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Full Length Research Paper

Temperature impacts on wheat growth and yield in the North China Plain

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To provide base for improving wheat capacity in warmer climate in the North China Plain (NCP), a four-year field experiment was conducted to study temperature effects on length of growth period (LGP), final leaf number (FLN) and yield with six wheat cultivars at 20 test sites (from 32°4´ N to 36°1´ N) of Henan Province in NCP. The results show that the accumulated and average temperature at main stages was significantly different among the four wheat growing seasons (P < 0.01), and LGP, FLN and yield also. In addition, LGP was significantly correlated with accumulated and average temperature at sowing-turning green stage and growth period, and FLN and yield, with the accumulated temperature at almost all stages, but with only the average temperature at jointing-blossoming (FLN) or sowing-overwintering stage (yield) and growth period. There was also a positive linear regression relationship between LGP and accumulated temperature at sowing-overwintering stage and growth period between FLN and accumulated and average temperature of growth period, while a negative linear regression relationship between LGP and average temperature of growing period was observed. There was a quadratic regression relationship between yield and accumulated and average temperature at sowing-overwintering stage and growth period. In general, with temperature increase, FLN was increased, although LGP decreased. Therefore, if farmers give full consideration to sowing dates and field management when planting, the wheat yield will not suffer too much influence of the global warming in NCP in the future.

Key words: Temperature, wheat, length of growth period (LGP), final leaf number (FLN), yield.

INTRODUCTION

Food security is increasingly important for human beings all over the world, and food availability and quality still are the big challenges for scientists due to changing climate (Kang et al., 2009). The North China Plain (NCP) is one of the most important agricultural regions of China, with an area of 320, 000 km^2 and supplies more than 50% of wheat and 33% of maize produced in China (Yang and Zehnder, 2001). So, it is very important to maintain the NCP wheat output stably in order to supply sufficient food for the increasing population, while sustaining the already stressed environment in the 21st century.

Along with the global warming, it is obvious that temperature of wheat growing season was higher in recent years in China (Gao et al., 2002). For example, the average temperature of wheat growing period has increased to 2.1°C during 56 years from 1952 to 2007 as indicated by analysis on average temperature of Zhengzhou City in Henan Province. Moreover, temperature increment mainly occurred after 1990 (the data has not published). Studies on climate impacts and adaptation strategies of wheat production are increasingly becoming major areas of scientific concern (Dhungana et al., 2006; Challinor and Wheeler, 2008) for the reason that the effects of meteorological factor on wheat was greater than other crops due to the longer growth period of wheat (Yu et al., 2000).

Both plant growth and development are affected by temperature (Porter and Gawith, 1999), and although the influence of temperature varies during wheat developmental phases, its action remains crucial throughout the whole plant life cycle (Entz and Fowler, 1988; Slafer and

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Rawson, 1994). Many valuable conclusions about effects of temperature on wheat growth and yield were reported through different research methods (Zhou et al., 2003; Zhang et al., 2006). For example, Zhang et al. (2006) reported that the entire growth period of winter wheat was shorted by 8.3 days $10a^{-1}$ based on the phonological observation data of winter wheat and metrological data of weather station from 1981 to 2004 in the Plain Area of the Loess Plateau. Ortize et al. (2008) also discussed how wheat can adapt to climate change in Indo-Gangetic Plain for 2050s and suggested that global warming is beneficial for wheat crop production in some regions, but may reduce productivity in crucial temperature areas. Hence, it is urgent to develop some heat-tolerant wheat germplasm to mitigate climate change.

However, climate change impacts on crop yield are different in various areas; in some regions it increases, while in others it decreases, which is concerned with the latitude of the area and irrigation application (Kang et al., 2009). The reports about effects of temperature change at main stages during wheat development on wheat growth and yield is few, although numerous studies forecasted the length of growth period and yield by experimental data or by crop growth simulation models, according to the average temperature change during many years in some given area (Luo et al., 2003; Zhou et al., 2003; Che et al., 2005; Anwar et al., 2007; Challinor and Wheeler, 2008; Li, 2009). Moreover, average temperature and accumulated temperature was interdependence and has different significance on the wheat development; the former reflected temperature change, while the later indicated the thermal resources situation.

