Impact of increased temperature on spring wheat yield in northern China

Jun Ye1,2 | Zhen Gao1 | Xiaohua Wu2 | Zhanyuan Lu1,2 | Cundong Li1 | Xiaobing Wang2 | Liyu Chen2 | Guohui Cui2 | Meiling Yu2 | Guijun Yan3 | Hui Liu3 | Haibin Zhang2 | Zhanxian Wang4 | Xuefen Shi4 | Yuanqing Li2

1College of Agronomy, Hebei Agricultural University, State Key Laboratory of North China Crop Improvement and Regulation/Key Laboratory of Crop Growth Regulation of Hebei Province, Baoding, China
2Inner Mongolia Academy of Agricultural & Animal Husbandry Sciences, Inner Mongolia Key Laboratory of Degradation Farmland Ecological Restoration and Pollution Control/Inner Mongolia Conservation Tillage Engineering Technology Research Center, Hohhot, China
3UWA School of Agriculture and Environment and The UWA Institute of Agriculture, The University of Western Australia, Perth, WA, Australia

Abstract

Global warming has been reported to cause reductions in crop yields. However, it was suggested that warming temperature might benefit crop productivity in some cool areas at high latitude. In this study, we conducted a 17-year field experiment (2002–2018) on spring wheat in Inner Mongolia. Temperature changes during each growth stage of spring wheat were investigated. Responses of spring wheat yield to temperature changes during the specific growing stages were evaluated. Average annual maximum temperature \((T_{\text{max}})\) and minimum temperature \((T_{\text{min}})\) significantly increased over the past 17 years. However, \(T_{\text{max}}\) did not show obvious increase trend during spring wheat growing seasons \((p = 0.0672)\). Furthermore, \(T_{\text{max}}\) also had no distinct change before or after anthesis. \(T_{\text{min}}\) significantly increased during the whole growing season, as well as in pre- and post-anthesis stages. Correlation analysis indicated that \(T_{\text{max}}\) in the entire growing season and post-anthesis did not affect spring wheat yield, but high \(T_{\text{max}}\) during pre-anthesis can improve grain yield. The \(T_{\text{min}}\) during the life cycle and pre-anthesis both had positive relationship with grain yield. Moreover, elevated temperature from seedling to stem elongation can benefit tiller formation and thus increasing spike number, which contributed to the significant yield increase \((p = 0.0093)\). Overall, climate warming affect spring wheat yield in cool area, and increasing temperature that was below the optimum temperature can benefit wheat productivity.
INTRODUCTION

With climate change, global air temperature is predicted to increase by ~1.0–1.7°C by 2050 (IPCC, 2013). Increased heat stress generally reduces crops yield as temperature is a critical factor affecting crops growth and development (Abdelrahman et al., 2020; Edreira et al., 2014; Telfer et al., 2018; Wang et al., 2018). Many studies indicated that climatic warming resulted in the decline of wheat productivity (Liu et al., 2014; Lobell et al., 2011; Zhang et al., 2013; Zheng et al., 2017). A study reported that each 1.0°C increase in mean temperature resulted in a 3%–10% reduction in wheat yield in China (You et al., 2009), whereas another study predicted that a 1.0°C increase in global average temperature might reduce wheat yield by 4%–6% (Asseng et al., 2015). However, global warming occurring in the northern high latitude (>45°N) was argued to be beneficial to crop production (Meng et al., 2014; Xiao et al., 2008). As the northern regions experience more obvious warming temperature trend in recent decades compared to global temperature change, many crops are reaching the optimal level for maximum photosynthesis rates, thus increasing temperature may enhance crop productivity in these regions (Meng et al., 2014). Moreover, rising temperature could expand crop cultivation into regions currently constrained by cold temperature (Olesen et al., 2007). Therefore, global warming might benefit crop production in Inner Mongolia (average altitude 1000 m) as a cool farming area located in northern China.

Inner Mongolia is one of the most important regions for spring wheat production. Its diurnal temperature variation makes it appropriate for spring wheat production (Cao et al., 2009) and grain yield from the area is about one-third of total spring wheat production in China (Zhao et al., 2017). Moreover, spring wheat is the main food source, and fluctuations in its yield directly threaten food security of the region's population (Dong et al., 2018).

