Effects of temperature rising on soil hydrothermal properties, winter wheat growth and yield

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Abstract: *Global warming has become evident and rising temperature has great influence in ecosystem balance and crop growth. To simulate climate warming, the infrared radiators were applied in field to increase temperature. The increased soil temperature up to 40 cm depth and the difference was larger in night than in daytime. The magnitude of elevated temperature was reduced with rising atmosphere temperature. Warming increased soil heat flux, but soil heat storage was not influenced. Moreover, the elevated temperature changed water distribution and storage in soil profile. Before mid-April, soil water content and water storage were lower for the elevated temperature than for normal temperature. However, after mid-April, the elevated temperature produced the reverse effect on soil water content and water storage. Furthermore, warming accelerated winter wheat growth, and shortened the growth season by about 10 days. Meanwhile, warming increased the key biological parameters of winter wheat, e.g. plant height and spikes length, under no fertilizer limitation. Elevated temperature decreased biomass, spikes per mu and grains per spike of wheat. In the field of elevated temperature, thousand grain weight of winter wheat was increased, while winter wheat yields decreased by 25%.*

Keywords: *elevated temperature; winter wheat; soil water content; soil thermal properties*

Introduction

Global warming has become pronounced in recent years. Global mean temperature has increased by 0.6°C since the late 20th century. It is predicted that global average surface temperature will increase by 1.4–5.8°C during this century (IPCC, 2001). The effects of global warming on agro-ecosystems and crop have been studied extensively (Rykbost et al., 1975; Miglietta et al., 1995; Wan et al., 2002).

Rising temperature influenced the storage and distribution of water and energy in soil. Many studies found that global warming increased evapotranspiration, and reduced soil moisture (Valdes et al., 1994; Beringer et al., 2005; Wang et al., 2008). The changes of soil hydro-thermal properties have effects on crop growth and yield. According to statistics of many years, warming accelerated crop growth, and shortened the growth stages. Meanwhile, crop water use efficiency and crop yield was decreased (Gao et al., 1996; Guo et al., 1998; Zhou et al., 2003; Asseng et al., 2004; Liu et al., 2005). Zhou et al. (2003) found that high temperature increased evaporation, and thereby resulted in soil water deficit in mid and late wheat growth season, although temperature increase improved wheat growth condition in winter. Consequently, the grain weight and yield of winter wheat decreased. You et al. (2009) also found a 1□ increase in wheat growing season reduced wheat yields by about 3–10%. Some other studies, however, obtained the contrary results, which winter wheat yield increased with temperature increase (Nicholls, 1997; Xiao et al., 2008). Also, Gao et al. (1996) found warming increased grains per spike and thousand grains weight of winter wheat. However, these results were obtained by using mainly statistical method or indirect crop and ecological models, which could be without fertilizer and water stress. Experimental observations of warming effects on winter wheat growth and yield are scarce under field condition.

Many studies in laboratory indicated that high temperature induced wheat senescence and shortened grain-filling stage that resulted in reduced grain weight and quality. Hu et al. (2008) showed that high-temperature restrained wheat grain filling rate. The duration of grain filling was shortened, which lead to a decline in grain dry matter accumulation. Furthermore, high temperatures in the late growth season of winter wheat decreased roots activity, and increased spikelet sterility (Gao et al., 1996). These studies, however, focused mainly on a given stage of winter wheat. Moreover, studies were conducted in a closed or semi-closed artificial climate box or in the laboratory. Thus, the effects of high temperature on winter wheat are not clear in field.

Winter wheat is the main crop in North China plain and has suffer due to high temperature in terms of yield and quality (Li et al., 2005; Song et al., 2005; Shi et al., 2005; You et al., 2009). So, rising temperature adaptation strategies to overcome the adverse effects on the growth of winter wheat become an urgent need for sustainable development of agriculture and food security. So, the objective of this study is to investigate the effects of increased temperature on soil hydro-thermal properties, winter wheat growth and yield under simulated warming under field conditions. It is expected to provide adaptation strategies to overcome the impact of global warming on wheat North China plain.