Accumulated temperature was usually used to quantify temperature effects and describe the timing of biological processes (Undersandera and Christiansen, 1986; Sharratt et al., 1989; McMaster and Wilhelm, 1997). Some publications report that suitable accumulated temperature before winter of semi-winterness and weak springness wheat was 650 to 750 and 550 to 600°C ·day (°C·d) in Henan province, respectively, through the experiment with scope of accumulated temperature before winter from 350 to 900°C in 2007 to 2008 wheat growing season (Li et al., 2010). Therefore, it is important to analyze the effects of temperature change on wheat growth and yield, considering two aspects of accumulated and average temperature in different area under the climate warming condition.

This study analyzes the effects of average temperature and accumulated temperature of main stages during wheat growing season on wheat LGP, FLN and yield. The objectives of this work were (i) to describe the changes tendency of LGP, FLN and yield due to the accumulated and average temperature change at main stages during wheat growing season, and (ii) to discover the regulative function of temperature change on LGP, FLN and yield, through analyzing the correlation and regression relationship between accumulated and average temperature, and LGP, FLN and yield. If successful, these results could provide scientific basis for adjusting wheat production and obtaining high and stable yield with climate warming in NCP.

MATERIALS AND METHODS

Six wheat (*Triticum aestivum* L.) cultivars, most widely sown in the NCP were used in this study, including three semi-winterness wheat cultivars, namely Jimai 20 (strong-gluten), Yumai 49 (middle-gluten) and Zhengmai 004 (weak-gluten), and three weak springness wheat cultivars, namely Zhengmai 9023 (strong-gluten), Yanzhan4110 (middle-gluten) and Yumai 50 (weak-gluten). All the seeds used in this study were provided by Henan Academy of Agricultural Science.

Experimental station

Field experiments were conducted in 20 ecological sites of Henan Province, a typical area of intensive agriculture in the NCP, located at latitude from 31°23′ to 36°22′N, and longitude from 110°21′ to 116°39′E, as the transitional zone from north subtropics to warm temperature zone.

The mean annual temperatures and annual actual sunshine hours were 13 to 15°C and 2,000 to 2,600 h, respectively (Chen et al., 2010). There are 50, 375 km^2 wheat-planting fields in this given regions, accounting for about 14.3% of wheat cultivated area in China. The total yield of wheat was over 2.5×10^{10} kg in Henan Province after 2005, approximately composing 25% of the wheat produced in China (Guo and Cui 2008). Trials were carried out at 20 ecological test sites from latitude 36°1′ N to latitude 32°4′ N in Henan province. The details characteristics of the 20 sites are presented in Table 1.

Experimental design

Field experiment was carried out during four wheat growing seasons, namely 2007 (from the end of September 2006 to the beginning of June 2007), 2008 (from the end of September 2007 to the beginning of June 2008), 2009 (from the end of September 2008 to the beginning of June 2009) and 2010 (from the end of September 2009 to the beginning of June 2010), respectively. In each season, treatments were randomized in a split-plot design with three replications. The treatments applied consisted of three sowing dates and three wheat cultivars for each type of semi-winterness and weak springness. Sowing date treatments were assigned as the main plots and cultivars as the subplots.

The three sowing dates were suitable sowing (according to the optimized sowing date in practices in each site), early sowing (7 days before optimized sowing date) and late sowing (7 days after optimized sowing date). For semi-winterness wheat cultivars, the sowing rate of early sowing, suitable sowing and late sowing was 120, 195 and 270 m^{-2}, respectively, and for weak-springness wheat cultivars it was 150, 225 and 300 m^{-2}, respectively. The experimental plot size was 5 m long and 14 rows wide with 20 cm between rows. The experiment design and seeds supplying was unified in every site.

Field management

Plots were supplemented with fertilizers and water to ensure optimal growing conditions consistent with local agronomic practices. Weeds, pests and diseases were chemically controlled.

Table 1. Geographical condition, scope of sowing date, rainfall, sunshine percentage and solar radiation of the 20 ecological test sites in Henan Province during four wheat growing seasons from 2006 to 2010.

