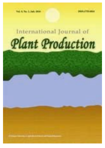

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Actual impacts of global warming on winter wheat yield in Eastern Himalayas

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Abstract

Himalayas, are among the areas most vulnerable to global warming, however, little is known about warming impacts on the crops. Therefore, the actual affects of anticipated warming on winter wheat were tested in Tibet, China. During the period 1988-2012, Tibet region has experienced a large increase in daily mean, minimum and maximum temperatures during wheat growing seasons by 0.50, 0.67 and 0.51 ^{o}C every ten years, respectively. The de-trended wheat yield increased by 34.4 kg ha^{-1} year^{-1} during this period. According to the historical data, 1 ^{o}C increase in daily mean temperature could get 370.6 kg ha^{-1} gain in wheat yield. Similar gains in wheat yield were found in a field warming experiment with an increase of 1.1 ^{o}C in daily mean temperature. The field warming caused a significant reduction in the pre-anthesis phase and entire growth period by 14 and 13 days, respectively. The green leaf areas and spike number in the warmed plots were significantly higher than that in non-warmed plots, while the grain number per spike was significantly lower in the former than the later ($P<0.05$). The main mechanism underlying the positive affects of this moderate warming on wheat yield is through improving plant development and growth during the pre-anthesis phase by mitigating the low temperature limitation. This study suggests that further efforts should be directed towards the improvement on agriculture infrastructure to utilize the positive affects of climatic warming on crop production.

Keywords: Climate change; Food security; Free air temperature increase; Tibetan Plateau; Wheat cropping.

Introduction

Global warming has been and is expected to be the strongest in high altitude mountain areas like the Himalayas (IPCC, 2007; Xu et al., 2009), where they are seriously ecologically fragile and economically marginalized (Gentle and Maraseni, 2012). The mountain region, one of the least developed regions in the world, is among the areas most vulnerable to global warming (IPCC, 2007; Martin et al., 2010). Since Himalayas are the origin of ten of the largest rivers in Asia, many researches have been conducted to detect the impacts of warming on forest and grass lands (Yi and Yang, 2007; Shrestha et al., 2012) and water cycle (i.e. changes in snow line and glacier) (Shrestha et al., 2000; Xu et al., 2009). These studies have greatly enhanced our knowledge about the implications of global warming in Himalayas to natural ecosystems and people livelihoods out of the mountain areas. For the indigenous people, however, more than 80% population depends on subsistence agriculture for their livelihoods (Macchi et al., 2011). Therefore, exploring the impacts of global warming on indigenous crop production will be important to make decisions and devise strategies for food security and crops adaptation in Himalayas.

Recently, many efforts have been made on air temperature increase effects on grain yield and crop growth (Aronson and McNulty, 2009; Wei et al., 2014; He et al., 2015). Theoretically, increase in temperature might reduce the crop growth period, likely leading to decrease in grain number and weight (Al-Khatib and Paulsen, 1999; Wang et al., 2014). For instance, according to historical data analysis, Lobell et al. (2011) found that global wheat yield decreased by 5.5% from 1980 to 2008 due to increased temperatures. Other modeling researches in China also showed that an increase of 1 ◦C in mean daily temperature might decrease wheat yield by 0.5% (You et al., 2009). However, warming might also directly reduce frost/chilling before flowering and indirectly avoid high temperature stress after flowering due to warming-led earlier anthesis (Sadras and Monzon, 2006; Wang et al., 2008). Therefore, a moderate increase in air temperature might benefit winter wheat production with higher yield in China, where chilling damage before flowering and heat injury after flowering usually happened. Moreover, Xiao et al. (2008) and Sommer et al. (2013) predicted that climate warming could mostly benefit wheat production in China and Central Asia, respectively. Nevertheless, there are still uncertainties associated with the crop modeling studies on wheat production. And it is difficult for the present models to predict the wheat production under climatic change conditions, particularly because these models may not well covered some of the effects of extreme climatic factors (Aronson and McNulty, 2009). Thus, relevant field and experimental evidences are essential to predict climate change effects on wheat productivity.

Recently, a few experiments were conducted to simulate the affects of climate warming on crops in the growth chambers and greenhouse, which can change environmental parameters for plant grown in these controlled environment systems (Nijs et al., 1996; Aronson and McNulty, 2009; Wall et al., 2011). Although some studies were conducted under field conditions, they were mainly executed for a short period, such as the post-anthesis period (Slafer and Rawson, 1995; Larmure et al., 2005; Gregersen et al., 2008), or even only for several days post-anthesis (Savin and Nicolas, 1996). Furthermore, the setting of temperature increment in most experiments was often higher than the warming rate predicted by climate models (Savin and Nicolas, 1996; Aronson and McNulty, 2009; Shah et al., 2014), which in the case may not exactly represent the expected increase in the near future. The impact of global warming on winter wheat growth might be overestimated by existing observations and projections. It implies that a system which can increase the temperature at a moderate level over the entire growth period under field conditions is required to assess the effects of climate warming on future wheat production (Rehmani et al., 2011).

Winter sown wheat and barley are becoming the major staple crops in Eastern Himalayas. During the period 1985-2012, for example, the sown area and the production of winter wheat have increased 81.3 and 125.9%, respectively in Tibet, China. Meanwhile, winter cereal crops are predicted to be most likely affected by warming because air temperature increase is the strongest during winter and spring seasons (IPCC, 2007). Tibet is a typical area of Eastern Himalayas. As far as we know, there is a lack of convincing arguments about the influence of warming on winter crop production. Based on historical data from 1988 to 2012, a multiple regression analysis was adopted to study the relationship between wheat yield and the key climatic factors (i.e. temperature and precipitation). Meanwhile, we used a facility of free air temperature increase to simulate the predicted warming level to test the actual effects on wheat productivity. The objective of the integrated study was to examine the realistic affects of air temperature increase on winter wheat yield in Tibet, China.

