Fertilization regulates the response of wheat yield to interannual temperature variation in North China

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Abstract

Aims
Understanding the effect of long-term fertilization on the sensitivity of grain yield to temperature changes is critical for accurately assessing the impact of global warming on crop production. In this study, we aim to assess the impacts of temperature changes on grain yields of winter wheat (*Triticum aestivum* L.) under different fertilization treatments in a long-term manipulative experiment in North China.

Methods
We measured grain yields of winter wheat under four fertilization treatments at the Yucheng Comprehensive Experimental Station each year from 1993 to 2012. We also measured air temperature at 0200, 0800, 1400 and 2000h each day since 1 January 1980. We then used the first-difference method and simple linear regression models to examine the relationship of crop yield changes to mean air temperature, mean daytime and nighttime air temperature in crop growing seasons.

Important Findings
We found that increases in mean daily temperature, mean daytime temperature and mean nighttime temperature each had a positive impact on the grain yield of winter wheat. Grain yield increased by 16.7–85.6% for winter wheat in response to a 1°C increase in growing season mean daily temperature. Winter wheat yield was more sensitive to variations of nighttime temperature than to that of daytime temperature. The observed temperature impacts also varied across different fertilization treatments. Balanced fertilization significantly enhanced grain yields for winter wheat under a warming climate. Wheat plots treated with nitrogen and phosphorous balanced fertilization (NPK- and NP-treated plots) were more responsive to temperature changes than those without. This report provides direct evidence of how temperature change impacts grain yields under different fertilization treatments, which is useful for crop management in a changing global climate.

Keywords: grain yield, fertilization, daytime temperature, nighttime temperature, winter wheat

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INTRODUCTION

Agricultural production is strongly and extensively influenced by climate change (You et al. 2009). The most recent Intergovernmental Panel on Climate Change (IPCC) report predicted that global temperature would increase by 1.0–3.7°C by the end of the 21st century, with substantial changes in the precipitation pattern (IPCC 2013). Such a significant warming trend is likely to have a major yet uncertain impact on agricultural productivity (Piao et al. 2010), which is essential for feeding the rapidly expanding human population (Godfray et al. 2010). Process-based model simulations and statistical analyses of empirical data at multiple scales have revealed a mixed effect of global warming on agricultural production (Chen et al. 2013; Christopher and Shawn 2008; Lobell and Asner 2003; Lobell and Field 2007; Lobell

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MATERIALS AND METHODS

Study site

This study was conducted at the YCES in Shandong Province, China, located at 36°57′ N, 116° 36′ E at 20-m elevation. The site is located on an alluvial plain in the lower reaches of the Yellow River. It lies in the warmer temperate zone dominated by a semi-humid and monsoon climate, which is characterized by a dry winter and spring but a humid summer. Mean annual temperature is 13.2°C, and mean annual precipitation is 610 mm, 80% of which falls between June and September. The soil at the research station is mostly sandy loam (22% sand, 66% silt and 22% clay), classified as Cambisols by the Food and Agriculture Organization of the United Nations standards, with a pH value of 6.46 and 1.19% organic matter. The initial physical and chemical properties of the soil are presented in Table 1, showing that the soil was deficient in nitrogen (N) and phosphorous (P) but rich in potassium (K). A winter wheat–maize double cropping system (wheat–maize rotation) is the predominant farming practice in the area, where winter wheat (*Triticum aestivum* L.) is usually grown from November to June and maize (*Zea mays* L.) from July to October.

Experiment design

This study was part of the long-term fertilizer addition trials at YCES from 1989 to 2012. The experimental area was 50×40 m, with twenty 5×6-m plots arranged into four rows and five columns. Plots were separated by a cement wall ~10 cm thick, extending 60 cm deep into the soil and 15 cm above ground. A 100-cm buffer was maintained between neighboring plots to prevent the movement of water and fertilizer. The experiment included five types of fertilization treatments with different combinations of N, P and K: addition of all the three nutrients (NPK), addition of N and P (NP), addition of N and K (NK), addition of P and K (PK) and no fertilization (CK). Each treatment had four replicates, and the assignment of treatment to each of the 20 plots was fully randomized. The amount of each fertilizer type added was consistent across treatments; NPK and NP treatments, for instance, were given the same amounts of N and P fertilizers. The N, P and K were supplied through urea (46% N), superphosphate (18% P) and potassium sulfate (50% K), respectively, and each application consisted of 252 kg ha⁻¹ N, 202 kg ha⁻¹ P₂O₅ and 208 kg ha⁻¹ K₂O, depending on the treatment. The fertilizer amount and application schemes were based on common practices employed by local farmers. For example, it was estimated that