Material and Method

Study site

The study was conducted at the Luancheng Agro-ecosystem Experimental Station (37°53’N, 114°41’E, elevation 50 m) of the Chinese Academy of Sciences, located on the piedmont of the Taihang Mountains. The average annual air temperature is about 12.2°C, and the annual mean precipitation is about 536 mm, with 70% of it occurring from July to September. The soil texture is loam (54% sand and 12% clay). In the tillage layer (0-20 cm), the average organic matter content was 15.1 g/kg and the total N, available P and available K content was about 10 g/kg, 9.3 mg/kg and 95.6 mg/kg, respectively.

The warming experiment was established in the plots of N fertilizer treatments (N1 and N5) during the winter wheat season in 2008. The plot size was 7 m×4 m. After corn harvest, all crop residues were chopped into small pieces and then incorporated into the soil using a moldboard plow. At winter wheat seeding, fertilizer rates were 0 kgN/ha for N1 and 240 kgN/ha for N5 respectively, and 195 kg/ha for P_2O_5. Winter wheat *(Triticum aestivum L.*, Shixin828) was sown in Oct. of 2008, and harvest in Jun. of 2009. Seeding was accomplished manually at the same rate for all the treatments. Depending on rainfall, three or four irrigations (40-50 mm each time) were applied.

Experimental treatments and measurement

The experiments were designed into two temperature treatments: warming (HT) and normal temperature (NT). There were three replications per treatment. The infrared radiant tubes (1.8 m length) were applied to simulated ecosystem warming. Two infrared radiant tubes were placed at 0.9 m distance in parallel on the location of 1.6-m height in each plot. The area of the elevated temperature is about 4.2 m^2. The control experiment (normal temperature) was located in the same plot. The power was applied to the infrared radiant tubes continually during the growth season of winter wheat.

A trench was dug in the middle of each observation plot, and time domain reflectometry (TDR) probe (20 cm long, 0.4 cm rod diameter, and 2.25 cm between the inner rod and outer rods) were installed horizontally into the soil at 0.05, 0.10, 0.20, 0.40, and 0.60 m depths. The T-type thermal couples were inserted horizontally at depths 0 (soil surface), 0.05, 0.10, 0.15, 0.20, and 0.40 m respectively. After installation of the instruments, trench was refilled with the soil. Volumetric water content (⍰$_v$) was determined by TDR 100 system (Campbell Lt. Co. USA) weekly. Soil temperatures (T) were recorded automatically by datalogger (CR10X, Campbell, USA) at hourly resolution.

Soil heat flux (H) and heat storage (S) are important components of the study on evaporation and surface energy balance. So, we calculated soil heat flux (at 2.5cm below soil surface) and soil heat storage in 0-10 cm for each treatment.

Soil heat flux by conduction through the soil is described by Fourier's Law

$$H = -\lambda\, dT/dz \qquad (1)$$

where λ is the thermal conductivity of the soil (W/m/K), and dT/dz is the vertical temperature gradient (K/m). Soil thermal conductivity was obtained by Lu et al. (2007) model,

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e - \lambda_{dry} \qquad (2)$$

where λ_{sat} is the thermal conductivity of the saturated soil (W/m/K). It related to soil porosity and thermal conductivity of soil solids. λ_{dry} is the thermal conductivity of dry soil (W/m/K), and it is a linear function of soil bulk density. K_e is the normalized thermal conductivity of the soil

$$K_e = \exp\{B[1 - S_r{}^{(B-C)}]\} \qquad (3)$$

where B is a soil texture dependent parameter (0.96), and C is a shape parameter (1.33). S_r is soil saturation.