Materials and Methods

Study site description

The study site is in East Tibetan Plateau, comprising Lhasa, Qamdo and Shigatse Prefectures, Tibet Autonomous Region, China (Figure 1). This area is classified as semi-arid plateau temperate monsoon climate. The elevation ranges from 3800 to 4200 m above sea level. The mean values of daily mean, maximum and minimum temperatures are respectively 5.6, 13.6, -1.0 ^{o}C with an accumulated temperature above zero ranging from 2100-3200 ^{o}C. The annual precipitation is reaching 310-520 mm and the frost-free period is from April to August. The major staple crops are winter wheat, barley and corn.

In order to detect the effects of warming on wheat growth, a field warming experiment was conducted in Caigongtang town, Lhasa city, China (29° 64′ N, 91° 22′ E, 3673 m above the sea level) (Figure 1). The experimental site is a typical location of winter wheat cropping in Tibetan Plateau. The facility of Free Air Temperature Increase (FATI) was performed from October 2011 to August 2012 for the entire growth period of winter wheat. The field warming facility was designed according to our previous experiment (Zhang et al., 2005; Tian et al., 2012), which has been successfully used to explore warming impacts on plant growth at ecosystem scale (Wan et al., 2002). The annual precipitation at the experiment site was 442 mm with a daily mean temperature 7.8 ^{o}C. The sunshine hours were 3100 h with 110 frost-free days. During the period of winter wheat growing seasons, the precipitation was ca. 260 mm. The soil type was classified as a silty loam soil. Other relevant soil properties were: pH 7.0; organic matter content 21.8 g kg^{-1}; total N 0.8 g kg^{-1}; available K 71.0 mg kg^{-1} and available P 31.2 mg kg^{-1}.

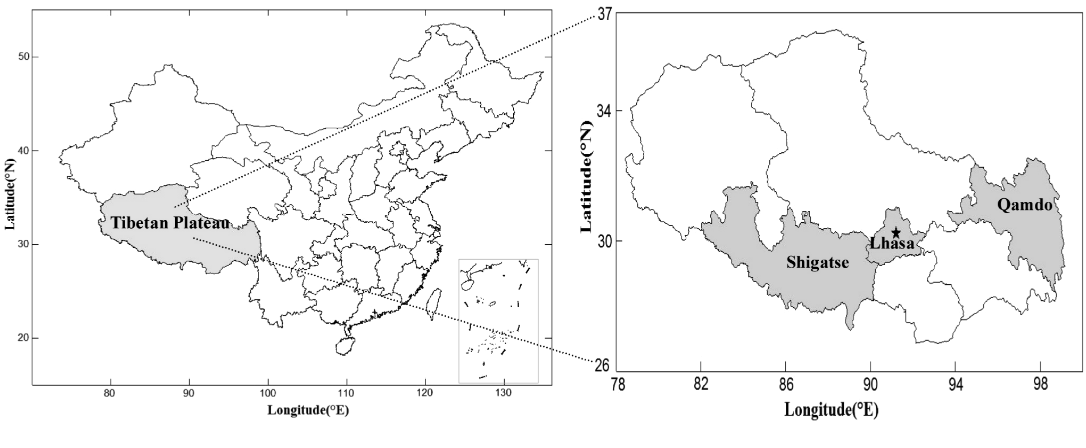

Figure 1. Spatial locations of the study areas (filled area) and experimental site (★) in Tibetan Plateau, China.

Historical database and analysis methods

Two historical databases were used in this study, including Chinese Meteorological Administration (CMA archives, 2010) for climate database and Planting Information Network of China (PINC archives, 2010) for wheat yield database. Based on the completeness of the records from 1988 to 2012, we selected three meteorological observation stations of Lhasa, Qamdo and Shigatse. Daily precipitation and maximum, minimum and mean temperatures during the wheat growth seasons (from October to August) were used to study the relationship between wheat yield and climatic factors. The data of winter wheat yields for the three study areas from 1988 to 2012 were acquired from PINC. The PINC data were collected by enumerators according to the facts, filled in the census forms in a truthful and timely manner at and above county level and then checked by the National Bureau of Statistics.

The annual temperatures (mean, maximum and minimum temperature) from 1988 to 2012 were the daily temperature average value and the annual precipitation was total value of daily precipitation during the winter wheat growing season. Based on the historical data, a linear trend model was used to analyze the relationship between wheat yield and climatic factors from 1988 to 2012. Because of improvements in genetics and cultivation techniques, the winter wheat yield shows increase trends (Hu and Buyanovsky, 2003), thus, crop yield time series must be de-trended with some method. In this paper, the piecewise line regression method (Goldblum, 2009) and Mann-Kendall method (Kendall and Gibbons, 1990) were adopted to remove the yield trend. Hence, the left part may be hypothesized to indicate the actual impacts of climatic factors.

The mean and minimum temperature anomalies of the entire growing season and winter wheat yield anomaly from 1988 to 2012 were calculated as the differences between observed and average values. Pearson correlation coefficients were adopted to indicate the relationship between the climate factors (i.e. temperature and precipitation) and de-trended wheat yields.

Field experimental design and crop management

Field warming experiment used a completely random design with three replicates, including two treatments of warmed and non-warmed. The infrared heater (180 cm in length and 20 cm in width) with 1500 W was suspended above by 1.5 m in each warmed plot. In each non-warmed plot, a 'dummy' heater with the same shape was also suspended 1.5 m above the ground to mimic the shading effects. The distances between plots were five meter to avoid heat contamination. The warming treatment was performed from the sown date to the harvest date. The FATI system has been tested and successfully used in winter wheat field, East China (Tian et al., 2012) and in grassland, USA (Wan et al., 2002). Each replicate plot size was 30.0 m^2 and the FATI facility could provide about a 2 m × 2 m area with reliable warming effects. Plant and soil samples were done in the 4 m^2 area of each replicate plot.

