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Warming and nitrogen fertilization effects on winter wheat yields in northern China varied between four years

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ABSTRACT

Global warming is expected to affect wheat productivity significantly, but with large regional differences depending on current climatic conditions. We conducted a study that aimed to investigate how wheat growth and development as well as yield and yield components respond to warming combined with nitrogen fertilization. Infrared heaters were applied above the crop and soil to provide a warming of around 2 °C at 5 cm soil depth during the whole winter wheat growing season from 2008 to 2012 at a site near Shijiazhuang in the North China Plain. Two temperature levels (warming and ambient) for winter wheat were compared in a factorial combination with (N2, 240 kg N ha^{-1} y^{-1}) and without nitrogen fertilizer (N1) in a field experiment. Measurements showed that the infrared heater increased soil temperature by 1.6 to 2.2 °C in N2 and by 1.3 to 2.0 °C in N1 depending on soil depth (0.05 to 0.40 m). The volumetric water content decreased significantly before heading by 9.3, 3.9, 2.4 and 1.2 vol% in the soil depth of 0.10, 0.20, 0.40, 0.60 m in N2 and by 5.9, 1.4, 1.3 and 1.2 vol% in N1 from heating compared with no heating. The duration of the entire growth period was shortened by on average 7 days in the warming compared with control treatment. The early growth stages before re-greening in spring were shortened by 12 to 18 days, whereas the later stages were prolonged by up to 6 days. Warming reduced grain yield by 36%, 39% ($P<0.05$) and 12% for N2 and 33%, 7% and 10% for N1 in 2009, 2011 and 2012, respectively, which can be considered years with normal winter weather. However, warming increased grain yield by 1% and 31% ($P<0.05$) in N1 and N2, respectively, in a year with unusually cold and snowy winter conditions (2010). Warming increased plant height and 1000-grain weight, but reduced spike number per m^2. This suggests that the wheat yield loss may be related to reduction of spike number, which was affected by decreased soil water content under warming. Warming tended to give larger yield reductions at higher nitrogen fertilizer rates, and this may be related to larger water consumption with both higher nitrogen and temperature leading to water shortages. These effects indicate that wheat yield loss from warming was primarily associated with more severe water shortage from greater evapotranspiration under warming. The large crop canopy in the fertilized plot may further have enhanced evapotranspiration and thus severity of the drought leading to larger yield reduction in fertilized plots. Yield increased under warming when water was not a limited factor in a year with unusual cold and wet winter.

1. Introduction

Global mean air temperature has been increasing over the past century, and the Intergovernmental Panel on Climate Change (IPCC) has projected that global temperatures may increase by 1.8 to 5.8 °C at the end of the 21st century (IPCC, 2007). Climate change will thus exert a crucial, yet not quantified, effect on wheat productivity and thus also on production (Ortiz et al., 2008; Asseng et al., 2011; Roberson et al., 2011). This is of particular importance, considering the fact that wheat is the third largest crop in terms of food supply to humans worldwide (Asseng et al., 2011).

Globally cereals (primarily wheat, rice and maize) account for 58% of the global area of annual crops and provide about 50% of food calories (Fischer et al., 2009). The demand for cereals is projected to increase by 70% by 2050 (Pierna et al., 2012; Vermeulen et al., 2012). Since there is no trends towards expansion of the agricultural or

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cereal area there is a need to increase cereal crop productivity, and this need is being challenged by climate change (Ortiz et al., 2008).

Many studies that make use of experimental and field data to feed simulation models have been conducted for assessing the effect of global warming on crop production. Some studies have used temperature gradient techniques (Wheeler et al., 1996a,b), or changes in sowing date to obtain different temperatures during crop growth (Ishag and Mohamed, 1996), while others have compared temperature at different sites, or just focused on extreme hot days (Gerilowski et al., 2011). Night warming effects (Fang et al., 2012), or high temperature stresses have also been studied (Stone and Nicolas, 1996; Ferris et al., 1998; Gibson and Paulsen, 1999; Farooq et al., 2011; Bian et al., 2012; Weldearegay et al., 2012). Based on yield response models at country scale, there is evidence that global wheat yield has declined by 5.5% for the period 1980–2008 due to increased temperatures (Lobell et al., 2011). Other modeling studies also predicted that wheat yield would decrease due to global warming, primarily increased temperature (Semenov and Shewry, 2011). You et al. (2009) found for China that a temperature increase of 1 °C during the wheat growing season could reduce wheat yield by 0.5%. There are other reports as well showing that warming decreases grain yields of wheat, rice, soybean, and maize (Alewell et al., 2011; Lobell et al., 2011). Nevertheless, there are major uncertainties associated with the crop modeling studies on which many of these climate change projections are made (Basset-Mens et al., 2009). Current models may face greater challenges to predict the wheat yield under global warming (Nisbet and Fowler, 2011), in particular because some of the effects of extreme temperatures may not be well covered in the models. The lack of relevant field and experimental data makes it difficult currently to verify model predictions of climate change impacts on crop productivity.

Winter wheat is the major crop in the People's Republic of China. However, so far it is not clear how climate change will impact on productivity of winter wheat in China. For example, Tian et al. (2012) reported an increase of wheat yield by 16% under increased air temperature of 1.5 °C (Tian et al., 2012). Xiao et al. (2008) projected that the yields would increase by 3% at low altitudes and 4% at high altitudes by 2030 (Xiao et al., 2008). However, other studies found that wheat yield was reduced by 3 to 6% in a warming experiment (Hou et al., 2012). Moreover, analysis of wheat yield data from China for the period 1979 to 2000 has indicated that wheat yields have decreased by about 3–10% for each 1 °C temperature increase (You et al., 2009). Yet, several factors influence productivity of wheat, and the effect of temperature interacts with other crop growth factors such as water and nitrogen availability (Trnka et al., 2012). There is therefore a need to study how productivity of wheat is affected by warming and how it interacts with management factors such as nitrogen fertilization. This is particularly important in China, where the highly intensive production systems are being challenged both by increasing demands for grain and from the need to reduce environmental impacts from the production systems.