Soil heat storage (W/m^2) is estimated based on the soil volumetric heat capacity (C_v) and temperature

$$S = \int_0^z C_v \frac{\partial T}{\partial t} dz \qquad (4)$$

where *z* is soil depth (m), *t* is time, and $\partial T/\partial t$ is soil temperature gradient with time (°C/s). Soil volumetric heat capacity is determined by the volumetric heat capacity and fractions of its component (the soil matrix, liquid water, and air). Since the density and specific heat capacity of air are very small relative to the other terms, the contribution of soil air is negligible (Campbell et al., 1991). So,

$$C_v = \rho_b c_s + \rho_w c_w \theta_v \qquad (5)$$

where ρ_b is bulk density (1.39 g/cm^3 in this study), ρ_w (1.0 Mg/m^3) and c_w (4.18 kJ/kg/K) are the density and the specific heat capacity of water, respectively, and c_s (0.85 kJ/kg/K) is the specific heat capacity of the soil solids.

Prior to crop harvest, wheat biological properties (e.g. spike numbers, crop height, spike length and biomass) per m^2 were recorded. And 40 spikes from each plot were collected randomly to determine grain numbers per spike. After harvest, Grains were air-dried, and yield and 1000 seed weight were determined.

Results and Discussion

Effects of rising temperature on soil thermal properties

The temporal and spatial variation of soil temperature

The results showed that the trend of temperature variation were almost the same in each soil layer. It was waved with the air temperature in the day and night time. Temperature and its difference between day and night time were high for the top soil, and kept stable for the deep soil. For the two fertilizer treatments, temperature and the magnitude of temperature increasing were comparable in each soil layer. Figure 1 showed that the temperature changes in soil surface and 40 cm depth during the first week at February and during the last week at May for HT and NT treatment. Soil temperature was increased by about 3-5 °C at soil surface, and 1-3 °C in the 40 cm for HT than for NT.

The effects of elevated temperature were obvious in night time with an increase of 4.5 °C. And temperature difference was 3.5 °C at noon. The temperature difference between HT and NT gradually decreased with air temperature increasing. The daily temperature difference was about 2-3 °C between HT and NT in May. Soil temperature became comparable at noon, even higher for NT. The highest temperature at the soil surface could reach to 45 °C during the last week of May. Soil temperature was about 20 °C at 40 cm depth, and temperature difference was 0-2 °C between HT and NT.

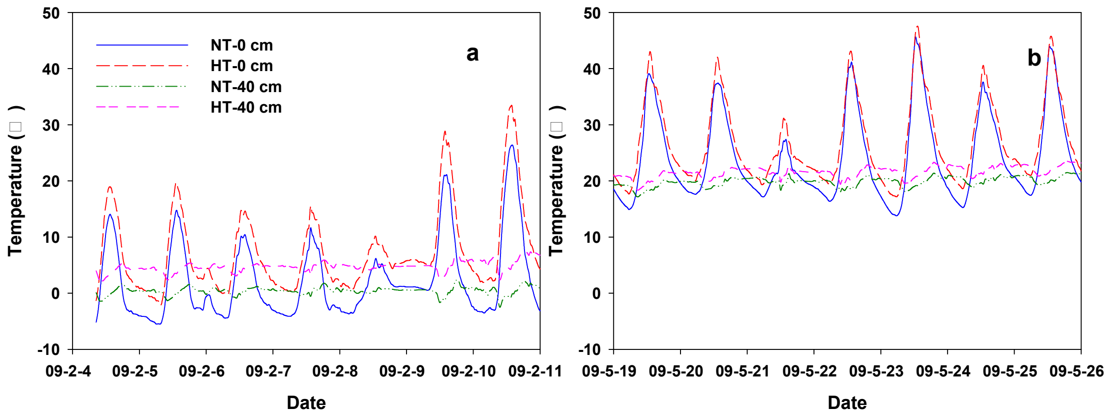

Figure 1. Comparison of temperature at soil surface and 40 cm depth between treatments of elevated temperature (HT) and normal temperature (NT).