The tested wheat variety was Shandong 6 (*Triticum aestivum* L. cv Shandong 6), which is a leading local cultivar in the study area. Common agronomic practices, such as fertilization and irrigation, were conducted in all warmed and non-warmed plots with a same regime. Wheat seeds of the test varieties were manually sown on 26 October, following the recommended density of 180 plants m^{-2} and maintaining spacing of 20 cm between rows. Fertilizers were used for each of the treatments at the rate of

210 kg N ha^{-1}, 100 kg P_2O_5 $ha^{-1}$and 80 kg K_2O ha^{-1}, respectively. All P and K fertilizers and half of N fertilizer were applied as basal dressing two days prior to sowing. The remaining N fertilizer was added as a side dressing at jointing stage of the cultivars. Due to the irrigation, there was no soil moisture limitation to wheat growth in all plots.

Field sampling and measurement methods

Temperatures and soil moisture: Across the experimental duration, wheat canopy air temperature and field soil temperature were automatically measured at a 30 minute interval by a digital monitor system. Each monitor system owned two monitors, one was on the wheat canopy and the other was in the soil layer of 5 cm. The field topsoil (0–20 cm) was sampled from each treatment at wheat anthesis and maturity stages. In each treatment, six cores (5 cm in diameter) were taken and then mixed as a composite sample. The composite samples were weighed wet and dried for 48 h in an oven set at 105 °C and weighed again to calculate the soil water content (Ferraro and Ghersa, 2007).
Plant sampling and determinations: At flowering, 15 plant samples were taken to examine the aboveground biomass production and leaf area, respectively. Green leaf area per stem (GLA) was calculated with the following formulae (Zhao, 1986; Li et al., 2004).

$$GLA = \{ [(L_1 \times B_1) + (L_2 \times B_2) + \cdots + (L_{n-1} \times B_{n-1}) + (L_n \times B_n)] \times 0.75 \} / n$$

where, L and B are the length and breadth of each leaf, respectively, n was the total number of green leaves harvested and 1, 2, 3, ., ., n-1 and n^{th} leaf.

At harvesting, 15 stems were taken from each plot and were oven-dried at 75 °C for about 48 h to determination of total biomass production. The grain yield and yield components were measured by harvesting 1 m^2 wheat plants after maturity.

Statistical analysis

Analysis of variance (ANOVA) for randomized block design was used to examine the effects of warming in the experiment. The means were compared using Least Significant Differences (LSD) and significant differences were considered at $P<0.05$. All statistical analyses were conducted using SPSS 11.5 statistical software.

Results

Variations of air temperatures and precipitation

During 1988–2012, Tibetan Plateau experienced a significant climate changes in air temperature and precipitation from October to August (Figure 2). In Lhasa (Figure 2a), the mean values of daily mean temperature (T_{avg}), daily minimum temperature (T_{min}) and daily maximum temperature (T_{max}) were respectively 7.07, -0.12 and 15.50 °C during wheat growing seasons. The increments in T_{avg}, T_{min} and T_{max} were 0.55, 0.81 and 0.51 °C every ten years, respectively. In Qamdo (Figure 2b), the mean values of T_{avg}, T_{min} and T_{max} were respectively 5.73, -0.99 and 14.28 °C. The temperatures of T_{avg}, T_{min} and T_{max} increased by 0.42, 0.57 and 0.50 °C every ten years, respectively.

In Shigatse (Figure 2c), the mean values of T_{avg}, T_{min} and T_{max} were respectively 6.04, -1.58 and 14.16 °C, with an increase by 0.52, 0.62 and 0.51 °C every ten years, respectively. The mean increases in T_{avg}, T_{min} and T_{max} per 10-year period were 0.50, 0.67 and 0.51 °C, respectively, in Tibetan Plateau.

Across the past twenty-four years, large variations were found in seasonal precipitation during wheat growing seasons (Figure 2d). The highest and the lowest amounts of precipitation were respectively 401 and 129 mm in Lhasa, 444 and 182 mm in Qamdo and 374 and 119 mm in Shigatse. The mean values of precipitation during wheat growing seasons were 259.9, 318.9 and 243.6 mm, respectively in Lhasa, Qamdo and Shigatse during 1988-2012. No significant increasing or decreasing trend was found in the amount of precipitation in Tibetan Plateau since 1988.