Simulation models have been employed to demonstrate the negative effects of high temperature on spring wheat productivity in the cool regions (Xiao et al., 2017; Zhao et al., 2017). However, simulating sometimes is prone to errors and results always have a level of uncertainty (Vitantonio-Mazzini et al., 2020). Inversely, other studies have shown that increased temperature in these regions improved wheat yield (He et al., 2020; Xiao et al., 2008). Although investigations on the impacts of warming temperature on wheat yield were conducted (Xiao et al., 2008, 2016), wheat yields were usually evaluated against average meteorological changes over the entire growing season rather than specific growth stages that were most sensitive to environmental limitations (Xiao et al., 2008, 2016). Therefore, it is important to investigate the effects of temperature change, especially in critical growing stages, on spring wheat productivity through a long-term field experiment in the target region.

To better understand the effects of temperature change on spring wheat in the cool region, this study analyzed results of a 17-year field experiment without water deficit in Ordos, Inner Mongolia. This 17-year study aimed to (i) investigate significant trends in temperature variability during specific growing phases of spring wheat, (ii) evaluate the relationship between grain yield of spring wheat and yield components, and (iii) identify the responses of grain yield to temperature change at varied growing stages of spring wheat.

MATERIALS AND METHODS

2.1 Experimental site conditions

This 17-year field experiment was conducted from 2002 to 2018 at the Ordos Academy of Agriculture and Animal Husbandry Sciences (110.0°E, 40.5°N, altitude 1010 m). The soil in the experimental field is classified as light loam texture. The upper 20 cm soil profile contained 22.7 g kg⁻¹ organic matter, 1.02 g kg⁻¹ total N, 117.5 mg kg⁻¹ available K, and 16.2 mg kg⁻¹ available P. Averaged air maximum temperature (\(T_{\text{max}}\)) and minimum temperature (\(T_{\text{min}}\)) were 14.8°C and 1.1°C in the past 45 years, respectively (recording at 1.5 m height). The average annual solar radiation and rainfall were 5791 MJ m⁻² and 310 mm during the past 45 years, respectively.

2.2 Experimental design

Yongliang 4, a widely sown spring wheat cultivar in China, was planted at a seeding rate of 375 kg ha⁻¹ around March 29 each year for 17 growing seasons (Table 1). During the whole growth period, irrigation with surface flooding was timely supplemented to avoid drought stress. This experiment plot area was 25 m² (5 m × 5 m) with three
replications. Before seed sowing each year, basal fertilizer was broadcasted at a per hectare rate of 180 kg nitrogen fertilizer (urea), 175 kg phosphate fertilizer (diammonium phosphate) and 125 kg potash fertilizer (potassium sulfate). There is no other fertilizer application during the wheat growing season.

2.3 | Data collection

Wheat phenology was recorded using the Zadoks scale (Zadoks et al., 1974). When 50% of plants reached seedling (Z09), tillering (Z20), jointing (stem elongation; Z30), anthesis (Z60), and maturity stage (Z91), corresponding dates were recorded to calculate the temperature change in each specific growth stage.

Before harvest, spike number was counted from 3 one-meter wheat rows, and grain number per spike was evaluated by counting from 50 plants in each plot. In mid-July, spring wheat was harvested from a 2 m² area to determine grain yield. Final yield was calculated under 13% moisture content. Thousand kernel weight (TKW, dry weight) was measured from the harvested wheat plants.

Meteorological data (air temperature, rainfall, sunshine hours) in 2002–2018 were downloaded from the China Meteorological Data Sharing Service System (http://www.cdc.nmic.cn). The daily solar radiation (SR, MJ m⁻²) was calculated from sunshine hours following the methods in Gao et al., (2018). The climatic data during the 17-year spring wheat growing periods were calculated based on the sowing and harvest dates of field experiment from 2002 to 2018.

2.4 | Statistical analyses

Regression analysis of grain yield with climate factors, and yield components were conducted using SPSS 17.0 (SPSS Inc). All of the figures in the manuscript were constructed using SigmaPlot 12.5 (Systat Software Inc).