In this study, we used infrared heaters to mimic climate warming for measuring the impact on wheat productivity at field scale during 4 years. The study aimed to assess the effects of warming, with or without nitrogen fertilization, on wheat productivity, growth and development, and different yield components. We aimed to increase surface temperature by 2 °C with the infrared heater during the wheat growing period from autumn 2008 until June 2012. The study was performed in the North China Plain (NCP) in Hebei province, which is a dominating region for cereal grain production in China. We hypothesized that warming would decrease wheat yield since the wheat growth period will shorten in a warmer climate. The objectives of this study were to (1) investigate how warming affects productivity of winter wheat in Northern China, and (2) how this effect of warming interacts with nitrogen fertilization.

2. Materials and methods

2.1. Experimental site

Experiments with winter wheat (*Triticum aestivum* L.) were conducted from autumn 2008 to summer 2012 at the Luancheng research station of the Chinese Academy of Sciences in Hebei province, China (37°53′N, 114°41′E, 50 m above the sea level). The mean annual temperature is 12.3 °C, and the annual precipitation is around 481 mm. A double cropping system (two crops per year) was employed at the site, with winter wheat followed by either maize (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.). These cropping systems are typical of the North China Plain. The soil at the experimental site is loam with 14.5 g kg^{-1} organic matter, 1.1 g kg^{-1} total-N, pH of 8.1, Olsen P of 15.4 mg kg^{-1} and available K of 95 mg kg^{-1} in the top 15 cm soil layer.

2.2. Experimental design

A two-factorial experimental design was used with two nitrogen (N) treatments (N1: no N fertilizer, and N2: 240 kg N ha^{-1} in mineral N fertilizer) and two temperature treatments (C: control with no warming, and T: temperature increased around 2 °C at 5 cm soil depth on average during 4 wheat growing seasons). This gave the following experiment combinations: N1 C, N1 T, N2 C and N2 T. Each treatment had three replicates, deployed in different parts (east, middle and west, respectively) of the experimental area. The size of each plot was 4 × 4 m. The experiment plots were randomized within each of the blocks (east, middle and west).

Twelve infrared heaters (Niu et al., 2007) with rated power of 1000 W were operated in the increased temperature treatments (T) throughout the wheat growing season from seeding to harvest. In every heated plot, a pair of 200 × 20 cm infrared heaters were placed 1.8 m above ground at 1 m distance from each other. The effective warming area of each pair of infrared heating tubes was 2 × 2 m. Therefore, samplings and measurements were conducted within this effective area. The unheated plots were spaced 1 m from heated plots, with the same device at the same height but without electric power thus providing similar shading effects.

The 12 plots were randomly assigned as without (N1) and with (N2) nitrogen fertilizer application. In N2, 240 kg N ha^{-1} was applied to the wheat crop every year, which is the amount commonly used in this region of NCP. Half of the N fertilizer was applied at sowing in October, the other half was applied in April.

Other important management practices were as follows. Winter wheat seeds of variety Shixin 828 (common local breed in Hebei province) were sown manually in the first ten-day period of October. The row distance was 20 cm and the seed rate was 300 kg ha^{-1}. The crop was harvested at the end of May or the start of June in the following year. Thereafter, soybean was sown in June 2009, 2010 and 2011. The residues of soybean were removed after harvesting. *P* fertilizer at the rate of 65 kg *P* ha^{-1} year^{-1} was applied at sowing of the wheat. No other fertilizers were applied. The wheat crop was irrigated twice with approximately 80 mm per time in April and May.

2.3. Measurements

The soil temperature at the soil surface (0 m), and at 0.05, 0.10, 0.15, 0.20, and 0.40 m was continuously monitored by T-type thermal couples in all plots and recorded every hour by datalogger (CR10X, Campbell, USA). The water content in the soil depths of

0.10, 0.20, 0.40 and 0.60 m was measured once a week by time domain reflectrometry (TDR 100 system, Campbell Ltd. Co. USA).

Crop phenology was monitored at four main stages using the BBCH scale (Lancashire et al., 1991), i.e. re-greening stage, jointing stage (GS33), heading date (GS55) and ripening stage (GS92). Re-greening stage was defined as when leaves returned green and started to grow in spring after winter dormancy. The different stages were determined and recorded when more than half of the wheat plants had reached the stage.

At harvest maturity, 20 wheat plants were sampled randomly from each plot. The samples were used to measure number of tillers, plant height, spike length and number of grains per spike, 1000-grain weight, and total plant weight. Above-ground biomass was sampled as 20 stems, which were collected randomly within a 1 m row (row distance 0.02 m), and the total number of stems in this 1 m row was counted. The 20 stems were air dried and weighed, and the weight divided by 20 and then multiplied by the total number of stems in the $1 \times 0.02\ m^2$ area to obtain aboveground biomass.

In order to determine wheat grain yield, a sample area of 150 cm × 150 cm was used for harvesting. The wheat grains from this sample area were weighed after air drying to determine grain yield. The harvest index was calculated as crop grain yield (kg ha^{-1}) divided by crop aboveground biomass (kg ha^{-1}).