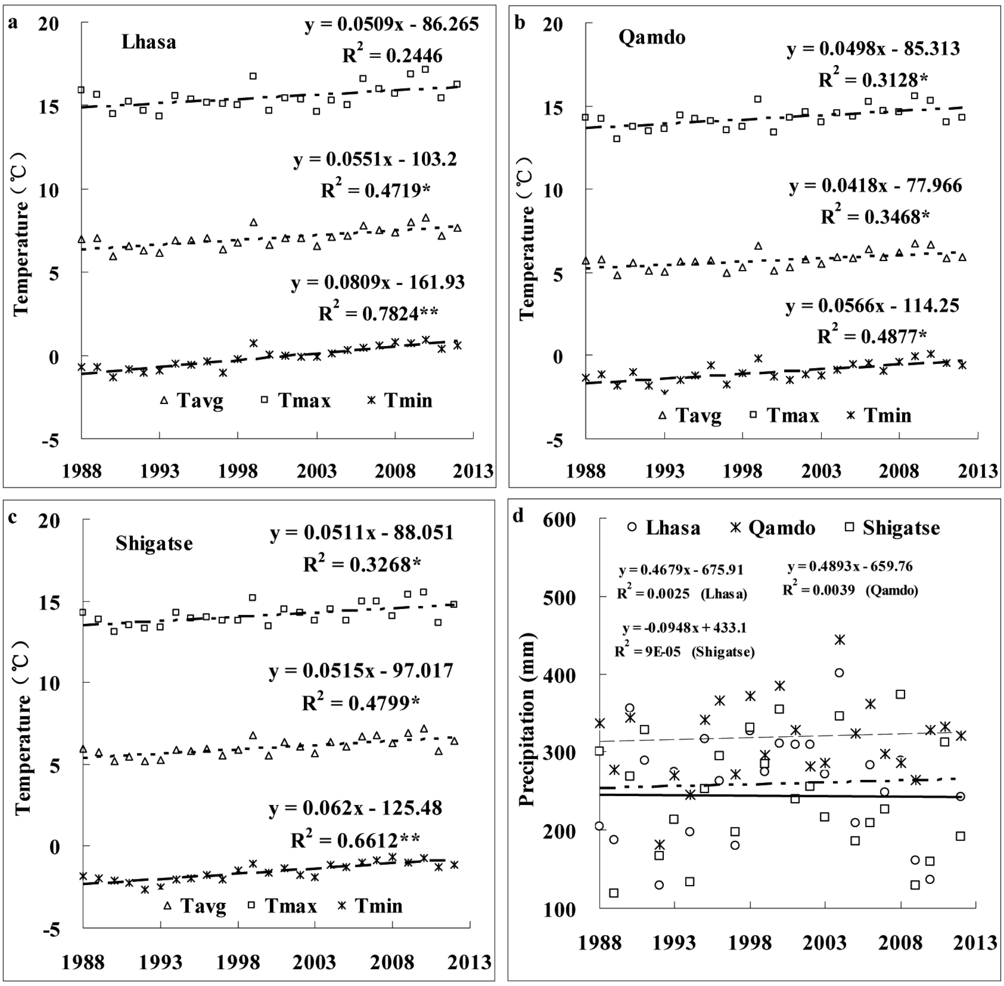

Figure 2. Variations in air temperatures in Lhasa (a), Qamdo (b) and Shigatse (c) and changes of precipitation (d) during wheat growing seasons across 1988-2012 in Tibetan Plateau. * and ** indicate significant at P<0.05 and at P<0.01 levels, respectively.

Historical trends of wheat yield variations

According to the historical data, Tibetan Plateau has got a great success in the improvement of wheat yield since 1988 (Figure 3). The increases in the actual yields were 204.7, 98.6 and 327.0 kg ha^{-1} $year^{-1}$ in Lhasa, Qamdo and Shigatse (Figure 3, P<0.01), respectively. To detect the realistic contribution of climate change to the variation of wheat yield, the contributions of agronomic technique innovation (i.e. modulating sown date and crop mode and using high-yield and heat resistant varieties) to wheat yield were moved out using the piecewise-line regression and first difference method (Goldblum, 2009). After removing the technique contributions, greatly increasing trends of de-trended yields were found with annual increment of 20.1 kg ha^{-1} in Lhasa (Figure 3a), 19.8 kg ha^{-1} in Qamdo (Figure 3b) and 63.2 kg ha^{-1} in Shigatse (Figure 3c) since 1988.

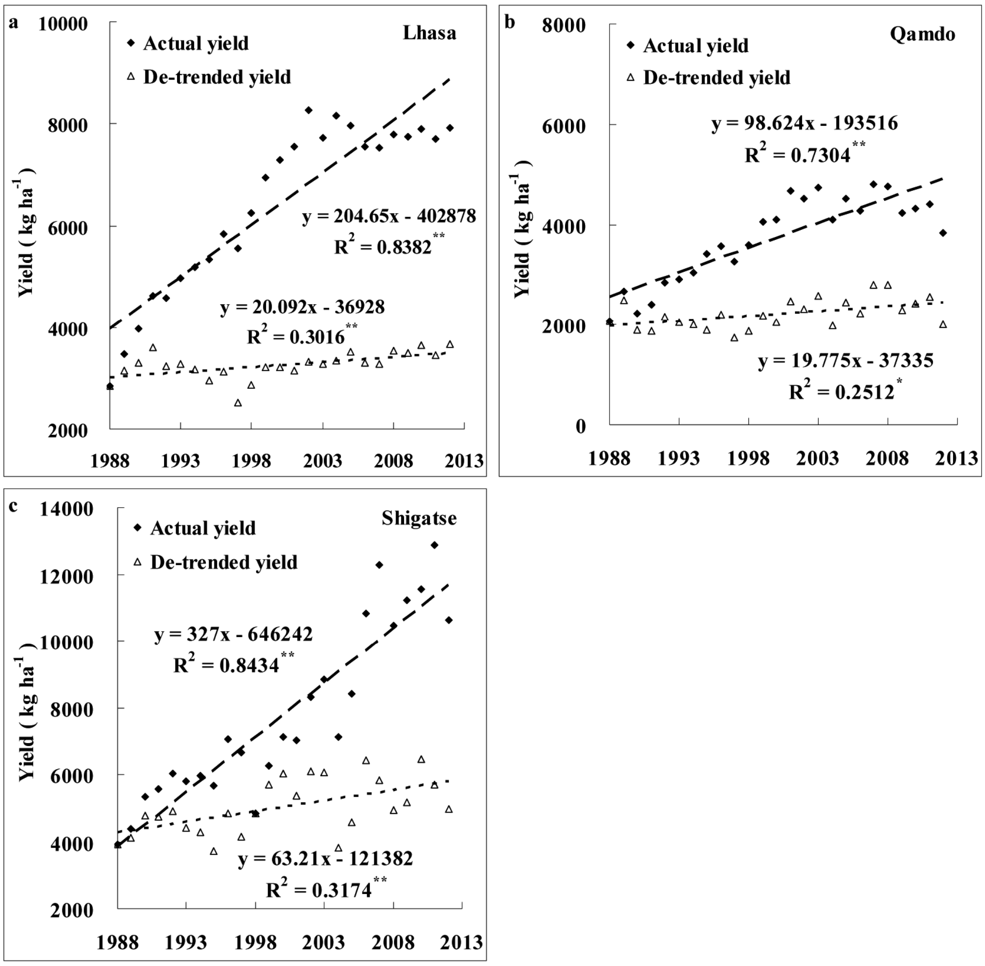

Figure 3. Variations in wheat yields in Lhasa (a), Qamdo (b) and Shigatse (c) during 1988 - 2012 in Tibetan Plateau. * and ** indicate significant at P<0.05 and at P<0.01 levels, respectively.