| Depth (cm) | Bulk density (g cm⁻³) | Organic matter (g kg⁻¹) | Total N (g kg⁻¹) | Available N (mg kg⁻¹) | Available P (mg kg⁻¹) | Available K (mg kg⁻¹) |
|------------|-----------------------|-------------------------|-----------------|----------------------|----------------------|----------------------|
| 0–20       | 1.31                  | 9.86                    | 0.412           | 46.11                | 8.06                 | 148.95               |
| 20–40      | 1.48                  | 8.24                    | 0.356           | 44.98                | 5.18                 | 125.40               |
| 40–60      | 1.49                  | 7.00                    | 0.344           | 30.46                | 4.62                 | 95.00                |

Table 1: physical and chemical properties of the soil before the fertilization experiment (1990)
~257 kg ha\(^{-1}\) N was applied on average in farmlands across China (Chen et al. 2011). The fertilizers were applied by hand before irrigation or rainfall. About 30.3% of the total N and total P was consolidated into the surface soil (0–15 cm) by ploughing before sowing; 12.1% of the total N and total K was applied at the re-greening stage; and 42.4% and 15.2% of the total N was applied at the jointing stage and the booting stage, respectively.

During the study period, cultivars of wheat were changed frequently (see online supplementary table S1). The selected crop varieties and planting densities were similar to those used by local farmers. Aside from rotating cultivars, other traditional management practices remained unchanged during the study period. Winter wheat was planted in 20 cm rows at a density of 263 kg ha\(^{-1}\) during the first half of October. During the growing season, the fields were irrigated three times, depending on precipitation, and weeds were removed by hand. Fungicides and pesticides were applied when needed.

From 1987 to 1992, crops were planted every year without fertilizer application in any plot to increase soil homogeneity between plots. Observed data for grain yields of winter wheat began in 1993 (see the appended database for yearly yields and temperature data). The plots were hand harvested at grain maturity every year and grain yield was determined by weighing air-dried grains per plot. Water content of the grains was ~13%. In this study, the growing period of winter wheat was divided into pre re-greening and post re-greening stages. The pre re-greening stage is from sowing to re-greening, which includes the sowing and the emergence stages of winter wheat, lasting from November to February of the next year. The post re-greening stage is from re-greening to maturity, which includes the re-greening, jointing, anthesis, grain filling and physical maturity stages of winter wheat, lasting from March to the first half of June.

**Weather data**

An automatic weather station AMRS-I (Changchun Meteorological Equipment Company, China) was set <10 m from the experiment field at 1 January 1980, to measure daily minimum and maximum air temperatures, dry- and wet-bulb temperature, rainfall, daily solar radiation, relative humidity and wind speed. All instruments used in the experiment were calibrated regularly. Standard measurements of air temperature were recorded four times each day at 0200, 0800, 1400 and 2000 h.

**Data analysis**

For each treatment, yields over the study period were calculated as means ± standard error of the four plots and further analyzed with one-way analysis of variance, followed by comparisons according to the least significant difference procedure at the 0.05 or 0.01 probability level only when F was significant. We then used simple linear regressions to examine the relationship between crop yield changes and mean air temperature (Tm), mean daytime air temperature (Td) and mean nighttime air temperature (Tn) in selected crop growing seasons (see online supplementary table S2). We also performed stepwise regressions in which crop yield changes were regressed against Td, Tn and growing season precipitation. However, the precipitation variable was always excluded from the models regardless of different fertilization treatments. Therefore, here we only reported results of the simple linear regressions. To eliminate genetic influences of crop varieties, we adopted an approach (Lobell and Field 2007; Lobell et al. 2011; Nicholls 1997) based on the first-difference time series for yield (ΔYield) and climate (i.e. year-to-year changes; ΔTm, ΔTd and ΔTn) in exploring the impacts of temperature variables on wheat yield. As noted above, the selected growing seasons included November to February (pre re-greening stages) and March to the first half of June (post re-greening stages). All statistical analyses were conducted in SPSS 11.0 for Windows (SPSS Inc., Chicago, IL, USA).

