_{\max}$ effects on winter wheat yield might also hold if the temperature effects on winter wheat yield were estimated using a less-aggregated data set.

References

Asseng, S., F. Ewert, P. Martre, R.P. Rotter, D.B. Lobell, D. Cammarano, B.A. Kimball, M.J. Ottman, G.W. Wall, J.W. White, M.P. Reynolds, P.D. Alderman, P.V.V. Prasad, P.K. Aggarwal, J. Anothai, B. Basso, C. Biernath, A.J. Challinor, G. De Sanctis, J. Doltra, E. Fereres, M. Garcia-Vila, S. Gayler, G. Hoogenboom, L.A. Hunt, R.C. Izaurralde, M. Jabloun, C.D. Jones, K.C. Kersebaum, A.K. Koehler, C. Mueller, S. Naresh Kumar, C. Nendel, G. O'Leary, J.E. Olesen, T. Palusuo, E. Priesack, E. Eyeshi Rezaei, A.C. Ruane, M.A. Semenov, I. Shcherbak, C. Stoeckle, C. Stratonovich, T. Streck, I. Supit, F. Tao, P.J. Thorburn, K. Waha, E. Wang, D. Wallach, J. Wolf, Z. Zhao, and Y. Zhu. 2015. Rising Temperatures Reduce Global Wheat Production. *Nature Climate Change 5*(2): 143-147. http://dx.doi.org/10.1038/nclimate2470

Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential Uses and Limitations of Crop Models. *Agronomy Journal* 88: 704-716. https://doi.org/10.2134/agronj1996.00021962008800050005x

Chen, J., Y. Tian, X. Zhang, C. Zheng, Z. Song, A. Deng, and W. Zhang. 2014. Nighttime Warming Will Increase Winter Wheat Yield through Improving Plant Development and Grain Growth in North China. *Journal of Plant Growth Regulation* 33(2): 397-407. https://doi.org/10.1007/s00344-013-9390-0

Chen, S., X. Chen, and J. Xu. 2016. Assessing the Impacts of Temperature Variations on Rice Yield in China. *Climatic Change* 138(1-2). https://doi.org/10.1007/s10584-016-1707-0

Chen, X., and G. Tian. 2016. Impacts of Weather Variations on Rice Yields in China Based on Province-level Data. *Regional Environmental Change* 16: 2155-2162. https://doi.org/10.1007/s10113-016-0952-0

Easterling, D.R., B. Horton, P.D. Jones, T.C. Peterson, T.R. Karl, D.E. Parker, M.J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, and C.K. Folland. 1997. Maximum and Minimum Temperature Trends for the Globe. *Science* 277(5324): 364 LP-367. http://science.sciencemag.org/content/277/5324/364.abstract

Fang, S., D. Cammarano, G. Zhou, K. Tan, and S. Ren. 2015. Effects of Increased Day and Night Temperature with Supplemental Infrared Heating on Winter Wheat Growth in North China. *European Journal of Agronomy* 64: 67-77. https://doi.org/http://dx.doi.org/10.1016/j.eja.2014.12.012

Gibson, L.R., and G.M. Paulsen. 1999. Yield Components of Wheat Grown under High Temperature Stress during Reproductive Growth. *Crop Science* 39: 1841-1846. https://doi.org/10.2135/cropsci1999.3961841x

Li, S., T. Wheeler, A. Challinor, E. Lin, H. Ju, and Y. Xu. 2010. The Observed Relationships between Wheat and Climate in China. *Agricultural and Forest Meteorology* 150(11): 1412-1419. https://doi.org/http://dx.doi.org/10.1016/j.agrformet.2010.07.003

Liu, B., S. Asseng, C. Müller, F. Ewert, J. Elliott, D.B. Lobell, P. Martre, A.C. Ruane, D. Wallach, J.W. Jones, C. Rosenzweig, P.K. Aggarwal, P.D. Alderman, J. Anothai, B. Basso, C. Biernath, D. Cammarano, A. Challinor, D. Deryng, G. De Sanctis, J. Doltra, E. Fereres, C. Folberth, M. Garcia-Vila, S. Gayler, G. Hoogenboom, L.A. Hunt, R.C. Izaurralde, M. Jabloun, C.D. Jones, K.C. Kersebaum, B.A. Kimball, A.-K. Koehler, S.N. Kumar, C. Nendel, G. O'Leary, J.E. Olesen, M.J. Ottman, T. Palosuo, P.V.V. Prasad, E. Priesack, T.A.M. Pugh, M. Reynolds, E.E. Rezaei, R.P. Rötter, E. Schmid, M.A. Semenov, I. Shcherbak, E. Stehfest, C.O. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, P. Thorburn, K. Waha, G.W. Wall, E. Wang, J.W. White, J. Wolf, Z. Zhao and Y. Zhu. 2016. Similar Estimates of Temperature Impacts on Global Wheat Yield by Three Independent Methods. *Nature Climate Change* 1(September): 1-8. https://doi.org/10.1038/nclimate3115