Correlations between wheat yield and climatic factors

For both the actual wheat yield and de-trended yield, significant correlations were found between wheat yield and T_{avg} and T_{min} in the three locations (Table 1). No significant impacts of precipitation changes were found on actual wheat yield and de-trended wheat yield. Therefore, an anomaly analysis was conducted between the daily mean and minimum temperature and the de-trended wheat yield (Figure 4). Significant correlations were found between the de-trended wheat yield anomaly and the daily mean temperature and minimum temperature anomaly in the three locations.

De-trended wheat yields increased by 217.2 and 192.7 kg ha^{-1} in Lhasa (Figure 4a), by 239.7 and 207.1 kg ha^{-1} in Qamdo (Figure 4b) and by 654.9 and 659.0 kg ha^{-1} in Shigatse due to a raise of the daily mean and minimum temperature by 1 ^{o}C, respectively (Figure 4c).

Table 1. Correlation coefficients between climatic factors and wheat yield in Tibet, China.

Location	Wheat yield	Daily mean temperature	Daily maximum temperature	Daily minimum temperature	Precipitation
Lhasa	Actual yield	0.576**	0.326	0.828**	0.220
	De-trended yield	0.423*	0.301	0.545**	0.020
Qamdo	Actual yield	0.472*	0.522**	0.557**	0.010
	De-trended yield	0.431*	0.413*	0.426*	-0.282
Shigatse	Actual yield	0.622**	0.520**	0.709**	-0.109
	De-trended yield	0.434*	0.374	0.447*	-0.001

* and ** indicate significant at P<0.05 and P<0.01 levels, respectively.

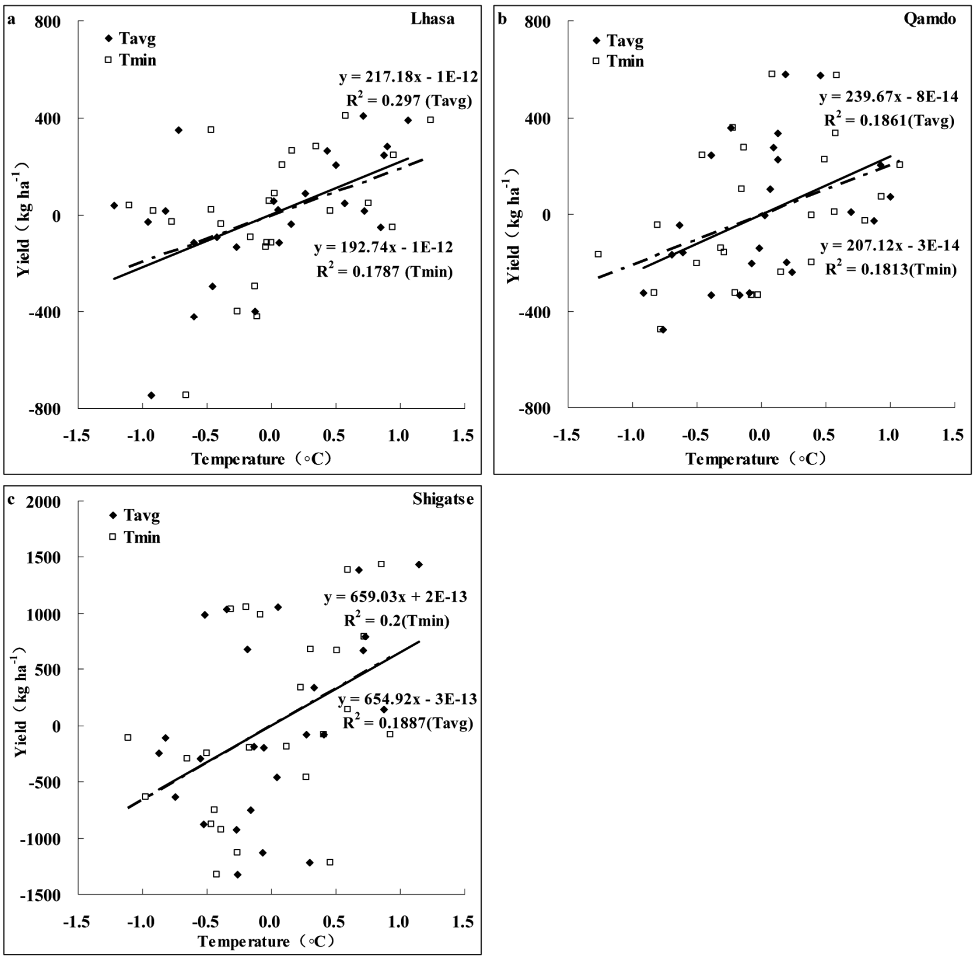

Figure 4. The relationships between de-trended wheat yield anomaly and mean and minimum temperature anomaly in Lhasa (a), Qamdo (b) and Shigatse (c) during 1988-2012 in Tibetan Plateau. * and ** indicate significant at P<0.05 and at P<0.01 levels, respectively.

Warming effects of FATI facility

To evidence the positive effects of air temperature increase on wheat production in Tibetan Plateau, a field warming experiment was conducted with a FATI system in Lhasa. This facility was able to increase the daily mean temperature in the soil layer of 5 cm and on the wheat canopy by about 2.1 and 1.1 °C, respectively, from the sown date to the harvest date (Figure 5a, b). Similar trends of seasonal and diurnal variations in air temperature and soil temperature were found between the different treatments (Figure 5c, d). Warming reduced soil water contents at the surface layers of 0–20 cm by 5.5 and 3.0% at anthesis and maturity stage, respectively. However, there were no significant differences between the non-warmed and warmed plots.