2.4. Statistical analyses

A two way ANOVA was applied for each experimental year to determine the main and interactive effects of warming and fertilization. Differences were defined as significant at 95% confidence level, i.e. $P < 0.05$. Multiple comparisons were calculated using LSD (Least Significant Difference). The statistical analyses were conducted using SPSS 18.0 and Excel 2003.

3. Results

3.1. Climate condition during the experimental period

The experimental wheat growing years could be divided into an anomalous cold year (2009–10) and normal years (Table 1 and Fig. 1). In the winter of 2009, the average temperature was −2.0 °C, compared to 0.9, −0.4 and −0.6 °C in 2008, 2010 and 2011, respectively. In spring of 2010, the temperature was still lower than for other years. Regarding mean precipitation, 2009 was also a snowy year, the rainfall reached 46 mm during winter, whereas it was 6, 11 and 31 mm in other years.

Table 1
Mean monthly air temperature and precipitation in each month of the wheat growing season from 2008 to 2012. Winter contains November, December, January and February and Spring contains March, April and May.

Month	2008–09	2009–10	2010–11	2011–12
	Temperature (°C)			
Nov	6.3	0.3	5.6	6.2
Dec	−0.9	−2.6	−0.6	−1.7
Jan	−3.3	−4.7	−5.8	−4.5
Feb	1.4	−0.8	−0.8	−2.2
Mar	7.5	4.7	7.2	5.6
Apr	14.4	11.2	13.9	15.4
May	20.2	20.2	18.7	21.3
Winter	0.9	−2.0	−0.4	−0.6
Spring	14.0	12.0	13.3	14.1
	Precipitation (mm)			
Oct	18	0	4	15
Nov	0	41	0	30
Dec	0	0	2	1
Jan	0	0	0	0
Feb	6	5	9	0
Mar	8	9	0	6
Apr	8	12	1	19
May	41	7	30	0
Winter*	6	46	11	31
Spring*	57	28	31	25

* is seasonal sums.

3.2. Soil temperature difference

The increase in soil temperature induced by heating was largest during winter and smallest during summer. The warming was largest near the soil surface and declined with increasing soil depth

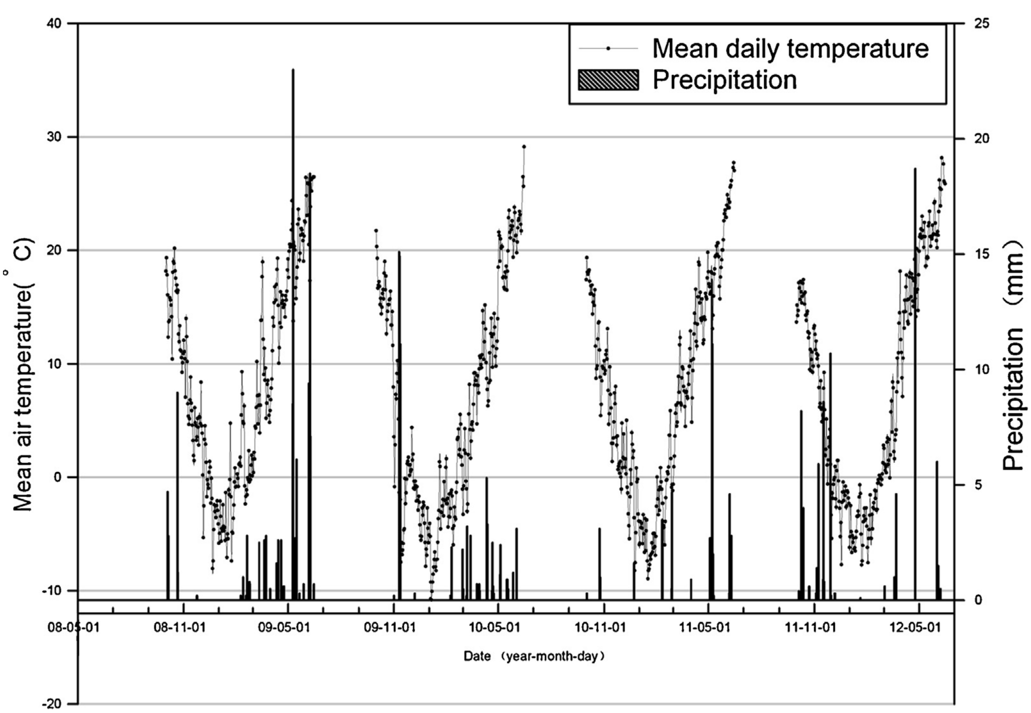

Fig. 1. Daily mean air temperature and mean precipitation during wheat growing season in 2008–2012.