Lobell, D.B., and C.B. Field. 2007. Global Scale Climate–crop Yield Relationships and the Impacts of Recent Warming. *Environmental Research Letters* 2(1): 14002. http://stacks.iop.org/1748-9326/2/i=1/a=014002

Lobell, D.B., and J.I. Ortiz-Monasterio. 2007. Impacts of Day Versus Night Temperatures on Spring Wheat Yields. *Agronomy Journal* 99: 469-477. https://doi.org/10.2134/agronj2006.0209

Lobell, D.B., J.I. Ortiz-Monasterio, G.P. Asner, P.A. Matson, R.L. Naylor, and W.P. Falcon. 2005. Analysis of Wheat Yield and Climatic Trends in Mexico. *Field Crops Research* 94(2-3): 250-256. https://doi.org/http://dx.doi.org/10.1016/j.fcr.2005.01.007

Lobell, D.B., W. Schlenker, and J. Costa-Roberts. 2011. Climate Trends and Global Crop Production Since 1980. *Science* 333(6042): 616-620. http://science.sciencemag.org/content/333/6042/616.abstract

Lobell, D.B., A. Sibley, and J.I. Ortiz-Monasterio. 2012. Extreme Heat Effects on Wheat Senescence in India. *Nature Climate Change* 2(3): 186-189. https://doi.org/10.1038/nclimate1356

Nicholls, N. 1997. Increased Australian Wheat Yield Due to Recent Climate Trends. *Nature* 387(6632): 484-485. http://dx.doi.org/10.1038/387484a0

Peng, S., J. Huang, J.E. Sheehy, R.C. Laza, R.M. Visperas, X. Zhong, G.S. Centeno, G.S. Khush, and K.G. Cassman. 2004. Rice Yields Decline with Higher Night Temperature from Global Warming. *Proceedings of the National Academy of Sciences of the United States of America* 101(27): 9971-9975. https://doi.org/10.1073/pnas.0403720101

Peng, S., S. Piao, P. Ciais, R.B. Myneni, A. Chen, F. Chevallier, A.J. Dolman, I.A. Janssens, J. Peñuelas, G. Zhang, S. Vicca, S. Wan, S. Wang, and H. Zeng. 2013. Asymmetric Effects of Daytime and Night-time Warming on Northern Hemisphere Vegetation. *Nature* 501(7465): 88-92. http://dx.doi.org/10.1038/nature12434

Porter, J.R., and M. Gawith. 1999. Temperatures and the Growth and Development of Wheat: A Review. *European Journal of Agronomy* 10: 23-36.

Prasad, P.V.V, S.R. Pisipati, Z. Ristic, U. Bukovnik, and A.K. Fritz. 2008. Impact of Nighttime Temperature on Physiology and Growth of Spring Wheat. *Crop Science* 48: 2372-2380. https://doi.org/10.2135/cropsci2007.12.0717

Tack, J., A. Barkley, and L.L. Nalley. 2015. Effect of Warming Temperatures on US Wheat Yields. *Proceedings of the National Academy of Sciences of the United States of America* 112(22): 6931-6. https://doi.org/10.1073/pnas.1415181112

Tao, F., M. Yokozawa, J. Liu, and Z. Zhang. 2008. Climate–crop Yield Relationships at Provincial Scales in China and the Impacts of Recent Climate Trends. *Climate Research* 38(1): 83-94. http://www.int-res.com/abstracts/cr/v38/n1/p83-94/

Tashiro, T., and I. Wardlaw. 1989. A Comparison of the Effect of High Temperature on Grain Development in Wheat and Rice. *Annals of Botany* 64(1): 59-65. http://aob.oxfordjournals.org/content/64/1/59.abstract

Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe. 2010. Rice Yields in Tropical/subtropical Asia Exhibit Large but Opposing Sensitivities to Minimum and Maximum Temperatures. *Proceedings of the*

National Academy of Sciences 107(33): 14562-14567. https://doi.org/10.1073/pnas.1001222107

Xiong, W., I.P. Holman, L. You, J. Yang, and W. Wu. 2014. Impacts of Observed Growing-season Warming Trends Since 1980 on Crop Yields in China. *Regional Environmental Change* 14(1): 7-16. https://doi.org/10.1007/s10113-013-0418-6

You, L., M.W. Rosegrant, S. Wood, and D. Sun. 2009. Impact of Growing Season Temperature on Wheat Productivity in China. *Agricultural and Forest Meteorology* 149(6-7): 1009-1014. https://doi.org/http://dx.doi.org/10.1016/j.agrformet.2008.12.004

Zhang, Z., X. Song, F. Tao, S. Zhang, and W. Shi. 2016. Climate Trends and Crop Production in China at County Scale, 1980 to 2008. *Theoretical and Applied Climatology* 123(1): 291-302. https://doi.org/10.1007/s00704-014-1343-4).