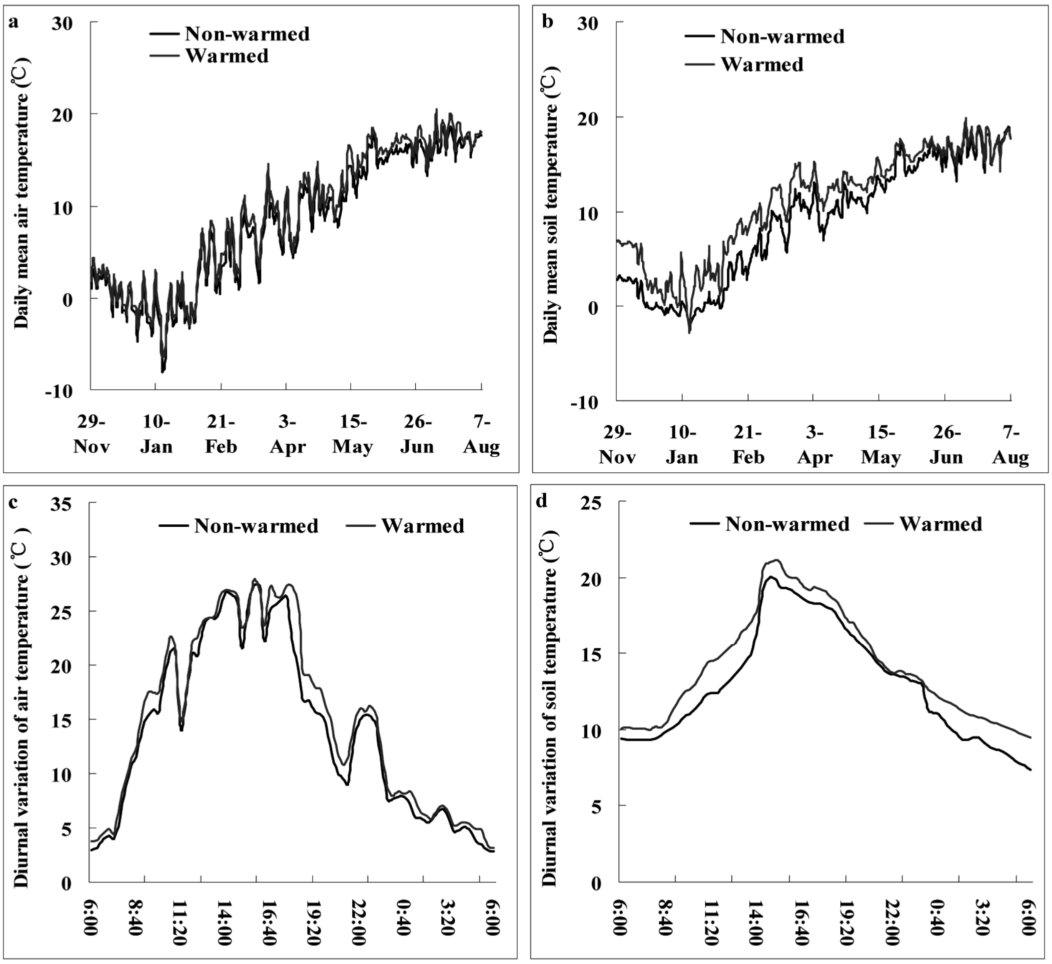

Figure 5. Seasonal variations in daily mean temperature on wheat canopy (a) and in soil layer of 5 cm layer (b) and diurnal variations in temperature on wheat canopy (c) and in soil layer of 5 cm (d) in the warmed and non-warmed plots under the Free Air Temperature Increase facility. The diurnal temperature variations were monitored at anthesis.

Actual responses of wheat productivity and phenophase

An increase of 1.1 °C in wheat canopy air temperature enhanced winter wheat growth significantly (Table 2). Wheat grain yield and aboveground biomass in the warmed plot were respectively 8.1% and 11.6% higher ($P<0.05$) than that in the non-warmed plot. The productive spike number in the warmed plot was 31.2% higher than that in the non-warmed plot, however, experimental warming reduced the 1000-grain weight and filled grain number. The decrease in the 1000-grain weight and the filled grains was respectively 6.0% and 13.3% as compared to the control.

Significant impacts of warming were found on the dates of winter wheat phenophase (Table 2). An increase of 1.1 °C in daily mean air temperature greatly advanced wheat anthesis, resulting in a decrease of pre-anthesis period by 14 days. However, the post-anthesis period was prolonged by 1 day. Consequently, the entire wheat growth period was curtailed 13 days in the warmed plot.

Table 2. Wheat phenophase dates and durations, plant productivity and yield components in the warmed and non-warmed plots under the Free Air Temperature Increase facility in Lhasa.

Treatment	Non-warmed	Warmed
Sown date (dd-mm)	26-October	26-October
Anthesis date (dd-mm)	16-Jun	2-Jun
Maturity date (dd-mm)	7-Aug	27-Jul
Length of pre-anthesis period (day)	234	220
Length of post-anthesis period (day)	52	53
Length of entire growth period (day)	286	273
Grain yield (g m^{-2})	880.0 ± 24.66[b]	951.7 ± 22.05[a]
Aboveground biomass (g m^{-2})	2135.0 ± 52.37[b]	2382.8 ± 40.39[a]
Productive spike no. (spike m^{-2})	353.7 ± 4.38[b]	464.0 ± 0.76[a]
Grain number (grain $spike^{-1}$)	47.3 ± 0.89[a]	41.0 ± 0.39[b]
1000-grain weight (g)	55.0 ± 0.72[a]	51.7 ± 0.88[a]

Data are means ± S.E.
Means in a column with a same letter are not statistically different at 5% level.

Actual responses of plant population and leaf area

Warming caused significant differences in plant population and leaf areas (Figure 6). At the seedling stage, the population density was 5.6% greater in the warmed plot than the non-warmed plot, suggesting a significant increase in seed germination rate caused by warming (Figure 6a). Meanwhile, the population density in the warmed plot was 20.4% higher than that in the non-warmed plot at the anthesis stage ($P<0.05$). The flag leaf area, top three leaves area and total green leaves area at anthesis were respectively 25.7, 41.7 and 48.1% higher ($P<0.05$) in the warmed plot than non-warmed plot (Figure 6b).