Ecological test site	Geographical condition (Longitude/latitude/ elevation (m)	Scope of sowing date (month - date) [a]				Rainfall(mm) [b]				Sunshine percentage (%)				Solar radiation (MJ/m²)			
		2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
Anyang	114.2/36.1/76.4	10.24-10.31	10.05-10.18	9.29-10.20	9.28-10.18	162.9	140.3	159.7	131.8	38.7	36.5	48.4	41.9	2233.0	2367.3	2645.0	2593.4
Puyang	115.0/35.4/53.1	10.15-10.20	10.10-10.22	10.3-10.24	10.3-10.24	180.1	191.4	181.2	136.6	50.2	44.5	51.6	49.3	2736.0	2605.1	2799.4	2990.2
Xunxian	114.3/35.4/62.6	10.16-10.23	10.9-10.23	10.3-10.24	10.6-10.27	179.5	178.3	183.2	121.6	44.8	38.6	46.6	44.0	2583.3	2372.4	2650.6	2615.3
Xinxiang	113.5/35.2/74.0	10.12-11.2	10.9-10.23	10.8-10.29	10.3-10.24	132.4	140.7	151.8	118.2	45.2	45.3	48.5	45.6	2504.4	2642.8	2592.4	2696.2
Wenxian	113.1/34.6/108.5	10.11-10.25	10.8-10.22	10.11-11.1	10.12-11.1	202.1	140.7	200.9	155.0	49.0	47.1	48.8	42.3	2669.5	2691.1	2588.8	2509.6
Sanmenxia	111.1/34.5/411.8	10.14-10.27	10.8-10.22	10.8-10.28	9.30-10.29	238.5	165.2	259.5	197.8	44.3	48.7	45.4	39.9	2480.4	2711.7	2530.3	2383.4
Zhengzhou	113.4/34.4/111.3	10.10-10.31	10.12-10.26	10.7-10.28	10.10-10.31	161.4	201.2	207.6	173.2	44.0	43.0	43.5	41.9	2458.2	2481.9	2476.1	2464.3
Luoyang	112.3/34.4/137.9	10.11-10.19	10.12-10.26	10.14-11.4	10.5-10.26	164.8	143.6	189.6	162.8	53.1	50.9	36.6	39.5	2782.2	2726.6	2107.0	2455.4
Yucheng	115.5/34.2/47.2	10.20-11.3	10.13-10.26	10.5-10.26	10.5-10.26	203.4	247.2	281.3	275.2	46.6	46.9	42.1	41.4	2522.0	2736.6	2505.2	2581.5
Xuchang	113.5/34.0/67.7	10.11-10.29	10.04-10.25	10.4-10.25	10.5-10.26	249.6	216.2	238.8	268.4	35.0	39.9	37.0	35.8	2161.3	2449.4	2298.1	2377.6
Yongcheng	116.2/33.6/32.7	10.15-11.6	10.04-10.25	10.6-10.25	10.8-10.29	190.1	243.4	243.9	289.4	40.8	37.5	40.0	34.9	2341.2	2344.9	2408.7	2349.0
Huaiyang	114.5/33.4/46.3	10.16-11.6	10.12-10.26	10.7-10.28	10.9-10.27	240.5	256.2	285.9	346.8	50.2	50.8	46.4	40.3	2606.0	2787.2	2511.4	2493.9
Yancheng	114.0/33.4/62.1	10.15-11.3	10.5-10.26	10.9-10.30	10.8-10.29	161.0	140.6	289.0	334.5	53.3	50.8	38.6	38.1	2671.7	2677.4	2285.4	2479.2
Shangshui	114.4/33.3/47.3	10.15-11.6	10.17-10.24	10.7-10.30	10.7-10.28	250.9	281.9	243.6	379.4	44.0	42.5	41.5	39.0	2390.6	2506.3	2393.9	2441.2
Xiping	114.0/33.2/60.6	10.14-11.1	10.16-10.30	10.6-10.27	10.6-10.27	293.4	254.0	292.8	386.8	46.0	41.9	41.9	42.5	2522.2	2496.0	2405.8	2560.7
Fangcheng	113.0/33.2/161.5	10.16-10.30	10.11-10.24	10.12-11.2	10.8-10.30	214.9	250.2	257.2	359.8	44.3	43.2	38.2	35.8	2415.6	2513.5	2270.6	2305.4
Shangcai	114.2/33.2/60.8	10.20-10.30	10.13-10.27	10.8-10.30	10.8-10.30	242.7	344.7	295.1	412.5	44.4	36.9	34.4	39.4	2492.1	2307.4	2161.2	2463.7
Dengzhou	112.1/32.4/112.7	10.24-10.30	10.22-11.5	10.12-11.2	10.13-11.3	197.3	210.3	268.3	289.1	44.8	45.6	37.0	35.0	2369.8	2508.5	2189.2	2261.3
Tanghe	112.5/32.4/109.9	10.16-11.5	10.15-10.29	10.9-10.30	10.6-10.27	170.5	298.2	240.4	369.3	39.8	40.0	33.5	33.7	2139.6	2356.7	2092.2	2306.4
Zhengyang	114.2/32.4/79.0	10.17-11.1	10.16-10.30	10.13-11.1	10.6-10.27	379.8	607.3	340.5	466.2	46.7	45.1	40.3	39.8	2410.3	2575.3	2273.0	2525.7