Tables and Figures

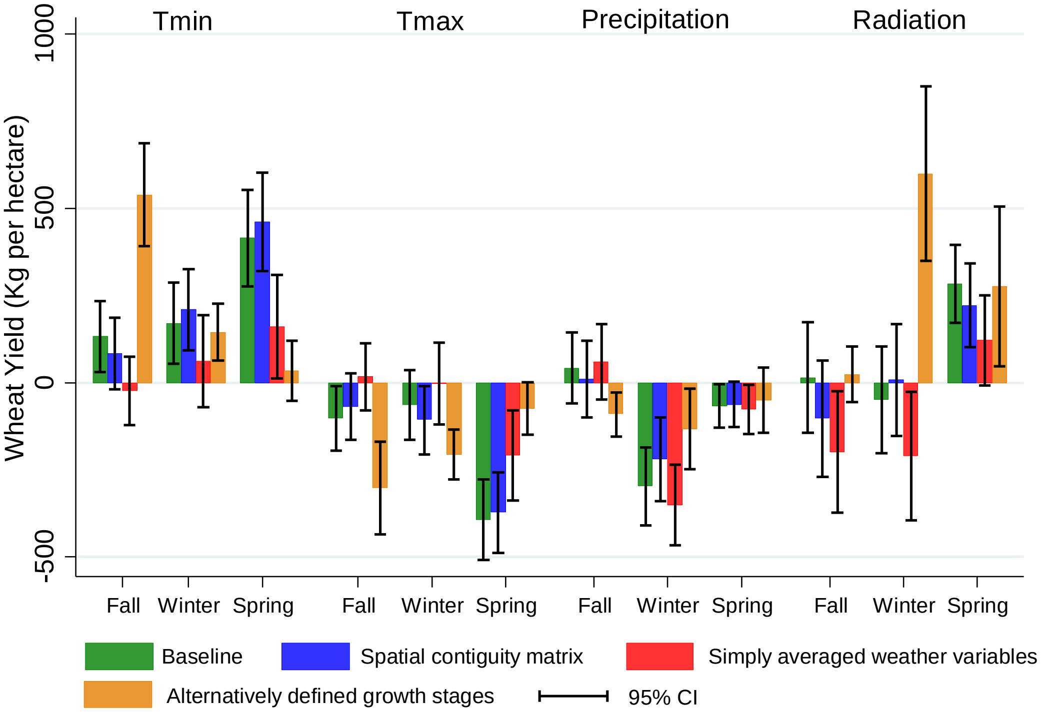
Table 1. Main Regression Results Showing the Effects of Weather and Input Use on Winter Wheat Yield (kg•ha^{-1}) under Three Model Specifications (Model 1, Model 2, Model 3)

Variables	Model 1	Model 2	Model 3
T_{min}: Fall	168.20***	145.50***	133.10**
	(44.21)	(55.03)	(51.90)
T_{min}: Winter	234.70***	164.90**	170.90***
	(52.12)	(64.57)	(59.68)
T_{min}: Spring	289.50***	519.50***	415.30***
	(65.09)	(75.92)	(70.80)
T_{max}: Fall	-101.60***	-95.45*	-102.30**
	(36.80)	(50.46)	(47.30)
T_{max}: Winter	-140.10***	-60.59	-63.42
	(37.23)	(55.21)	(51.04)
T_{max}: Spring	-191.90***	-459.90***	-392.60***
	(44.53)	(63.44)	(59.16)
Precipitation: Fall	0.15	0.08	0.42
	(0.56)	(0.56)	(0.52)
Precipitation: Winter	-3.18***	-3.14***	-2.98***
	(0.60)	(0.62)	(0.57)
Precipitation: Spring	-0.85**	-0.78**	-0.67**
	(0.35)	(0.34)	(0.32)
Radiation: Fall		-0.42	0.15
		(0.87)	(0.81)
Radiation: Winter		-1.02	-0.49
		(0.85)	(0.78)
Radiation: Spring		3.54***	2.84***
		(0.62)	(0.57)
Labor (day•ha^{-1})			21.54***
			(6.38)
Machinery (RMB•ha^{-1})			13.73***
			(1.22)
Pesticide (RMB•ha^{-1})			-5.59
			(8.75)
Parameter of spatial correlation	0.770***	0.786***	0.761***

Note: Coefficient estimates of weather variables were obtained using the inverse distance matrix as our spatial weights matrix. Parameter estimates are interpreted as the marginal effects of per-unit change in the temperature (°C), precipitation (mm), and radiation (hour) variables on yield. Standard errors, adjusted for heteroscedasticity, autocorrelation, and spatial correlation of the error terms, are shown in parentheses.