**RESULTS**

**Temperature trends in YCES over the observed period**

Annual mean temperature and daytime and nighttime temperatures from 1993 to 2012 are shown in Fig. 1. Although there was some interannual variation for all the three temperature variables at the experiment site, none of them showed a significant trend during the experiment period of 1993–2012 (Fig. 1).

**Fertilization and grain yield**

Figure 2 shows the average grain yield under different fertilization treatments. The result confirms the critical role of both N and P for enhancing grain production of winter wheat. A balanced fertilization of both N and P is required to significantly enhance grain production. For instance, the mean grain yields of winter wheat in the NPK- and NP-treated plots were 6032 and 5887 kg ha\(^{-1}\), respectively, more than five times that of unfertilized plots (Fig. 2). In contrast, fertilizer combinations that lacked either N or P showed no effect; grain yields in NK- or PK-treated plots were not statistically different from those of unfertilized plots (Fig. 2). Furthermore, adding K did not significantly promote wheat grain production, probably because K is already rich in the soil of the NCP (He et al. 2012).

**Relationship between grain yield and temperature**

In general, rising temperature increased the grain yield for winter wheat (Fig. 3). However, temperature variations in the pre re-greening season and the post re-greening season may have different impacts on grain yield, and a simple correlation analysis reveals that pre re-greening season temperature had almost no impact on the grain yield of winter wheat in all plots. For example, in the NPK-treated plots, the values of correlation coefficient R\(^2\) between wheat yield and pre re-greening season temperature were 0.01 (P = 0.66), 0.08...
Thus, in the below text, we only discuss results on the impacts of post re-greening season temperature.

Winter wheat grain yields responded significantly to post re-greening season temperature change in NPK- and NP-treated plots, as well as in unfertilized plots, but not in the NK- or PK-treated plots (Fig. 3). Among the temperature-sensitive plots, grain yield in the NP-treated plots was significantly correlated with all three temperature variables, and it also had the highest temperature sensitivity (Fig. 3). In response to a 1°C increase in Tm, grain yields of NPK-, NP- and CK-treated plots increased by ~16.7% ($R^2 = 0.25$, $P = 0.028$), 21.3% ($R^2 = 0.34$, $P = 0.009$) and 85.6% ($R^2 = 0.22$, $P = 0.044$) of their mean annual grain yields, respectively. Yet with a 1°C increase in Tn, grain yields increased by ~54.1% ($R^2 = 0.23$, $P = 0.035$), 56.5% ($R^2 = 0.21$, $P = 0.052$) and 94.6% ($R^2 = 0.25$, $P = 0.030$) of their mean annual grain yields, respectively (Fig. 3). In addition, grain yields were more strongly correlated with Td than with Tn for the NPK- and NP-treated plots. Contrasting results were observed in the NK-, PK- and CK-treated plots, where wheat grain yields were more strongly correlated with Tn than with Td (Fig. 3).

**DISCUSSION**

**The relationship between crop yield change and temperature variation**

Our analyses suggested that the yield of one of the major crops on the NCP, winter wheat, is sensitive to temperature variations. The positive response of winter wheat yields to warming revealed in this study are consistent with the findings of Tao et al. (2012), but inconsistent with those of Lobell and Field (2007) and You et al. (2009). Furthermore, yield variations estimated from our manipulative experiments tended to be larger than those estimated from model simulations (Lobell and Asner 2003; Lobell et al. 2011; You et al. 2009).