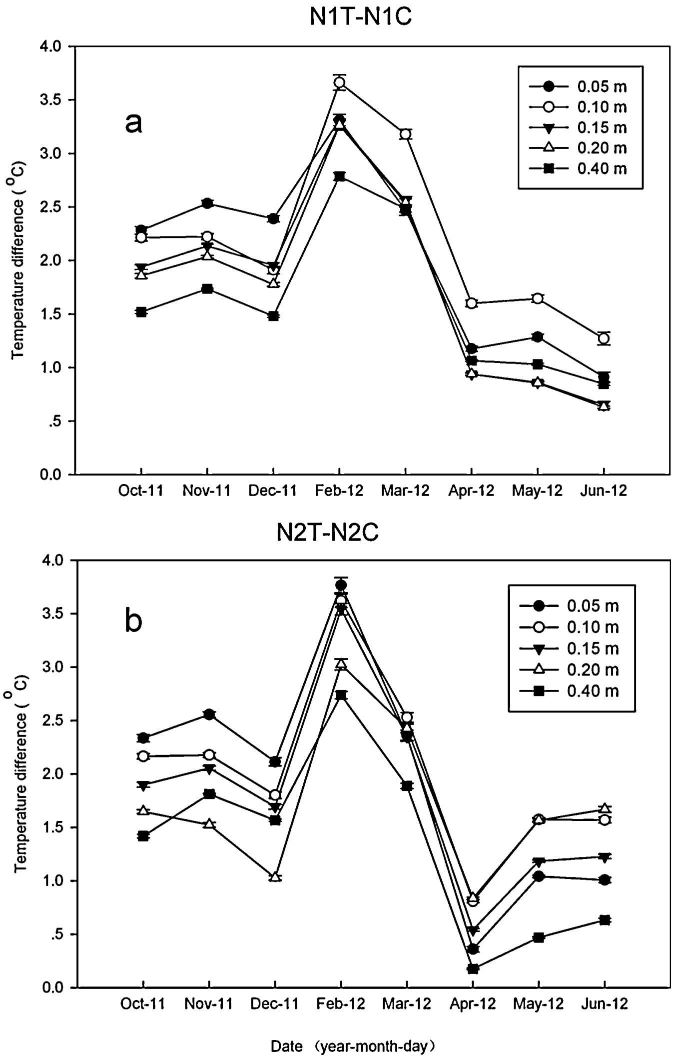

Fig. 2. Average monthly mean temperature difference at 0.05, 0.10, 0.15, 0.20 and 0.40 m depth from sowing to harvest in treatment combinations with no (N1) or full (N2) nitrogen fertilization and without (C) and with (T) warming during 2011–2012. (a. N1 T – N1 C; b, N2 T – N2 C). S.E., standard error of mean.

(Fig. 2). At 5 cm depth, the warming increased soil temperature by between 0.9 to 3.3 °C in N1, and 0.4 to 3.8 °C in N2 treatment. At 40 cm depth, the warming increased temperature by 0.8 to 2.5 °C in N1 and 0.2 to 2.7 °C in N2 treatment in 2011 to 2012.

3.3. Soil water dynamics

The temporal dynamics of soil water content were similar in both warming and control treatments in 2011–12 (Fig. 3). The soil water contents during the growth stages before April were stable, without drastic fluctuations, and the highest water contents were reached after irrigation (April 6th and May 8th, 2012). Soil water content was significantly lower by 9.3, 3.9, 2.4 and 1.2 vol.% in the soil depth of 0.10, 0.20, 0.40, 0.60 m in N2 T and by 5.9, 1.4, 1.3 and 1.2% in N1 T, compared to the control before the heading stage. However, after heading and two times of irrigation, soil water content in N2 T declined by 1.8, 2.8, 4, 3.5%, whereas water content in N1 T increased for 3, 2.3, 2.3 and 0.6% at soil depths of 0.10, 0.20, 0.40, 0.60 m respectively, though not significantly (Fig. 3). The trends in soil water content during 2008–09 and 2010–11 were similar to 2011–12, but in 2009–10, where soil water content showed little and no significant difference between treatments (data not shown).

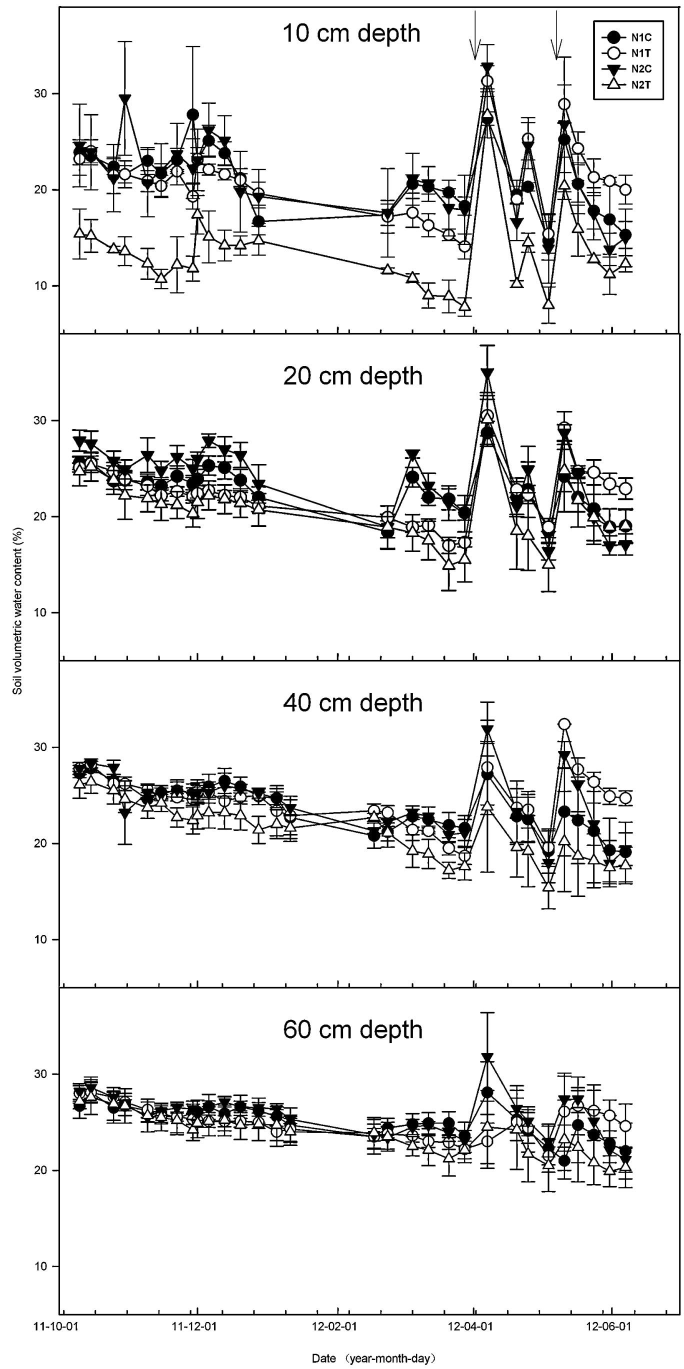

Fig. 3. Average volumetric water content at 10, 20, 40, 60 cm depths from sowing to harvest during 2011–2012 in treatment combinations with no (N1) or full (N2) nitrogen fertilization and without (C) and with (T) warming. Error bar means standard error of mean. Arrows mean irrigation, 80 mm every time.