Comparison of diurnal change for soil heat flux (2.5 cm depth) between warming and normal condition

Figure 2 shows the diurnal variation of soil heat flux at 2.5 cm and heat storage at 0-10 cm soil layer on 1 April and 20 May 2009 for HT and NT treatments. We found the trend of soil heat flux showed bell shape curve for HT and NT treatments. Soil heat flux was negative before 8:00 h and after 17:00 h. It indicated that heat energy transfer took place from the lower to the upper soil layers. The soil stored heat between 8:00-17:00 h, and the value of soil heat flux was positive. The maximum heat flux was up to 660 W/m^2 at 13:00 h (1 April) for HT treatment. Soil received the most heat energy during this time.

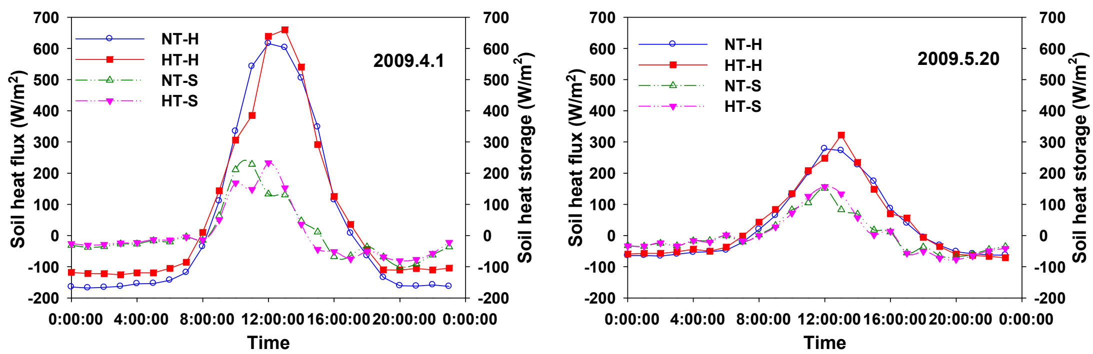

Figure 2. Diurnal change of soil heat flux (H, at 2.5 cm depth) and soil heat storage (S, 0-10 cm) for treatment of elevated temperature (HT) and normal temperature (NT).

Before mid-April, soil heat flux was significantly higher for HT than for NT, with an average difference of 31 W/m^2 (1 April). Warming increased the heat input to the inside of soil profile. Heat flux differences were obvious before 8:00 h and after 17:00 h. The estimated heat flux was large from Equation (1) due to relative large vertical temperature gradient at night. After mid-April, the differences of soil heat flux were gradually reduced between the HT and NT. And 20th May the average difference of daily heat flux between HT and NT was only 3.0 W/m^2. The main reason might be the effect of warming was weakening, and the vertical temperature gradient in the 0-5 cm soil decreased with the temperature increasing.

Comparison of diurnal change for soil heat storage (10 cm depth) between warming and normal condition

From Fig. 2, the differences of soil heat storage did not exist between NT and HT. Heat storage in soil (0-10 cm) was positive at 9:00 h, and then it showed a rapid growth along with increasing soil temperature. Soil heat storage reached the maximum at about 11:00 h and then decreased rapidly. However, it was still positive and soil temperature continued to rise. After 16:00 h heat storage in the soil was negative and soil temperature decreased. In our study, soil heat storage was estimated using the daily average of soil heat capacity. So, the daily changes in heat capacity were ignored.

The infrared radiators could be applied in field to simulate global warming as soil temperature could be increased up to 1-2 °C at 40 cm depth. The effect of the elevated temperature is consistent with the temperature change of global warming. The temperature difference was larger in nighttime than in daytime, and was greater in winter than in summer. Warming increased soil heat flux, and not influence soil heat storage. So, experimental ecosystem warming influenced the sensible heat, latent heat and energy balance of ground surface

Temperature rising effects on the temporal and spatial variation of soil water distribution

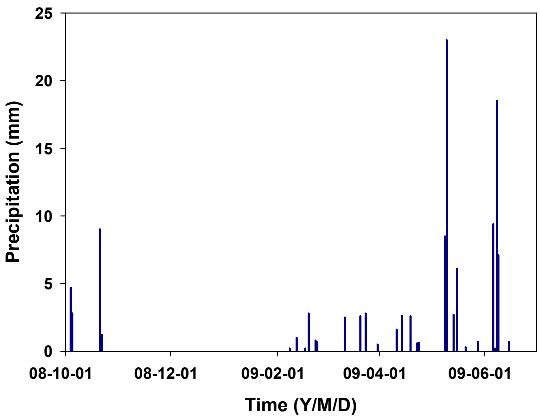

Figure 3. Precipitation in winter wheat growth season.