3 | RESULTS

3.1 | Trend of temperature change during the spring wheat growing seasons

From 2002 to 2018, trends of annual maximum temperature ($T_{\text{max}}$), minimum temperature ($T_{\min}$), and mean temperature ($T_{\text{mean}}$) levels were significantly rising (Figure S1). Temperature data were monitored and recorded from the sowing date to the harvest date of spring wheat for 17 years of production seasons (Table 1). Trends for both $T_{\min}$ and $T_{\text{mean}}$ were found increasing in this experiment, while $T_{\max}$ did not apparently increase ($p = 0.0672$; Figure 1a). Analyses of temperature changes at varied growing stages of spring wheat revealed no obvious increase in $T_{\max}$ either before or after anthesis (Figure 1b,c). Inversely, $T_{\min}$ significantly increased at both pre-anthesis and post-anthesis. $T_{\text{mean}}$ significantly rose during pre-anthesis, but no distinct change.

| Year | Z00 | Z09 | Z20 | Z30 | Z60 | Z91 |
|------|-----|-----|-----|-----|-----|-----|
| 2002 | Mar. 29th | Apr. 10th | Apr. 26th | May 15th | Jun. 6th | Jul. 14th |
| 2003 | Mar. 29th | Apr. 9th | Apr. 24th | May 12th | Jun. 7th | Jul. 17th |
| 2004 | Mar. 30th | Apr. 12th | Apr. 25th | May 10th | Jun. 3rd | Jul. 15 hours |
| 2005 | Mar. 28th | Apr. 13th | Apr. 26th | May 10th | Jun. 2nd | Jul. 17th |
| 2006 | Mar. 29th | Apr. 10th | Apr. 24th | May 11th | Jun. 3rd | Jul. 13th |
| 2007 | Mar. 29th | Apr. 14th | Apr. 25th | May 9th | Jun. 2nd | Jul. 11th |
| 2008 | Mar. 30th | Apr. 12th | Apr. 27th | May 12th | Jun. 7th | Jul. 15th |
| 2009 | Mar. 29th | Apr. 12th | Apr. 22th | May 5th | May 29th | Jul. 12th |
| 2010 | Mar. 28th | Apr. 12th | Apr. 26th | May 16th | Jun. 6th | Jul. 10th |
| 2011 | Mar. 29th | Apr. 13th | Apr. 25th | May 15th | Jun. 7th | Jul. 13th |
| 2012 | Mar. 30th | Apr. 12th | Apr. 25th | May 16th | Jun. 7th | Jul. 13th |
| 2013 | Mar. 30th | Apr. 14th | Apr. 24th | May 15th | Jun. 5th | Jul. 16th |
| 2014 | Mar. 29th | Apr. 8th | Apr. 26th | May 14th | Jun. 1st | Jul. 12th |
| 2015 | Mar. 27th | Apr. 14th | Apr. 27th | May 17th | Jun. 9th | Jul. 10th |
| 2016 | Mar. 29th | Apr. 13th | Apr. 26th | May 13th | Jun. 4th | Jul. 16th |
| 2017 | Mar. 28th | Apr. 10th | Apr. 24th | May 14th | Jun. 5th | Jul. 10th |
| 2018 | Mar. 29th | Apr. 8th | Apr. 20th | May 7th | May 31st | Jul. 11th |

Z00, dry seed (sowing); Z09, seedling; Z20, tillering; Z30, stem elongation; Z60, anthesis; Z91, maturity.
at post-anthesis ($p = 0.2408$; Figure 1). Consequently, we mainly analyzed the temperature changes before anthesis. Results showed no obvious changes from seed sowing (Z00) to Z30. From Z30 to Z60, $T_{\text{min}}$ and $T_{\text{mean}}$ exhibited significant increasing trend (Table 2).

### 3.2 Variability of spring wheat grain yield from 2002 to 2018

During the present field experiment, grain yield of spring wheat ranged from 4.4 t ha$^{-1}$ to 7.6 t ha$^{-1}$. The mean grain yield was 5.8 t ha$^{-1}$ in this experiment (Figure 2). The mean spike number per unit area was 594 per m$^2$ with a coefficient of variation (CV) of 14.0%. The grains per spike and thousand kernel weight (TKW) were 27.9 and 44.6 g with
a CV of 20.0% and 6.3%, respectively. Additionally, grain yield and grain number per spike significantly increased in this experiment, but spike number and grain weight did not show obvious change trends. Results of correlation analysis suggested spike number per square meter determined grain yield ($p = 0.0093$), where more spikes resulted in the higher yield levels. However, both TKW and grain number per spike had no significant correlations with grain yield (Figure 3).