3.4. Phenology

The wheat growth period was shortened 8, 6, 6 and 7 days by warming in the four growing seasons during 2008–2012 (Table 2). The date of re-greening advanced by 12, 18 and 12 days in 2010, 2011 and 2012, respectively, while the date of jointing advanced by 19, 10, 12 and 9 days in the respective experimental years (Table 2). Finally heading date advanced by 13, 8, 6 and 8 days during the 4 years under warming treatment. Thus, the shortened duration consistently happened from sowing to re-greening. The period from re-greening to jointing was prolonged by 2 to 4 days

Table 2
Dates of winter wheat phenological stages in warming and control treatments (data for re-greening stage of 2009 was lost).

Year	Treatment	Sowing	Re-greening	Jointing	Heading	Ripening
2008–09	Control	10-Oct		29-Mar	23-Apr	12-Jun
	Warming	10-Oct		10-Mar	10-Apr	4-Jun
2009–10	Control	14-Oct	26-Feb	10-Apr	6-May	16-Jun
	Warming	14-Oct	14-Feb	31-Mar	28-Apr	10-Jun
2010–11	Control	10-Oct	1-Mar	10-Apr	26-Apr	13-Jun
	Warming	10-Oct	11-Feb	29-Mar	20-Apr	7-Jun
2011–12	Control	3-Oct	29-Feb	3-Apr	24-Apr	6-Jun
	Warming	3-Oct	17-Feb	25-Mar	16-Apr	30-May

Table 3
Interval (days) between different growth stages during 2008–2012.

Year	Treatment	Sowing–re-green	Re-green–jointing	Jointing–heading	Heading–ripening
2008–09	Control			25	50
	Warming			30	55
2009–10	Control	134	43	26	41
	Warming	122	45	28	43
2010–11	Control	142	40	16	48
	Warming	124	46	22	48
2011–12	Control	148	34	21	43
	Warming	136	37	22	44

under warming. Warming also prolonged the following stages by 1 to 6 days during 2008–2012 (Table 3).

3.5. Effects of warming and nitrogen fertilizer

Most of the indicators and yield components were affected by the nitrogen fertilizer treatment (Table 4). For instance, number of spikes was significantly affected during 2010 to 2012, and 1000 grain weight, wheat yield, tillers, plant height and spike length were also controlled by nitrogen fertilizer in most of the four years.

Warming, and the interaction of both warming and fertilization, had an inconsistent impact on these indicators during the different years. Warming significantly influenced plant height in both 2011 and 2012, wheat yield and harvest index in 2011, and tiller and spike length in 2012, while it affected only number of kernels and 1000 grain weight in 2009. The interaction between warming and nitrogen occurred in wheat yield and above-ground biomass in 2011, wheat yield in 2010, number of tillers and kernels in 2009, and spike length in 2012. Grain number was affected significantly by warming and the interaction of warming and fertilizer in 2009.

3.6. Wheat growth characteristics

Wheat growth characteristics as affected by warming are shown in Table 5. The number of tillers per plant was significantly affected by warming only in the N2 treatment in 2009 ($P < 0.05$). Warming increased plant height by 10% and 15% (in 2011), 4% and 5% (in 2012), for the N1 and N2 treatments, respectively. The warming treatment increased plant height in the N2 treatment in all years, whereas less consistent results were obtained in N1. Spike length was increased by warming in 2011 and 2012 in N1 and N2 ($P < 0.05$). Warming consistently reduced above-ground biomass by 5, 3 and 6% in 2009, 2011 and 2012, respectively, but not significantly. In the N1 treatment, although not significantly, warming reduced harvest index by 21, 38 and 9% in 2009, 2011 and 2012, respectively. In N2, harvest index was reduced by 25, 22, and 37% in 2009, 2011 and 2012, respectively.

3.7. Grain yield components

Warming affected grain yield differently in different years. In 2009, 2011 and 2012, warming reduced grain yield by 26, 27 ($P < 0.05$) and 12% in N2, and by 25, 7 and 9% in N1 (Table 6). However, in 2010, wheat yield under warming was increased by 31% ($P < 0.05$) and 1% in N2 and N1, respectively.

Warming reduced spike numbers per m^2 by 10, 20, and 6% in N1 and 18, 9, and 15% in N2 during the normal climatic years (2009, 2011 and 2012), but not significantly. The number of spikes under warming was increased in 2010, which had an unusually cold winter with ample snow. Warming reduced the grain number significantly in N2 by 39% and N1 by 33% in 2009. The 1000 grain weight was enhanced significantly by warming in 2010, both in N2 (14%) and N1 (20%), and it increased consistently, but not significantly, in other years (Table 6).

Table 4
Two-way ANOVA analysis for wheat yield and growth characteristics of the four years as affected by warming (T), nitrogen fertilizer (N) and their interactive effect.