Figure 3 showed the precipitation in winter wheat growth season. The rainfall was only 117 mm during the whole season, with 73% of total precipitation occurring in the later growth stage (after Apr.). Figure 4 Compared water storage in soil profile (0-60 cm) between HT and NT. Before mid-April, water content and storage were lower for HT than for NT. Soil water storage decreased by 8% and 20% in comparison with NT for two fertilizer treatments (N1 and N5) respectively. Wheat field was always under the warming conditions. Micro-climate environment and the soil temperature were relatively high. Thus soil evaporation increased for HT treatment, and rising temperature accelerated the growth of winter wheat. The growing stages were ahead of time compared with NT. Plant transpiration was also improved for HT treatment. Therefore, the increased evapotranspiration reduced soil water content and storage for HT treatment.

However, after mid-April, wheat entered the maturity stage for HT treatment with air rising temperatures. Roots water uptake and then transpiration water loss decreased. While wheat growth continued for NT treatment, and water consumption of wheat increased. Therefore, soil water content and storage were lower for HT treatment than for NT treatment after mid-April. Soil water content and storage decreased by about 7% for N1 treatment. Zavaleta et al. (2003) also found that simulated warming increased spring soil water content by 5-10%. He suggested that lower transpiration water loss resulting from earlier senescence provided a mechanism for the unexpected rise in soil water content.

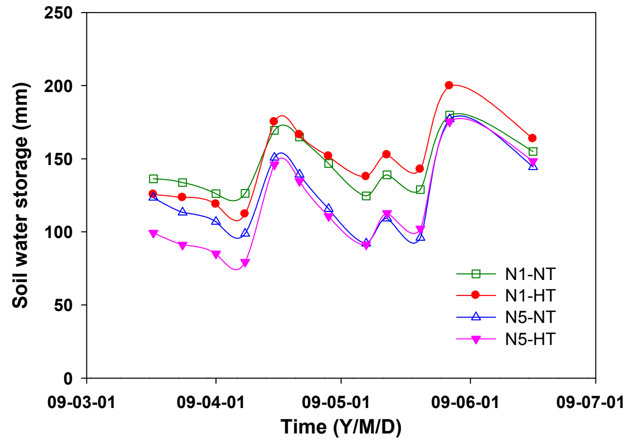

Figure 4. Comparison of water storage in soil profile (0-60 cm) for treatment of elevated temperature (HT) and normal temperature (NT).

For HT and NT treatments, soil water content was lower in top soil than in deep soil. Water content increased with depth increasing (Fig. 5, 2009.4.1 and 5.20). Correspondingly, we found that before mid-April soil water content was lower for HT than for NT at every soil layers. And water content differences were large in the top soil, with the average difference of about 0.02 cm^3/cm^3 for the 5-20 cm soil. The main reason might be water loss of top soil from evaporation was fast in wheat field of HT due to a relatively high temperature in comparison with NT. Additionally, the most of wheat roots mainly distributed in 0-20 cm soils. Water content loss by root uptake was increased for transpiration in HT treatment. The difference of water content was the smallest at soil layer of 60-cm between HT and NT, with an average of 0.01 cm^3/cm^3. The effect of warming conditions on water content of deep soil was small. However, after mid-April, soil water content was higher for HT treatment than for NT treatment (Fig. 5b). And the difference of water content was the smallest at the 60-cm depth. Possible reason was high temperature induced earlier plant senescence, and then crop transpiration decreased. While for NT treatment winter wheat was in a thriving growth period due to lower temperature. Crop transpiration was strong, thus resulting in soil water content lower than for HT treatment.