For example, our empirical study suggested that grain yield was enhanced by 16.7–85.6% in response to 1°C increase in mean daily temperature. However, model simulations predict a 3–10% yield decrease in response to 1°C increase in mean daily temperature. An asymmetric warming trend is expected to affect carbon assimilation and consumption in plants (Peng et al. 2013), and could have a differential effect on crop yields. For example, in Australia, wheat yield increased by 30–50% during 1952–92,
mostly due to the rising nighttime temperature (Nicholls 1997). In the Philippines, a decreased rice yield was found to be associated with nighttime warming (Peng et al. 2004). Our results were generally consistent with previous findings that nighttime warming has a higher impact on grain yield than daytime warming. The physiological mechanisms that caused the observed increase in wheat yield, and the differential effect of increases in nighttime versus daytime temperature, however, are unknown. For winter wheat, the re-greening stage was 5–10 days shorter, whereas reproductive periods remained the same following a warming treatment in a field experiment at the YCES (Hou et al. 2012). Wan et al. (2009) found the increase in photosynthesis in warmed plots tended to be greater than that of respiration, thereby increasing carbon accumulation in steppe ecosystems due to photosynthetic overcompensation. The increase in wheat yield in this study might have been caused by a greater increase in photosynthesis rate than that in the respiration rate during the wheat green season under increasing temperature, but further studies are needed to illuminate these processes.

Figure 3: the relationship between winter wheat yield change (ΔY) and changes in post re-greening season mean daily temperature (ΔTm, A–E), mean daytime temperature (ΔTd, F–J) or mean nighttime temperature (ΔTn, K–O) at the YCES. Fertilization treatments from the top to the bottom rows are: NPK (panels A, F and K), NP (panels B, G and L), NK (panels C, H and M), PK (panels D, I and N) and CK (panels E, J and O). Each treatment included four replicate plots, and the wheat yield for each treatment was the mean yield value of the four plots.
Effects of fertilization on the relationship between crop yield and temperature

Our results showed that both N and P are critical for the growth of winter wheat, and a balanced fertilization of both N and P nutrients is required to promote grain yields. This is in line with Liebig’s law, whereby the scarcest resource is the most important limiting factor for plant growth (Sinclair 1992). Furthermore, plots treated with N and P balanced fertilization (NPK- and NP-treated plots) were sensitive to temperature change, whereas plots without fertilization (the CK plots) were less sensitive to climate change (Fig. 3). However, this result could also be partly attributed to the increased efficacy of fertilizer under warmer conditions (Hejcman and Kunzová 2010). For example, it has been reported that continuous urea application enhances the rate of urea hydrolysis in soil, which can be further accelerated by rising temperature (Xu et al. 1993). Overall, our results suggest that in this area, N and P are both primary factors limiting the grain yield of winter wheat. Temperature is also a co-limiting factor in an N and P balanced system, but it has limited impact when the system is severely limited by N or P.

Many crop-simulation models have been used to evaluate the effects of projected climate change on crop yields (Chen et al. 2013; Christopher and Shawn 2008; Nicholls 1997; Lobell and Asner 2003; Lobell and Field 2007; Lobell and Ortiz-Monasterio 2007; Lobell et al. 2005). Yet few of those models incorporate the effects of observed climate change on crop yield with different fertilization treatments. Our results suggest that the impacts of climate change and fertilization on crop yields are interconnected. Thus, more experimental research as well as modeling efforts are necessary to incorporate the interactions of fertilization and climate change in accurately quantifying the temperature sensitivity of crop yield and to better understand the variation of crop yields under projected climate change.

CONCLUSIONS

In summary, our analyses showed a positive impact of increasing temperature during the post re-greening season on winter wheat yield. Additionally, balanced fertilization significantly enhanced winter wheat grain yields during the 20-year experiment. The responses of grain yields to temperature variables were influenced by different fertilization treatments, and plots treated with N and P balanced fertilization were most sensitive to climate change. Despite the potentially confounding effects of other factors, such as genetic improvement in crop varieties, increased CO₂ and plant adaptation, our work highlights the importance of balanced fertilization in enhancing crop yields and in altering the temperature impacts on grain yields.

SUPPLEMENTARY MATERIAL

Supplementary material is available at Journal of Plant Ecology online.

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