**3.3 Effects of temperature changes during critical stage on grain yield of spring wheat**

Figure 4 shows the relationship between grain yield and temperature data of the whole growing period. A significant relationship between $T_{\text{max}}$ and grain yield was not discovered. Interestingly, $T_{\text{min}}$ and $T_{\text{mean}}$ showed obvious increasing trends as grain yield increased, with a rate of 829.8 and 712.1 kg ha$^{-1}$C$^{-1}$, respectively. The relationships
between grain yield and pre-anthesis/post-anthesis temperature were further conducted. The results indicated that post-anthesis high temperature did not reduce spring wheat yield, but pre-anthesis temperature had positive correlation with grain yield, that is, spring wheat yield increased 427.1–545.2 kg ha\(^{-1}\) with each 1°C warming (Figure 5).

Table 3 summarizes the effects of temperature change during each growth stage before anthesis on grain yield. From Z00 to Z09, temperature fluctuation did not affect grain yield of spring wheat. However, higher temperature and high diurnal temperature range benefited grain yield from seedling to tillering. During tillering to jointing, high \(T_{\text{min}}\) and \(T_{\text{mean}}\) also presented positive relationship with spring wheat yield. The temperature changes over tillering to anthesis had no obvious effect on grain yield. Additionally, effective tiller number showed positive correlation with grain yield (Figure S2). High temperatures from Z20 to Z30 had beneficial effects on tiller number (Figure 6).

**4 | DISCUSSION**

**4.1 | Temperature changes during different growing phases are diverse**

At this experiment site, average annual temperature (\(T_{\text{max}}, T_{\text{min}}, T_{\text{mean}}\)) significantly increased over past years, which were consistent with previous research results (Gao et al., 2020; Meng et al., 2014; Zhao et al., 2017; Zhang et al., 2015). However, the annual \(T_{\text{mean}}\) in this study was obviously lower than that of low latitudes (<10°C vs <15°C, Zhang et al., 2015). Global warming has a close connection with crop phenology (Chmielewski et al., 2004). Increases in temperature generally shorten growth periods of spring wheat in northern China (Xiao et al., 2016). However, mean growing season temperature usually showed a relatively weak correspondence with that of critical stage, emphasizing the importance of separate analyses for temperature changes (Gourdji et al., 2013). Xiao et al., (2016) showed that different growth stages (vegetative, reproductive, and whole growth period) presented similar temperature rise, but field-observed data for the three growth stages had great ranges of variation due to phenological changes from 1981 to 2009 in northern China. But our results indicated that temperature change trends in different growing phases were not coincident. Moreover, the previous research usually did not evaluate the temperature change in specific growing stages, especially for the critical stages that determined final yield (Grassini et al., 2009). Therefore, climate change (including temperature) analysis should pay attention to changes in different growing stages. The detailed analyses of each growing phase could accurately assess the impact of climate change and in turn lead to adjusted sowing date to avoid abiotic stresses (Gao et al., 2018; Gourdji et al., 2013).
FIGURE 5 Regression analyses between grain yield and temperatures pre-anthesis (a) and post-anthesis (b)
4.2 Temperature changes in different growth stages have diverse effects on spring wheat

Climate change, especially the global warming, can affect all stages of crop growth from seedling emergence to maturity, suppressing the yield of major cereal crops (Hussain et al., 2019). In recent study about spring wheat in western and middle Inner Mongolia (including this study’s experiment site), spring wheat yield will likely reduce with the increase in temperature (Zhao et al., 2017). Additionally, He et al., (2020) also indicated that temperature rise shortened the whole growth duration and key growth phases, thus reducing grain yield of spring wheat in China. However, our long-term field experiment results were inconsistent with these studies. No significant relationship between spring wheat yield and \( T_{\text{max}} \) during the whole growing season was detected; inversely, ininverse relationship was detected during the whole growing season was detected; inversely, ininverse relationship was detected during the whole growing season was detected; inversely, in inverse relationship was detected during grain filling stage, high temperature stress over 31°C. It exceeded optimal temperatures for wheat growth (Porter & Gawith, 1999). During grain filling stage, high temperature resulted in wheat yield decline (Fan et al., 2018), which is against our results.