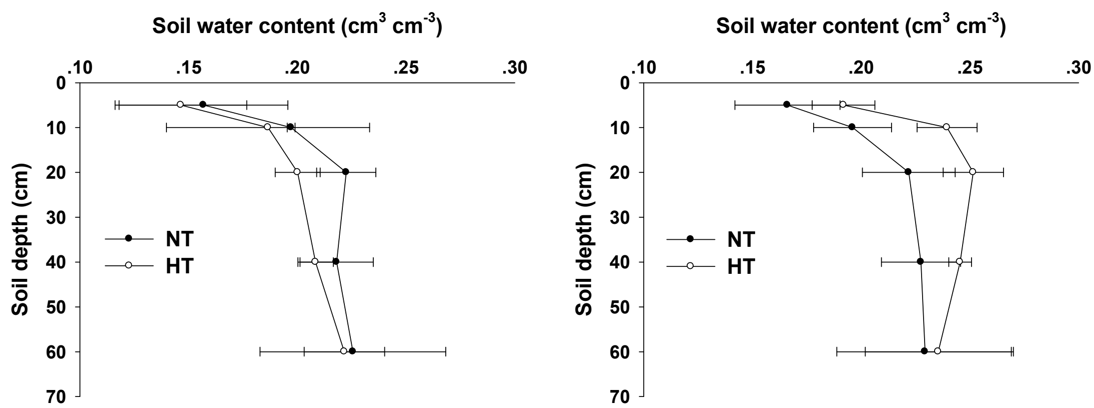

Figure 5. Comparison of soil water content in soil profile for treatment of elevated temperature (HT) and normal temperature (NT).

Effects of temperature rising on winter wheat growth and yield

Warming effects on biological properties of winter wheat

Rising temperature altered soil water and thermal distribution, and, it could influence crop demands for water and heat. Our observations showed the growth stages of winter wheat were ahead of time for HT than NT treatment. Winter wheat kept growth for HT treatment even during the wintering period. Plant height was 10-15 cm higher for HT than for winter wheat of NT. Table 1 listed the comparison of biological parameters of winter wheat under HT and NT treatment. Under no fertilization condition, rising temperature increased plant height (1.2 cm) and spike length (0.7 cm) of winter wheat. Number of tiller were not influenced by temperature due to fertilizer limitation. Under 240 kgN/ha condition, plant height, spike length and tiller number increased 5 cm, 0.4 cm, and 1.4 for HT treatment, respectively. Temperature rising, especially at late autumn and early winter, could improve the condition of winter wheat for over-wintering. And it shortened the time for wheat growth ages. Meantime, cell divisions of winter wheat and plant growth were accelerated, which benefited to winter wheat tiller.

Table 1. Comparison of biological indicators of winter wheat between treatment of elevated temperature (HT) and normal temperature (NT).

Treatment	Plant height	Tiller	Spike length	Maturing rate	Biomass aboveground	Harvest index
	cm		cm	%	g/m^2	
NT-N1	63.10±3.68a	1.0±0.1a	5.54±0.14a	0.81±0.02a	699.71±163.56a	0.40±0.04a
HT-N1	61.91±2.61a	1.0±0.1a	4.83±0.32b	0.70±0.02b	517.71±128.59a	0.33±0.03a
NT-N5	71.47±3.02a	2.0±0.2a	5.84±0.04a	0.80±0.05a	1156.03±263.31a	0.50±0.04a
HT-N5	76.49±6.53a	3.4±0.6b	6.21±1.04a	0.78±0.04a	1099.85±248.39a	0.40±0.04b

Besides growth period of winter wheat, temperature also influenced aboveground biomass accumulation and winter wheat growth. Results showed that the elevated temperature during the growth period reduced biomass by 26% and 11% for N1 and N5 treatment, respectively. And harvest index of winter wheat reduced by 7% and 10%, respectively. These were attributed to the shortened growth period and dry matter accumulation time caused by increasing temperature. Compared with NT, senescence of winter wheat occurred early for HT, and the harvest time was shortened. Harvest date of winter wheat is June 2, 2009 for HT, while June 14, 2009 for NT. The growth period of winter wheat was shortened about 10 days. This might be related to the mineralization of soil organic matter and nutrient loss acceleration, and plant roots senescence caused by soil temperature rising. From this study, we also found that increased nitrogen fertilization might compensate the negative effect of rising temperature on winter wheat, which needs further study.