Actual responses of biomass accumulation

There were significant differences in biomass accumulation between the warmed and non-warmed plot (Figure 6). At the single plant scale, warming decreased wheat biomass accumulation, especially during post-anthesis phase (Figure 6c). Post-anthesis biomass accumulation per stem in the warmed plot was 32.7% lower than that in the non-warmed plot ($P<0.05$), while there was no significant difference in pre-anthesis biomass accumulation between the treatments. Warming caused a reduction of 14.9% in the total biomass accumulation per stem as compared to the non-warmed control ($P<0.05$).

At the population scale, however, the differences in biomass accumulation between the treatments were reverse (Figure 6d). Warming increased pre-anthesis aboveground biomass accumulation by 17.5% ($P<0.05$), though there was no significant difference in post-anthesis biomass accumulation per unit area. Consequently, the total aboveground dry mass per unit area was significantly higher by 11.6% in the warmed plot than that in the non-warmed plot.

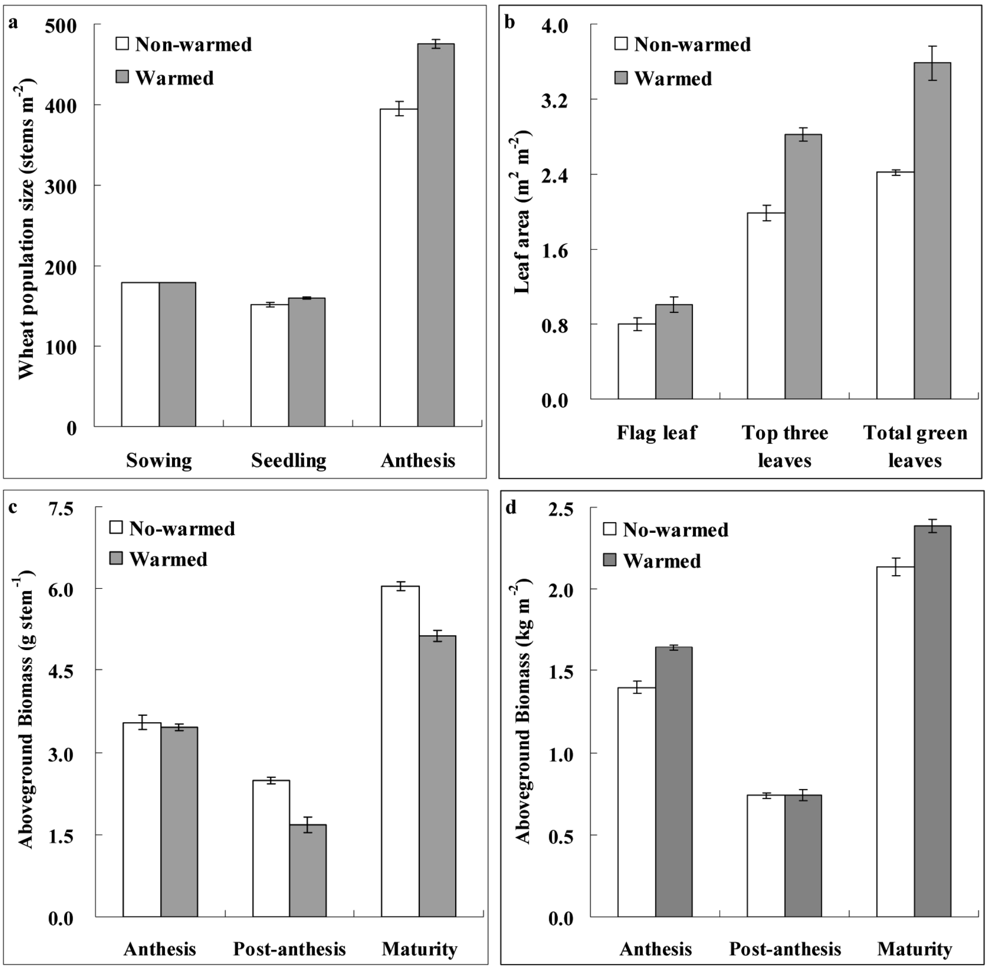

Figure 6. Plant population size (a), green leaf areas (b), aboveground biomass at plant scale (c) and at plant population scale (d) in the warmed and non-warmed plots under the Free Air Temperature Increase facility. Data are means ± 1S.E.

Discussion

According to the historical data analysis, Tibetan Plateau has experienced a significant warming trend during the whole growing seasons of winter wheat from 1988 to 2012, while there was no significant trend in the changes of precipitation amount (Figure 2). And the increase in the daily minimum and mean temperature was significantly higher than the daily maximum temperature. Similar changes in daily air temperatures and precipitation were also found in Western Himalayas (Kumar et al., 2009), in Nepal (Gentle and Maraseni, 2012; Duncan et al., 2013) and in Ladakh region of India (Vaish et al., 2011). As compared to the mean value of global warming rate, the increase in air temperature in Tibetan Plateau was greater (IPCC, 2007). Although there were no significant trends in the changes of precipitation during wheat growth period, the variations in precipitation were great among the different years during the period 1988-2012 (Figure 2d). Similar variations in annual precipitation were also observed by local farmers in Nepal (Shrestha et al., 2012; Duncan et al., 2013) and in Middle Yarlung Zangbo River Valley (Li et al., 2013). They noted an increase in annual precipitation with a decrease in rainfall days and the precipitation dates were also changed. Meanwhile, the increases in air temperature during wheat growth period were significantly higher than the recently reported annual increases in similar areas (Gentle and Maraseni, 2012; Shrestha et al., 2012; Li et al., 2013). Obviously, the air temperature elevation really happened during the past decades and will be still to prevail in future in Tibetan Plateau. And comprehending the realistic changes in air temperature during crop growth period rather than during the whole year may be more helpful for us to detect the actual impacts of global warming on crop production.