The main reason might be that the combined drought and heat usually resulted in greater yield losses than either stress alone (Cairns et al., 2013). Drought stress was avoided by supplemental irrigation in this experiment. Moreover, irrigation not only fulfilled crops water demand but also mitigated crop heat stress (Li et al., 2020; Tack et al., 2017). We therefore suggest that the major limiting factor of yield in spring wheat in Inner Mongolia area may be drought stress instead of heat. In addition, the temperature during past 17 seasons showed that minimum temperature had higher increase rate with a slope of 0.1147, the increase slope of maximum temperature was only 0.0711, that is, \( T_{\text{min}} \) had a faster increase rate than \( T_{\text{max}} \). Previous research also presented same change trends (Peng et al., 2004). Furthermore, numerous researches suggested that \( T_{\text{min}} \) reduced crop yield (García et al., 2015; Mohammed & Tarpley, 2009a; Mohammed & Tarpley, 2009b; Peng et al., 2004). Our results showed that rising \( T_{\text{min}} \) increased spring wheat yield (Figure 4), and both pre-anthesis \( T_{\text{max}} \) and \( T_{\text{min}} \) showed positive correlation with grain yield. This suggested increase of temperature (below the optimum temperature) in cool condition benefited spring wheat production.

In Inner Mongolia, the long seedling period and short panicle differentiation stage restricted the productivity of spring wheat (Dong et al., 2019). High temperature usually accelerated wheat development resulted in a shorter key stage duration (He et al., 2020), thus decreasing photosynthetically active radiation capture with negative results for biomass accumulation and final yield (García et al., 2015). However, this experiment indicated that increased temperature during seedling to jointing had beneficial effects on effective tiller number and final yield owing to improvement of temperature below optimized level. Additionally, our results showed that spike number variation contributed largely to yield fluctuation \((p = 0.0093)\). We concluded that increasing temperature (below the optimum temperature) had positive effects on tillering differentiation in spring wheat, which contributed to grain yield increase of spring wheat.

## 5 CONCLUSIONS

In this long-term field experiment, annual average \( T_{\text{max}} \) and \( T_{\text{min}} \) significantly increased, but during spring wheat growing
season $T_{\text{max}}$ did not show obvious increasing trend. Before anthesis, $T_{\text{max}}$ and $T_{\text{min}}$ significantly increased but $T_{\text{max}}$ did not increase after anthesis. The $T_{\text{max}}$ during the whole growing season did not affect spring wheat yield, but increased $T_{\text{min}}$ benefited wheat yield. High temperature before anthesis showed positive relationship with spring wheat yield. Moreover, the increasing temperature during seedling to stem elongation, contributed much to final yield owing to improved spike formation.

**ACKNOWLEDGEMENTS**

We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript. This work was supported by The Leading Talent Project of "Grassland Talents" in Inner Mongolia Autonomous Region; the Project of Natural Science Foundation of Inner Mongolia Autonomous Region (2017MS0312); National Natural Science Foundation of China (31860356); Inner Mongolia Science and Technology Achievement Transformation Project (2060404); Inner Mongolia Applied Technology Research and Development Fund Project (2019GG340); The Major Project of Science and Technology in Inner Mongolia (2019ZD009); High-level Talent Funding Project for Postdoctoral Research in Hebei Province (B2018003017); Wheat Regional Trial Project of Inner Mongolia Autonomous Region; the Global Innovation
REFERENCES
Abdelrahman, M., Burritt, D. J., Gupta, A., Tsujimoto, H., & Tran, L. S. P. (2020). Heat stress effects on source–sink relationships and metabolome dynamics in wheat. *Journal of Experimental Botany, 71*, 543–554. https://doi.org/10.1093/jxb/erz296.

Asseng, S., Ewert, F., Marte, P., Rötter, R. P., Lobell, D. B., Cammarano, D., & Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change, 5*, 143–147. https://doi.org/10.1038/NCLIMATE2470.

Cairns, J. E., Crossa, J., Zaidi, P. H., Grudloyma, P., Sanchez, C., Araus, J. L., Thaïtad, S., Makumbi, D., Magorokosho, C., Bänziger, M., Menkir, A., Hearne, S., & Atlin, G. N. (2013). Identification of drought, heat, and combined drought and heat tolerant donors in maize. *Crop Science, 53*, 1335–1346. https://doi.org/10.2135/cropsci2012.09.0545.

IPCC (Intergovernmental Panel on Climate Change) (2013). Climate change 2013. The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Cao, Y. F., Gu, Y., Xu, J., & Zhang, L. (2009). The influence of climate change on growing period of spring wheat in recent 47 years in Inner Mongolia. *Meteorology Journal of Inner Mongolia, 4*, 22–25. https://doi.org/10.3969/j.issn.1005-8656.2009.04.008.

Chmielewski, F. M., Müller, A., & Bruns, E. (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology, 121*, 69–78. https://doi.org/10.1016/j.agrformet.2006.0168-1923(03)00161-8.