[a]The sowing date of each ecological test site was not the same date in different years, as a result of rainfall and other factor. [b]The rainfall, sunshine percentage and solar radiation was the means of six wheat cultivars with three different sowing date at all the 20 sites during wheat growing season.

Measurements

Weather records (daily values of incoming solar radiation,
maximum and minimum temperature and rainfall) during the growing season were obtained from a local meteorological station in each site. The overwintering date was the date in which the average temperature of the five-day overlapping average was lower than 1°C. The turning green date was when the new growth part of heartleaf of 50% plants reveals 2 cm from sheath of the old leaf on main stem, and the jointing date was when the first internode on main stem of 50% plants reveals the ground 2cm. The blossoming date was when 50% plants blossomed, and the ripeness date was when the grains were hard and the grains color was invariable.

The average temperature was the means from the stage start to end, and the accumulated temperature of main wheat growth stages were calculated according to the methods of Subedi et al. (1998) with a base temperature of 0°C (Kirby, 1985), and the results was expressed as °C·day (°C·d). The LGP was the day lasted from sowing date to ripen date.

The FLN was determined each five days from seedling emergence to blossoming date by the cumulative number of leaves on the main stem of each of the five plants per plot, and the standard of new leaf was when the heartleaf reveals 2 cm from sheath of the old leaf. The grain yield was investigated at harvest. The ears of three 2 m^2 in each plot was harvested manually and then threshed using a stationary thresher. Grain yields were measured using electronic balance after air-dried, and converted into g m^{-1}.

Data analysis

With SPSS 11.5 program for Windows, the analysis of difference significance at $P < 0.01$ in LGP, FLN and yield

Table 2. The accumulated temperature and average temperature of main stages during the four wheat growing seasons from 2006 to 2010 in Henan Province.

Parameter	Year	Sowing-overwintering[a]	Overwintering-turning green[b]	Turning green -jointing[c]	Jointing - blossoming[d]	Blossoming-ripeness[e]	Growth duration[f]
Accumulated temperature (°C)	2007	546.19 ± 7.78[c]	151.41 ± 3.76[b]	184.65 ± 4.98[c]	561.47 ± 3.97[a]	802.12 ± 3.37[a]	2245.73 ± 9.76[b]
	2008	636.15 ± 5.91[a]	62.71 ± 2.17[c]	216.42 ± 3.53[b]	527.89 ± 4.16[b]	806.47 ± 3.12[a]	2247.83 ± 7.45[b]
	2009	606.58 ± 6.48[b]	149.42 ± 3.41[b]	183.82 ± 4.43[c]	566.64 ± 4.42[a]	781.92 ± 2.91[b]	2286.67 ± 8.61[a]
	2010	395.17 ± 6.94[d]	232.16 ± 3.28[a]	237.71 ± 4.70[a]	531.37 ± 4.31[b]	784.00 ± 3.21[ab]	2180.24 ± 7.28[c]
	CV%	30.36	58.47	42.79	15.68	8.33	7.38
Average temperature (°C·d)	2007	8.59±0.06[c]	2.72 ± 0.07[a]	6.98 ± 0.08[b]	13.94 ± 0.07[a]	21.91 ± 0.06[a]	10.18 ± 0.04[a]
	2008	7.99±0.04[d]	-0.27 ± 0.05[c]	9.39 ± 0.07[a]	13.91 ± 0.04[ab]	21.66 ± 0.04[b]	9.44 ± 0.03[c]
	2009	9.20±0.05[b]	1.94 ± 0.06[b]	6.49 ± 0.08[c]	13.67 ± 0.08[b]	20.31 ± 0.05[d]	9.84 ± 0.05[b]
	2010	12.89±0.13[a]	1.95 ± 0.04[b]	7.16 ± 0.06[b]	13.84 ± 0.05[ab]	21.16 ± 0.03[c]	8.96 ± 0.03[d]
	CV%	26.92	105.08	24.77	9.22	8.82	10.00