***$p<0.01$, **$p<0.05$, *$p<0.1$

Figure 1. Impacts of Weather Variations on Winter Wheat Yield across Three Growing Seasons (Fall, Winter, and Spring) under Different Scenarios
(including the baseline scenario and the three scenarios considered in the robustness check section)



Note: Each cluster shows the impacts of a given variable on yield, varied by winter wheat growing season. Parameter estimates are interpreted as the marginal effects of per-unit change in the temperature (°C), precipitation (10 cm), and radiation (100 hours) variables on yield (kg per hector). Bars show 95% confidence bands. In the scenario "Alternatively defined growth stages," Fall denotes the vegetative stage from germination/emergence to tillering, Winter denotes the reproductive stage from tillering to heading, and Spring denotes the maturation stage from heading to grain maturity.

Supporting Material

Table S1. Growing Cycles of Winter Wheat in all Winter Wheat-Producing Provinces in China

Growing cycle	Province
September—June	Beijing、Gansu、Hebei、Shaanxi、Ningxia、Tianjin
September—August	Xinjiang
October—May	Anhui、Chongqing、Guizhou、Hubei、Hunan、Jiangsu、Jiangxi、Shanghai、Sichuan、Yunnan、Zhejiang
October—June	Henan、Shandong、Shanxi
November—April	Fujian

Note: High daytime and nighttime temperatures exert large and opposing impacts on winter wheat yield in China.
Source: http://zzys.agri.gov.cn/nongshi.aspx.

Table S2. Summary Statistics Showing Means and Standard Deviations (SDs) of Winter Wheat Yield, Temperature, Precipitation, Solar Radiation and Inputs during the Three Growing Seasons (Fall, Winter and Spring) of Winter Wheat from 1979 to 2011

Variable	Mean	SD	Max	Min
Yield (kg•ha^{-1})	3,024.00	1,272.00	6,277.00	536.70
$T_{\min}$: Fall (°C)	9.02	3.67	18.07	0.41
$T_{\min}$: Winter (°C)	-1.17	5.91	11.85	-16.15
$T_{\min}$: Spring (°C)	10.96	2.23	16.20	4.24
$T_{\max}$: Fall (°C)	18.41	2.21	23.84	11.80
$T_{\max}$: Winter (°C)	7.73	4.49	19.44	-4.71
$T_{\max}$: Spring (°C)	21.22	2.03	25.79	15.92
Precipitation: Fall (mm)	99.24	58.69	366.00	0.97
Precipitation: Winter (mm)	70.98	75.86	471.40	0.01
Precipitation: Spring (mm)	233.60	135.50	903.50	42.21
Radiation: Fall (hours)	368.40	172.00	744.80	69.39
Radiation: Winter (hours)	404.20	142.20	681.70	77.89
Radiation: Spring (hours)	666.30	331.30	1,705.00	113.70
Labor (day•ha^{-1})	12.95	7.01	39.50	2.80
Machinery (RMB•ha^{-1})	23.05	28.65	126.50	0.02
Pesticide (RMB•ha^{-1})	4.56	4.56	23.72	0.01

Note: Means for $T_{\min}$ and $T_{\max}$, and sums for radiation and precipitation. Number of observations=726.

Table S3. Correlations of Weather Variables during the Three Growing Seasons (Fall, Winter and Spring) of Winter Wheat

Growing season	Variable	T_{min}	T_{max}	Radiation
Fall	T_{max}	0.35***	-	-
	Radiation	-0.30***	0.59***	-
	Precipitation	0.19***	-0.45***	-0.51***
Winter	T_{max}	0.58***	-	-
	Radiation	-0.07**	0.57***	-
	Precipitation	0.05	-0.17***	-0.37***
Spring	T_{max}	0.61***	-	-
	Radiation	0.06	0.65***	-
	Precipitation	-0.19***	-0.44***	-0.33***

***p<0.01, **p<0.05, *p<0.1

Figure S1. Spatial Distribution of Winter Wheat Production in China in 2011 (1000 hectares)