	2009			2010			2011			2012		
	N	T	N*T	N	T	N*T	N	T	N*T	N	T	N*T
Number of spikes				**	ns	ns	**	ns	ns	**	ns	ns
Grains in spikes	ns	**	*				ns	ns	ns	*	ns	ns
1000 grain weight	**	ns	ns	*	**	ns	ns	ns	ns	**	ns	ns
Wheat yield	**	*	ns	*	ns	*	**	*	*	*	ns	ns
Number of tillers	**	**	*	*	ns	ns	*	ns	ns	ns	*	ns
Plant height	**	ns	ns	ns	ns	ns	ns	**	ns	**	**	ns
Spike length	*	ns	ns	*	ns	ns	ns	ns	ns	**	**	**
Above-ground biomass							**	ns	*	**	ns	ns
Harvest index							ns	*	ns	ns	ns	ns

Table 5
Number of tillers, plant height, spike length, above-ground biomass (air dry) and harvest index from 2009 to 2012 in treatment combinations with no (N1) or full (N2) nitrogen fertilization and without (C) and with (T) warming.

Treatment	Tillers (per plant)	Plant height (cm)	Spike length (cm)	Above-ground biomass (g/m^2)	Harvest index (%)
2009					
N1C	1.0 ± 0.0b	63 ± 3.6	5.5 ± 0.1a	699 ± 164	40 ± 0.1a
N1T	1.0 ± 0.8b	61 ± 2.6	4.8 ± 0.3b	517 ± 129	33 ± 0.1a
N2C	2.0 ± 0.2c	71 ± 3.0	5.8 ± 0.0a	1156 ± 263	50 ± 0.1a
N2T	3.4 ± 0.6a	76 ± 6.5	6.2 ± 1.0a	1099 ± 248	40 ± 0.1b
2010					
NIC	1.0 ± 0.0	64 ± 1.7	9.2 ± 1.3b		
N1T	1.1 ± 0.1	69 ± 3.9	10.3 ± 0.3ab		
N2C	1.5 ± 0.1	63 ± 1.6	12.5 ± 0.8a		
N2T	1.4 ± 0.2	66 ± 0.9	12.4 ± 1.0a		
2011					
N1C	1.2 ± 0.1	66 ± 2.2b	5.8 ± 0.2c	1216 ± 80b	30 ± 2.1
N1T	1.0 ± 0.0	73 ± 1.5a	6.4 ± 0.2b	1766 ± 380ab	22 ± 6.3
N2C	1.6 ± 0.4	65 ± 0.7b	6.4 ± 0.1b	1948 ± 108a	35 ± 0.9
N2T	1.3 ± 0.2	75 ± 1.5a	7.2 ± 0.1a	1886 ± 85a	27 ± 2.7
2012					
N1C	1.1 ± 0.0	65 ± 0.9c	5.7 ± 0.0c	952 ± 111	38 ± 5.4
N1T	1.4 ± 0.1	67 ± 1.2b	5.7 ± 0.0c	912 ± 37	35 ± 3.2
N2C	1.2 ± 0.0	69 ± 0.1b	6.5 ± 0.0b	1735 ± 360	37 ± 2.7
N2T	1.5 ± 0.2	73 ± 0.1a	7.0 ± 0.0a	1640 ± 142	27 ± 2.4

Values are mean ± 1 SE. Values followed by different letters are significantly different among four treatments within a year ($P < 0.05$). Some data from 2010 was lost.

4. Discussion

4.1. Soil temperature

It is well known that soil temperature plays a key role for root growth, water and nitrogen uptake of winter wheat (Weldearegay et al., 2012). Moreover, the effect of temperature on wheat growth and development is non-linear, since there are threshold responses both at low and high temperatures (Porter and Gawith, 1999). In our study, infrared heaters increased soil temperature by 1.6 °C and 1.3 °C, in N1 and N2, to 40 cm soil depth. This magnitude of warming is larger than reported for another warming study in NCP (Hou et al., 2012). The soil temperature difference between the treatments became smaller during April and May when wheat reached the jointing and heading stages, and where the larger wheat canopy therefore most likely acted as an insulating layer between heaters and the soil.

4.2. Warming controls soil water content

Soil water content declined significantly more in both N2 T and N1 T compared to the controls before heading stage. However, after heading, soil water content was not affected by the warming treatment since irrigation was applied twice. After heading, in N2 T, soil water content was still lower than for N2 C, whereas water content in N1 T was higher than for N1 C.

Before heading, under warming, plants grew better and became higher, compared to control. This likely increased water uptake to support the greater transpiration, thus lowering soil water content. After flowering, wheat in N1 T was senescing, thus reducing transpiration relative to the wheat in the N1 C treatment, which did not develop so quickly. Therefore, the water content in N1 T soil was larger than N1 C in late season. However, due to the nitrogen fertilization in N2 T, the crop did not senesce so rapidly as in N1 T, leading to greater water demand to meet the requirement

Table 6
Wheat yield (air dry) and yield components factors between the treatment combinations with no (N1) or full (N2) nitrogen fertilization and without (C) and with (T) warming.