The data was the mean (± S.E) of six wheat cultivars with three different sowing date at all the 20 sites, and the means followed by different letters are difference significantly ($P < 0.01$). [a]The means of data from the sowing date to overwintering date; [b] the means of data from the overwintering date to turning green date; [c] the means data from turning green date to jointing date; [d] the means of data from jointing date to blossoming date; [e] the means data from blossoming date to ripeness date; [f] the means of data from sowing date to ripeness date.

among different years was carried out using Duncan's multiple range test. Correlation and regression analysis between LGP, FLN and yield, and accumulated temperature (°C·d) and average temperature (°C) were performed using bivariate correlations and curve estimation, respectively.

RESULTS

Variations of accumulated and average temperature of main stages

Table 2 shows that the accumulated and average temperature of main stages was significantly different ($P < 0.01$), and the varied degree of accumulated and average temperature at stages before jointing was higher than stages after blossoming during four wheat growing season. In addition, the variation coefficient of average temperature of growth period was higher than the accumulated temperature. For example, means of the former was 9.54°C, and the highest (10.18°C) was higher by 13.62% than the lowest (8.96°C), while means of the later was 2237.53°C·d, and the highest (2286.67°C·d) was higher by 4.88% than the lowest (2180.24°C·d). It can be seen that the temperature change was mainly displayed in the stages before jointing, and the accumulated temperature of growth period was more stable, although the average temperature varied greatly during wheat growing season.

Variations of LGP, FLN and yield

Change of LGP, FLN and yield are presented in Table 3. Our experimental data showed that LGP, FLN and yield were significantly different during the four wheat growing seasons ($P < 0.01$). For example, the longest LGP (234.18 d, 2010), the most FLN (12.43 leaves, 2008) and the highest yield (730.58 g m^{-2}, 2008) were increased by 7.27, 9.23 and 12.01%, respectively, compared with the lowest among four wheat growing season. Also, compared with FLN and yield, the varied degree of LGP was the smallest, reflected by the small variation coefficient. Yield varied greatly in different years and the highest was 2008, which was significantly higher than the other years, except 2007, while the lowest was 2010, which was decreased by 10.72% compared with the highest. In 2010, overwintering date was moved up to November 11, 2009 due to a wide range of snow in early November in most areas of Henan Province; so the tiller was insufficient because of the lower accumulated temperature before winter, and the grains $spike^{-1}$ was low because of the low sunshine percentage in the 2010 spring.

Correlation analysis between temperature and LGP, FLN and yield

The correlation analysis between LGP, LLN and yield, and accumulated and average temperature of main stages showed that there was significant

Table 3. Changes of length of growth period (LGP), final leaf number (FLN) and yield during four wheat growing seasons from 2006 to 2010 in *Henan Province.*

Year	LGP (days)	FLN (leaves)	Yield (g/m^2)
2007	218.30 ± 0.47^d	12.12 ± 0.08^{ab}	729.96 ± 6.72^a
2008	228.88 ± 0.43^b	12.43 ± 0.79^a	730.58 ± 5.09^a
2009	225.95 ± 0.43^c	12.01 ± 0.08^c	686.13 ± 6.36^b
2010	234.18 ± 0.38^a	11.38 ± 0.09^b	652.24 ± 5.16^c
CV (%)	4.35	11.89	15.96

The data was the mean (± S.E) of six wheat cultivars with three different sowing date at all the 20 sites, and the means followed by different letters are difference significantly ($P < 0.01$).

Table 4. Correlation analysis between accumulated temperature and average temperature of main stages, and length of growth period (LGP), final leaf number (FLN) and yield of six wheat varieties with three sowing dates at the 20 test sites in Henan Province during four wheat growing seasons from 2006 to 2010 in Henan Province.