Dong, Y., Wei, B., Wang, L., Zhang, Y., Zhang, H., & Zhang, Y. (2019). Performance of winter-seeded spring wheat in Inner Mongolia. *Agronomy, 9*, 507. https://doi.org/10.3390/agronomy9090507.

Dong, Z., Pan, Z., He, Q., Wang, J., Huang, L., Pan, Y., Han, G., Xue, X., & Chen, Y. (2018). Vulnerability assessment of spring wheat production to climate change in the Inner Mongolia region of China. *Ecological Indicators, 85*, 67–78. https://doi.org/10.1016/j.ecolind.2017.10.008.

Edreira, J. I. R., Mayer, L. I., & Otegui, M. E. (2014). Heat stress in temperate and tropical maize hybrids: Kernel growth, water relations and assimilate availability for grain filling. *Field Crops Research, 166*, 162–172. https://doi.org/10.1016/j.fcr.2014.06.018.

Fan, Y., Ma, C., Huang, Z., Abid, M., Jiang, S., Dai, T., Zhang, W., Ma, S., Jiang, D., & Han, X. (2018). Heat priming during early reproductive stages enhances thermo-tolerance to post-anthesis heat stress via improving photosynthesis and plant productivity in winter wheat (*Triticum aestivum* L.). *Frontiers in Plant Science, 9*, 805. https://doi.org/10.3389/fpls.2018.00805.

Fang, S., Cammarano, D., Zhou, G., Tan, K., & Ren, S. (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/10.1016/j.eja.2014.12.012.
terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change*, 81, 123–143. https://doi.org/10.1007/s10584-006-9216-1.

Peng, S., Huang, J., Sheely, J. E., Laza, R. C., Vesperas, R. M., Zhong, X., Centeno, G. S., Khush, G. S., & Cassman, K. G. (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, 9971–9975. https://doi.org/10.1073/pnas.0403720101.

Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, 10, 23–36. https://doi.org/10.1016/s1161-0301(98)00047-1.

Tack, J., Barkley, A., & Hendricks, N. (2017). Irrigation offsets wheat yield reductions from warming temperatures. *Environmental Research Letters*, 12, 114027. https://doi.org/10.1088/1748-9326/aa8d27.

Telfer, P., Edwards, J., Bennett, D., Ganesalingam, D., Ablec, J., & Kuchel, H. (2018). A field and controlled environment evaluation of wheat (*Triticum aestivum*) adaptation to heat stress. *Field Crops Research*, 229, 55–65. https://doi.org/10.1016/j.fcr.2018.09.013.

Vitantonio-Mazzini, L. N., Borrás, L., Garibaldi, L. A., Pérez, D. H., Gallo, S., & Gambin, B. L. (2020). Management options for reducing maize yield gaps in contrasting sowing dates. *Field Crops Research*, 251, 107779. https://doi.org/10.1016/j.fcr.2020.107779.

Wang, X., Hou, L., Lu, Y., Wu, B., Gong, X., Liu, M., & Xu, S. (2018). Metabolic adaptation of wheat grain contributes to a stable filling rate under heat stress. *Journal of Experimental Botany*, 69, 5531–5545. https://doi.org/10.1093/jxb/ery303.

Xiao, D., Cao, J., Bai, H., Qi, Y., & Shen, Y. (2017). Assessing the impacts of climate variables and sowing date on spring wheat yield in the Northern China. *International Journal of Agriculture and Biology*, 19, 1551–1558. https://doi.org/10.17957/ijab.15.0459.

Xiao, D., Tao, F., Shen, Y., & Qi, Y. (2016). Combined impact of climate change, cultivar shift, and sowing date on spring wheat phenology in Northern China. *Journal of Meteorological Research*, 30, 820–831. https://doi.org/10.1007/s13351-016-5108-0.

Xiao, G., Zhang, Q., Yao, Y., Zhao, H., Wang, R., Bai, H., & Zhang, F. (2008). Impact of recent climatic change on the yield of winter wheat at low and high altitudes in semi-arid Northwestern China. *Agriculture Ecosystems & Environment*, 127, 37–42. https://doi.org/10.1016/j.agee.2008.02.007.

You, L., Rosegrant, M. W., Wood, S., & Sun, D. (2009). Impact of growing season temperature on wheat productivity in China.

*How to cite this article*: Ye J, Gao Z, Wu X, et al. Impact of increased temperature on spring wheat yield in northern China. *Food Energy Secur*. 2021;10:e283. https://doi.org/10.1002/fes3.283.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.