Treatment	Spikes Spikes/m^2	Grain numbers per stem	1000 grain weight g	Wheat yield kg ha^{-1}
2009				
NIC	255 ± 41	31 ± 5.8a	46.8 ± 1.4	2751 ± 405
N1T	232 ± 21	19 ± 3.2b	49.8 ± 1.7	2067 ± 561
N2C	609 ± 47	39 ± 3.2a	36.2 ± 6.7	5931 ± 1201
N2T	516 ± 86	26 ± 3.7b	42.1 ± 5.5	4376 ± 638
2010				
NIC	263 ± 7b		40.3 ± 0.3c	4225 ± 327b
N1T	270 ± 13b		48.6 ± 0.6a	4251 ± 198b
N2C	373 ± 8a		38.5 ± 1.6c	4953 ± 45b
N2T	378 ± 61a		43.7 ± 1.3b	6504 ± 443a
2011				
N1C	540 ± 32b	25 ± 0.7	47.6 ± 1.2	3628 ± 38c
N1T	450 ± 35ab	32 ± 4.4	47.9 ± 0.8	3386 ± 529c
N2C	680 ± 2a	31 ± 3.8	46.1 ± 0.8	6922 ± 537a
N2T	626 ± 42ab	30 ± 0.8	48.1 ± 1.1	4995 ± 330b
2012				
N1C	340 ± 45	35 ± 0.8b	46.2 ± 0.2a	3591 ± 414b
N1T	321 ± 19	32 ± 1.3b	46.4 ± 0.6a	3255 ± 251b
N2C	663 ± 156	36 ± 1.4ab	39.0 ± 0.7b	4943 ± 245a
N2T	578 ± 47	39 ± 2.1a	39.2 ± 0.9b	4396 ± 272a

Values are mean ± 1 SE. Values followed by different letters are significantly different among four treatments within a year ($P < 0.05$). Data for grain number for 2010 was lost.

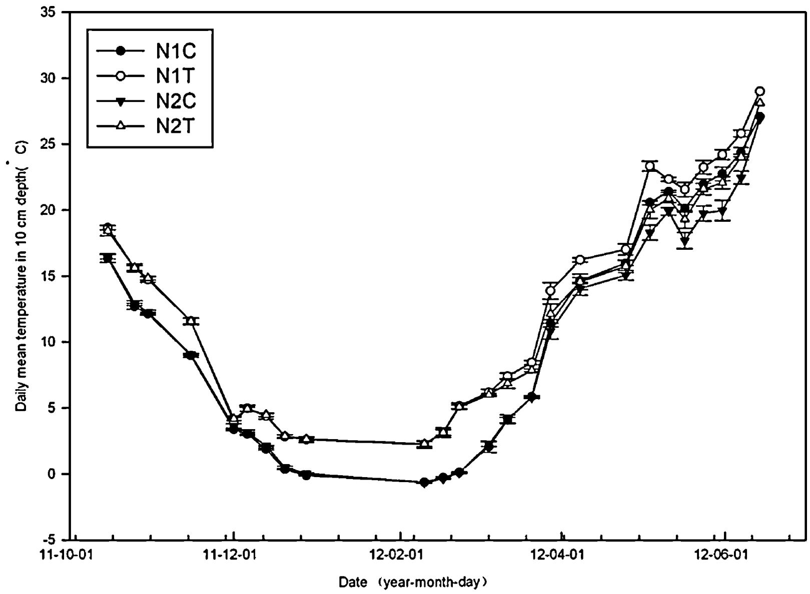

Fig. 4. Average daily temperature at 0.10 m depth from sowing to harvest during 2011–2012 in treatment combinations with no (N1) or full (N2) nitrogen fertilization and without (C) and with (T) warming.

for growth. Therefore, soil water content in N2 T was continuously lower than for N1 T towards the end of the season.

4.3. Warming effects on phenology

It is well known that warming shortens the wheat growth cycle (Stone and Nicolas, 1996; Sadras and Monzon, 2006; Wang et al., 2008; Patil et al., 2010a; Croitoru et al., 2012). However, wheat has different temperature thresholds during different phenological periods and photoperiod also plays a role in determining timing until flowering. In our study, warming accelerated wheat growth from sowing until re-greening, thus shortening the whole growth duration by 6–8 days during 2009 to 2012. After the re-greening stage, warming prolonged the growth period for up to 6 days. This effect of warming concurs with results of other studies (Liu et al., 2010; Patil et al., 2010b; Fang et al., 2012; Hou et al., 2012). In China in particular, Tian et al. (2012) found 10 days shorter wheat growth period due to warming of 1.5 °C, mainly during the pre-anthesis phase, while the next stages were prolonged by one day (Tian et al., 2012). This is likely mainly an effect of different temperature environments experienced by the heated and control crops during the different growth phases. Thus, after flowering, for the same stage, wheat under warming tended to be in a cooler environment than wheat in the control treatment, since wheat in warming plots were ahead of control plots in terms of phenological development. Therefore, more days are needed to reach similar accumulated growing degree days at maturity.

The effect of the heat treatment on soil temperature was largest during winter (Fig. 2). Winter, the period of wheat dormancy in NCP, was therefore the most sensitive period to the warming treatment. Wheat in the heated treatment continued growth later in autumn and started to grow earlier in spring, leading to a shorter overwintering stage, while wheat without warming had a longer dormancy. The soil temperature difference between the treatments became smaller during April and early May (Fig. 4), when wheat had developed a dense crop canopy. After that soil temperature differences had less impact on wheat growth and development.

4.4. Warming effects on grain yield and yield components

Our results showed that in most years with normal or near-normal winter temperatures, warming reduced grain yield, irrespective of fertilization. This yield reduction may come from hastened crop development and from higher evapotranspiration and thus lower soil water content under warming (Fig. 3) (Trnka et al., 2012). Both drought and high temperatures are major reasons for yield loss in NCP, where irrigation is normally used to supplement rainfall in winter wheat. Soil moisture in warming plots was persistently lower than that of control treatment before heading, even at 60 cm soil depth, and this may have led to yield loss due to water deficit (Richter and Semenov, 2005; Fang et al., 2010). Earlier and more adequate irrigation may therefore have increased grain yield in the heated treatments. This effect may also explain why yield losses were generally lower from the heat treatment in the N1 compared with the N2 treatment, since wheat in the N2 treatment consumed more water and therefore was more susceptible to drought. A similar study from a humid location with ample precipitation may provide some verification of this assumption (Tian et al., 2011, 2012), where warming did not change soil water content, and here warming of 1.5 °C increased grain yield significantly by 16%. The yield reductions that we obtained in a dry climate were supported by another experiment in North China Plain (Hou et al., 2012).