Parameter	Main growth stage	LGP (days)	FLN (leaves)	Yield (g/m^2)
Accumulated temperature (°C ·d)	Sowing- overwintering	0.3910**	0.7322**	0.3320**
	Overwintering-turning green	0.3233**	-0.3587**	-0.3435**
	Turning green -jointing	0.0616*	-0.4042**	-0.3572**
	Jointing - blossoming	0.0459	0.3955**	0.0446
	Blossoming-ripeness	0.0561*	0.0981*	0.1364**
	Growth duration	0.4245**	0.6353**	0.2478**
Average temperature (°C)	Sowing- overwintering	0.4702**	-0.0156	-0.1209**
	Overwintering-turning green	-0.3719**	0.0000	-0.0130
	Turning green -jointing	-0.0357	-0.0029	0.0650*
	Jointing - blossoming	0.0622*	-0.4219**	-0.0569*
	Blossoming-ripeness	0.0778*	0.0617	0.0121*
	Growth duration	-0.4298**	0.4448**	0.2587**

* and ** means the correlation is significant at the 0.05 and 0.01 level, respectively.

correlation between LGP and accumulated and average temperature of sowing - turning green stage and growth period, among which the correlation coefficient between LGP and average temperature of growth period was the highest (Table 4) ($P < 0.01$). The accumulated temperatureaffected the FLN more greatly than the average tempe- rature, because the FLN was significantly correlated with the accumulated temperature at almost all stages during wheat growing season, except the blossoming - ripeness stages, while it was only significantly correlated with the average temperature at jointing - blossoming stage and growth duration.

As was with the change tendency of FLN, yield was affected by the accumulated temperature more than average temperature, and this is reflected by the significant correlation between yield and the accumulated temperature at almost all the main stages during wheat growing season, except the jointing - blossoming stage, while only significantly correlated with the average tempe- rature of sowing - overwintering stage and growth duration, among which the correlation coefficient of accumulated temperature at sowing - overwintering stage and average temperature of growth duration was higher than the others.

Regression analysis between temperature and LGP, FLN and yield

Further regression analysis between LGP, FLN, yield and accumulated and average temperature which was significantly correlated, showed that there was a positive linear regression relationship between LGP and accumu- lated temperature of sowing - overwintering, overwintering - turning green stage and growth period. The accumulated temperature of the aforementioned stages was increased by 100°C ·d, while the LGP was lengthened by 37, 1.76 and 2.32 days, respectively (Table 5). As for the average temperature, there was a positive linear regression relationship between LGP and average temperature of sowing-overwintering stage, while there was a negative linear regression at overwintering-turning green stage and growth period. When the average temperature of overwintering-turning green stage and growing period

Table 5. Regression analysis between accumulated temperature and average temperature of main growth stages and length of growth period (LGP), final leaf number (FLN) and yield of six wheat varieties with three sowing dates at the 20 test sites in Henan Province *during four wheat growing seasons from 2006 to 2010 in Henan Province*.

Parameter		Main growth stage	Regression equation		
LGP (days)	Accumulated temperature (°C.d)	Sowing- overwintering	$y = 0.0137x + 220.30$	$R^2 = 0.1528$	$F > F_{0.01}$
		Overwintering-turning green	$y = 0.0176x + 226.58$	$R^2 = 0.1045$	$F > F_{0.01}$
		Growth duration	$y = 0.0232x + 175.75$	$R^2 = 0.1802$	$F > F_{0.01}$
	Average temperature (°C)	Sowing- overwintering	$y = 1.125x + 214.77$	$R^2 = 0.2211$	$F > F_{0.01}$
		Overwintering-turning green	$y = -3.115x + 234.94$	$R^2 = 0.1383$	$F > F_{0.01}$
		Growth duration	$y = -5.068x + 276.54$	$R^2 = 0.1847$	$F > F_{0.01}$
FLN (leaves)	Accumulated temperature (°C·d)	Sowing- overwintering	$y = 0.0065x + 8.42$	$R^2 = 0.5362$	$F > F_{0.01}$
		Overwintering-turning green	$y = -0.0028x + 12.35$	$R^2 = 0.1287$	$F > F_{0.01}$
		Turning green -jointing	$y = -0.0040x + 12.86$	$R^2 = 0.1634$	$F > F_{0.01}$
		Jointing - blossoming	$y = 0.0040x + 9.80$	$R^2 = 0.1564$	$F > F_{0.01}$
		Growth duration	$y = 0.0054x - 0.14$	$R^2 = 0.4037$	$F > F_{0.01}$
	Average temperature (°C)	Jointing - blossoming	$y = -0.123x + 13.67$	$R^2 = 0.1780$	$F > F_{0.01}$
		Growth duration	$y = 0.787x + 4.48$	$R^2 = 0.1978$	$F > F_{0.01}$
Yield (g m^{-2})	Accumulated temperature (°C·d)	Sowing- overwintering	$y = -0.0007x^2 + 0.871x + 435.57$	$R^2 = 0.1808$	$F > F_{0.01}$
		Overwintering-turning green	$y = -0.1703x + 720.67$	$R^2 = 0.1180$	$F > F_{0.01}$
		Turning green -jointing	$y = -0.2131x + 740.99$	$R^2 = 0.1276$	$F > F_{0.01}$
		Blossoming-ripeness	$y = -0.0023x^2 + 3.771x - 795.55$	$R^2 = 0.1337$	$F > F_{0.01}$
		Growth duration	$y = -0.0003x^2 + 1.348x - 801.80$	$R^2 = 0.1702$	$F > F_{0.01}$
	Average temperature (°C)	Sowing- overwintering	$y = -3.413x^2 + 70.142x + 369.54$	$R^2 = 0.1405$	$F > F_{0.01}$
		Growth duration	$y = -3.865x^2 + 75.85x + 350.21$	$R^2 = 0.1686$	$F > F_{0.01}$