Warming effects on yield and its components of winter wheat

Table 2 compared the yield and its components of winter-wheat between warming and normal temperature treatment. The results showed that rising temperature had a negative effect on spikes numbers and grains per spike irrespective of N fertilizer. Temperature rising decreased spikes per mu by 10%, not up to significant level. The grains per spike decreased significantly ($P \leq 0.05$) by 30%. Temperature rising reduced the maturing rate by 10% and 2% for N1 and N5 treatments respectively. The reason might be high temperature caused the sterility of winter wheat during heading and flowering stage. So, the empty shells increased. However, rising temperature increased thousand grains weight of winter wheat by 7% and 16% for N1 and N5 treatment. But the yield of winter wheat decreased by 25% for HT treatments compared with NT, not up to the significant level. A possible reason was that the every grain was filled fully due to the reduction of grains number in fertilization. Another probable reason is the filling time and rate might have effects on thousand grains weight (Xia et al., 2003; Hu et al., 2008). Many studies found that the suitable temperature range for winter-wheat filling was 18-22 °C. If the daily mean temperature was up to 30 °C, grain filling time would be shortened, which resulted in inadequate filling and lower thousand grains weight. In our study, the daily mean temperature was 20.2 °C in the late growth stage of wheat for NT. It closed to the upper limitation of the suitable temperature range. So, the grain filling time for wheat was shortened. Conversely, the grain filling stage was ahead for HT due to temperature rising. Relatively the longer grain filling stage increased thousand grains weight. It, however, did not make up the decreased yield resulting from the decrease of spikes per mu and grains per spike. Therefore, the main reason for yield decreasing was the reduction of spikes per mu and grains per spike

Table 2. Comparison of yield and its components between treatment of elevated temperature (HT) and normal temperature (NT).

Treatment	Spikes per mu	Grains per spike	1000 grains weight	Yield
	Ten thousand spike	grain	g	kg/ha
NT-N1	16.98±2.70a	31.27±5.84a	46.77±1.39a	2751.14±405.41a
HT-N1	15.47±1.39a	19.23±3.19b	49.83±1.66a	2067.43±560.69a
NT-N5	40.59±3.15a	36.67±3.22a	36.24±6.65a	5931.57±1200.82a
HT-N5	34.41±5.70a	26.35±3.74b	42.15±5.52a	4376.43±638.14a

Conclusion

This study showed that the infrared radiators applied in field simulated climate warming during the growth season of winter wheat. The results showed that the temperature was increased by about 1 to 4.5 °C in the soil profile of 0-40 cm, and the difference was larger in night than during day time. The magnitude of elevated temperature was reduced with rising atmosphere temperature. The passive nighttime and winter warming is consistent with the current IPCC assessment. Warming increased soil heat flux, but soil heat storage was not influenced. Moreover, the elevated temperature changed water distribution and storage in soil profile. Before mid-April, soil water content and water storage were lower for the elevated temperature treatment than for normal temperature treatment. However, after mid-April, the elevated temperature produced the reverse effect on soil water content and water storage.

Warming accelerated winter wheat growth, and shortened the growth season by about 10 days. Meanwhile, warming increased the key biological parameters of winter wheat, e.g. plant height and spikes length, under no fertilizer limitation. Elevated temperature decreased biomass, spikes per mu and grains per spike of wheat. In the field of elevated temperature, thousand grain weight of winter wheat was increased, while winter wheat yields decreased by 25%. In addition, N fertilizer could improve the biological parameters of winter wheat in the warming field. The yield of winter wheat, however, was lower for the warming treatment than for normal condition. Therefore, it is necessary to adapt crop planting time, fertilizing schedule and supplemented irrigation to overcome the effects of global warming.

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