In 2010, the yield increased under warming (significantly in N2). This is most likely because the winter of 2009 was unusually cold and snowy (Table 1 and Fig. 1). An unusually cold winter prevents good crop establishment and deep root development in wheat, and the crop therefore potentially becomes more susceptible to drought in spring (Kristensen et al., 2011). Thus a warming of the soil may led to better crop establishment in this year, and therefore to higher yields in the warming treatment in this cold year. This result was supported by Fang et al. (2012), who in field warming experiment found that warming in colder years can promote wheat yield significantly (Fang et al., 2012).

The wheat grain yield is a combined result of spikes, kernels per spike and the 1000 grain weight. In our study, the number of spikes was reduced by warming in normal years, but increased in the colder year 2009–10, although not significantly. The grain weight was higher in the warming treatments in all the 4 years, and significantly in 2010. This trend is in agreement with results from a soil warming experiment in Denmark (Patil et al., 2010b). However, 1000 grain weight decreased significantly in a night warming experiment (Fang et al., 2010), which may be due to enhanced crop development and higher respiration with night warming, especially during the development stages, leading to a reduction of grain weight. In contrast, in our experiment, the anthesis and milk maturity stages did not shortened but were slightly prolonged, which provided more time for grain filling and thus supported larger grains. Aside from that, the growth of grains mainly depends on ample water content in grain-filling phase. In our experiment, sufficient irrigation was given during this period, resulting in water not limiting grain weight.

Increasing temperature at the terminal spikelet stage has been observed to decrease the number of grains per head significantly (Johnson and Kanemasu, 1983; Fang et al., 2010). In our study, such a reduction occurred only in 2009. Warming did not affect the grain numbers in the other three years. Most studies have shown higher grain weight accompanying lower spike number per m^2 (Darwinkel, 1978; Patil et al., 2010b; Tian et al., 2011). Johnson et al. (1984) found that wheat yield tended to decline when not enough water was available before the flowering stage, which is in accordance with our results. Therefore, the lower yields in the warming treatment may be mainly attributed to lower spike number, which is linked to lack of water before the flowering phase.

Tian et al. (2011) found that plant height increased significantly with warming. Our results concur with this. In contrast Fang et al. (2010) reported that night warming reduced the height of wheat associated with a shorter growth duration. The effect may be related to the difference between day and night temperatures (DIF). Night warming reduced DIF, resulting in lower wheat height (Luo, 1994). In N2, warming reduced above-ground biomass, although not significantly, which is opposite to some other studies (Patil et al., 2010b; Hou et al., 2012; Tian et al., 2012). Although the development stage after re-greening was longer with warming, which was favorable to dry matter accumulation, the reduction in soil water content limited crop growth and dry matter accumulation. Even if soil water content tended to be higher in warming plots than control after anthesis, this was not sufficient to enhance above-ground biomass.

4.5. The interaction between fertilizer and warming

Although nitrogen fertilizer enhances crop growth and yield, this effect interacts with climatic conditions. In our study, the increase of wheat yield with nitrogen input was lower in the warming treatment than in the control treatment in normal climate years (2009, 2011 and 2012). The warming led to lower soil water content which may not only have reduced crop growth but also nitrogen uptake (An et al., 2005). In addition the larger crop canopy in the fertilized treatment would have consumed more water due to higher evapotranspiration, and this effect was further enhanced by the warming treatment that increased water vapor pressure deficit in the air and thus further increased the evaporative demand. During the colder year 2010, warming apparently facilitated a higher effectiveness of nitrogen fertilizer, and the N2 T had 2000 kg ha^{-1} (53%) higher wheat yield than N1 T, whereas the yield in N2 C was only 700 kg ha^{-1} (17%) higher than N1 C.

The yield of wheat is a result of a combination of factors. Ascribing the yield reduction from warming to higher temperatures alone is misleading without considering the complex impacts and interactions of other factors such as varieties, soil water content, crop management and rainfall (Asseng et al., 2011). However, our results show that wheat yield in NCP would generally decline under warming, although much of this effect is caused by increases in crop water demand and thus may be alleviated by increasing irrigation or applying other water saving methods.

The food production and safety, a “hot” topic within the increased Chinese population growth, remains a challenge. The results of our study suggest that a moderate warming could benefit wheat yields in the North China Plain, if irrigation is adequate. Since wheat have the capacity to be grown in a large range of latitudes, the selection of more suitable genotypes and soil and crop management systems better adapted to a warmer climate should be considered in the future research.

5. Conclusions

This study demonstrated that warming of around 2 °C at 5 cm soil depth, as induced by infrared heater, have the potential to reduce the duration of the wheat growth period by 6 to 8 days, and to shorten the duration of early growth phases before re-greening in spring, and thus prolonging the later stages within 6 days. Regardless of the fertilization treatment, the wheat yield was lower under warming in normal climate years, most probably because of larger soil water deficit under warming. However, warming increased wheat yield in a year with unusual cold and snowy conditions. As for the yield components, the reduction of spikes numbers from warming surpassed the increase of 1000 grain weight, indicating yield loss under warming to depend on the spikes numbers. The results suggest that wheat yield will increase under warming if adequate water is added in the reproductive stages. Warming can promote the utilization of nitrogen fertilizer in colder years, but limits the benefit in warmer years. The increment of yield by increased nitrogen fertilizer input in the warming treatment was much lower than that for the control temperature treatment in normal winter conditions.

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