During the same years, tremendous increases in the actual yields of winter wheat were simultaneously found with the historical warming trends in the three study areas of Tibetan Plateau (Figure 3a, b and c). It is well known that historical gains in crop yield should be attributed to the contributions of agronomic innovation, economic development and climate change. To identify the actual impacts of climate change on crop yield, contributions of agronomic and economic factors need to be separated from the total gains (Lobell et al., 2011). With a line regression method (Goldblum, 2009), the actual yield of winter wheat was de-trended. According to the Pearson correlation coefficients, there was significant correlation between the de-trended wheat yield and the daily mean and minimum temperature in all the three study areas (Table 1). No significant correlation was found between wheat yield and precipitation. Based on the correlation analysis of winter wheat yield anomaly and daily mean and minimum temperature, significantly increasing trends were found in the three study areas of Tibetan Plateau (Figure 4). This suggests that historical warming, especially the increase in daily mean and minimum temperature, might have promoted winter wheat production in the plateau over the past decades. Recently, indirect evidences of warming-led increases in wheat and barley yields were also noted by local farmers (Tiwari et al., 2008). For example, Li et al. (2013) reported that 45% of the local farmer respondents noted a large increase in wheat yields and 42% respondents noted a similar increase in barley yields during the past decades.

The positive impacts of historical warming on winter wheat production were also directly evidenced by our field experiment. An increase of 1.1 ^{o}C in air temperature during winter wheat growing seasons caused large increases in wheat grain yield and biomass (Table 2). Theoretically, warming might detriment crop production through shortening growth period and stimulating heat stress, it can also benefit crop production via mitigating low temperature limitation to crop growth and development (Porter and Gawith, 1999). Recent study reported that the actual impacts of warming on wheat yield depend on the background temperature during wheat growing season (Ottman et al., 2012). If the daily mean air temperature is lower than 14.9 ^{o}C, a moderate warming less than 1.5 ^{o}C will enhance wheat productivity. In the Tibetan Plateau, the daily mean temperature is commonly less than 10 ^{o}C with a very low daily minimum temperature during wheat growing season (Figure 2). Thus, a moderate warming less than 1.5 ^{o}C can largely mitigate low temperature limitation to wheat growth and development, especially during pre-anthesis phase. These warming-led positive effects were confirmed with the higher population density and leaf areas (Figure 6a, b). Although warming shortened wheat growth period, the reduction was mainly discovered in the pre-anthesis phase. In the study areas, the pre-anthesis phase period of winter wheat is relatively long with an over-wintering duration more than 100 d, suggesting a reduction of 14 d in the pre-anthesis phase period might not affect wheat yield seriously. Similar warming-led advances in plant phenology and increases in plant productivity were also found in Alps (Stöckli and Vidale, 2004; Menzel et al., 2006) and the mountain areas of East Asia (Piao et al., 2006; Julien and Sobrino, 2009). Thus, the warming-led positive effects on pre-anthesis plant development and growth can compensate the warming-led shorten of wheat growth period.

Recently, our other studies also showed that global warming might increase winter wheat yield in East China (Tian et al., 2012) and North China (Chen et al., 2014). However the mechanisms underlying the positive effects of warming on wheat yield are different as compared to this study in Tibetan Plateau. In the previous field experiments, the post-anthesis biomass production and 1000-grain weight in the warmed plot were significantly higher than that in the non-warmed plot. This suggests that warming increases winter wheat yield mainly through enhancing post-anthesis biomass production for grain filling in East and North China. Since high temperature and dry wind are the major stresses to wheat grain filling in East and North China (Liu and Kang, 2006; Zhong et al., 2008), warming-led advances in wheat anthesis might help wheat to avoid the heat and drought stresses (Porter and Gawith, 1999). In the Tibetan Plateau, however, the major limitations to winter crop production are the daily minimum and daily mean temperature and the effective accumulated temperature (Figure 2). A moderate warming can significantly improve the daily mean and daily minimum temperatures, consequently mitigating the low temperature limitations to wheat growth and development. These mitigating effects were confirmed by the warming-led greater population density and green leaf areas (Figure 6a, b) and pre-anthesis biomass accumulation per unit area (Figure 6d). However, no significant increases, caused by warming, were found in the post-anthesis biomass accumulation per unit area (Figure 6d) and 1000-grain weight (Table 1). Since wheat population density was largely increased by warming, the biomass production at single plant scale in the warmed plot was significantly lower than that in non-warmed plot (Figure 6c). The grain number per spike was also significantly lower in the warmed plot than the non-warmed plot mainly due to the tremendous increase in spike number per unit area (Table 1). Our results indicate that the mechanisms underlying positive warming impacts on wheat yield are mainly through mitigating pre-anthesis low temperature limitation in the plateau.

Conclusion

The historical data analysis demonstrates that global warming has contributed a large part to the historical gains in winter wheat yield since 1988 in Tibetan Plateau. Meanwhile, the field warming experiment further directly confirmed the positive impacts of climate warming on winter wheat yield, suggesting that predicted air warming might also increase winter wheat yield in the plateau. No significant correlation was found between the precipitation changes and wheat yields; however, local farmers and previous studies have noted that the timing of precipitation or rainfall is very important for crop seed germination and seedling, especially in rainfed fields. Without efficient irrigation and drainage systems, warming-led changes may seriously decline crop yield. Hence, the following adaptive strategies should be considered so as to utilize the positive effects of warming: (1) enhancing crop resistance to low temperature and drought through new variety breeding; (2) enlarging winter wheat or barley cropping area and adjusting the planting and harvesting dates; (3) improving the irrigation and drainage infrastructures; and (4) enhancing the farmers' understanding of global warming and the knowledge base and techniques of winter wheat and barley cropping.

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