was increased by 1°C, the LGP was shortened by 3.12 and 5.07 days, respectively, which means that the higher the average temperature of overwintering-turning green stage and growth period, the fewer the LGP.

Table 5 shows a positive linear regression relationship between FLN and accumulated temperature of sowing-overwintering, jointing-blossoming stage and growth period, and average temperature of growth period, and a negative linear regression relationship of accumulated temperature of overwintering-jointing stage, and average temperature of jointing-blossoming stage. When the accumulated and average temperature of growth period was increased by 100°C·d and 1°C, the FLN was increased to 0.54 and 0.79 leaves, respectively.

There was a quadratic regression relationship between yield and the accumulated temperature at sowing-overwintering, blossoming-ripeness stage and growth duration, and average temperature of sowing- over-wintering stage and growth duration (Table 5). According to the regression equation, the accumulated temperature of the aforementioned stages was 622.05, 819.57 and 2246.67°C·d, the yield was higher and reached 706.52, 750.16 and 712.45 g m^{-2}, respectively, and when the average temperature of sowing-overwintering stage and growth duration was 10.28 and 9.81, the yield reached 729.9 and 722.3 g m^{-2}, respectively. There was a negative linear regression between yield and accumulated temperature of overwintering–jointing stages. These result show that the yield was higher only when the accumulated and average temperature was suitable at sowing- overwintering and at the growth period.

DISCUSSION

Global food security is a very important issue in the 21st century with increasing population and already stressed environment (Kang et al., 2009), and global warming is a well known example of stressed environment (Gao et al., 2003; Yang et al., 2009; Li et al., 2010), therefore, it is urgent to determine the impacts of temperature change on crop production in order to develop possible adaptation strategies for obtaining enough crop yield in the world. Numerous studies reported that temperature increment tendency was obvious in recent years, especially autumn and winter in NCP (Yang et al., 2009; Li et al., 2010), so it is important to study the effects of temperature change in autumn and winter on the growth and yield of wheat in NCP.

This study measured the variation of LGP, FLN and yield affected by temperature change, and analyzed the correlation and regression relationship between these indexes mentioned and accumulated and average temperature at main stages during wheat growing season. The results show that LGP, FLN and yield varied greatly following temperature changes, which reflected that the wheat development and yield was greatly influenced by accumulated and average temperature. With the climate change, the growing period will reduce (Kang et al., 2009). Our analysis showed that there was a negative linear regression relationship between LGP and the average temperature of winter (namely overwintering-turning green stage) and growth period. This indicate that the higher the average temperature of winter, the shorter the LGP, which was consistent with the results reported by Che et al. (2005), Yu et al. (2007) and Li (2009). Furthermore, the accumulated temperature of growth period was stable, although the LGP was quite different among different wheat growing season. These results show that wheat could maintain the appropriate accumulated temperature required to complete growth and development through adjusting the LGP, which reflected that wheat not only need the appropriate average temperature, but also requires a certain temperature accumulation.

Recent developments in understanding wheat phenology have shown that most developmental events until anthesis can be related to the appearance of main stem leaves (Kirby, 1990; Hay and Kirby, 1991; Miglietta, 1991). Numerous literatures reported that changes of FLN depended on the external environment such as temperature, day length, sowing date and other closely related, in addition to genetic factors, so the FLN was not a stable constant, and described the effects of above mentioned factors on the FLN, area and so on, by modeling approach (Miglietta, 1991; Jamiesona et al., 1995; Brooking et al., 1995; Bos and Neuteboom, 1998) or studied mechanism by proteomics methods (Mäkinen and Stegemann, 1981; Rinalducci et al., 2011). The effect of temperature change on FLN and LGP was different, and there was positive correlation between FLN and accumulated and average temperature of growth period. For example, when the accumulated temperature of growth period was increased by 100°C·d, the FLN was increased by 0.54 leaves, which was consistent with the results reported by Wang et al. (2004) and Sun et al. (2011). In a sense, the increased leaf number was equal to the lengthen days of growth period, which weaken the adverse effect of shorten growth period result from global warming on wheat yield in certain degree. This is also reflected by the positive correlation between FLN and yield and LGP (the data was not reported). Furthermore, there was a quadratic regression relationship between yield and accumulated temperature of sowing-overwintering stage, blossoming-ripeness stage and growth period, and average temperature of sowing-overwintering stage and growth duration. This means that wheat yield was high only when the accumulated temperature and average temperature of sowing-overwintering stage and growth duration was suitable, which was consistent with the results reported by Grace (1988) who reported that both high and low temperatures decrease the rate of dry matter production and at extremes, can cause production to cease, and Li et al. (2010) who summarized that the suitable accumulated temperature of semi-winterness and weak springness wheat was 650 to 750 and 550 to 600°C·d, respectively, in Henan province.

According to the result of this paper, we could carry on corresponding adjustment to wheat production to copy with the warmer climate in the North China Plain. First, many research indicated that early sowing dates accumulate more dry matter and avoid terminal drought at the end of the growing season (Stapper and Harris, 1989; Bassu et al., 2009), while it easily lead to cold damage in winter and greater risk for late spring freeze injury (Gao et al., 2002; Dong et al., 2008) and delaying sowing date can cause different environmental conditions, especially causing grains to grow with increasing temperatures and diminishing moisture conditions, and as a consequence, the grain spike^{-1} is reduced and grain dry matter yield is decreased (Panozzo and Eagles, 1999; Subedi et al., 2007; Ferrisea et al., 2010).

So, we should reasonably arrange the sowing time of wheat variety with different growth characteristics calculated by the suitable accumulated temperature before winter and the average temperature from the end of September to middle of October in Henan Province to ensure the wheat safety overwintering and high yield through efficiently using accumulated temperature. Secondly, we could obtain high wheat yield to ensure food security by improving water and fertilizer management, and prevention measures of diseases and insects according to the temperature changes during the wheat growing season.

For example, increased quantity of insect induced by the mortality rate reduction of disease-carrying insect eggs results from fall and winter warm climate, due to the difficulty to prevent and control the wheat diseases and insects. Therefore, the farmer should pay more attention to discover, prevent and control it early. Moreover, we must strengthen the agricultural meteorology research to provide prompt and science instruction for the wheat production (Abbasi et al., 2010).

Conclusions

Accumulated temperature was a better index to indicate the effect of temperature change on growth and yield of wheat than average temperature, as reflected by the significant correlation between LGP, FLN and yield and accumulated temperature, especially between FLN and accumulated temperature of almost all the main stages during wheat growing season, except the blossoming-ripeness stage. Along with climate warming, the accumulated temperature was increased, which is advantageous for the wheat to overwintering safely and caused the FLN to increase. Therefore, the temperature change did not cause great changes in the wheat yield and was not harmful to food security at present, so long as the average temperature did not surpass the appropriate scope and the farmers fully consider the sowing date and field management when planting wheat.

Of course, many factors such as rainfall, CO_2 concentration, sunshine percentage, solar radiation, as well as other factors interactions and so on, influence the wheat growth and yield. Meanwhile, we only analyzed the effect of temperature change on LGP, FLN and yield of wheat, which was simultaneously affected by the other factors mentioned above, using the data of 20 ecological test sites in Henan Province during four wheat growing seasons. The correlation coefficient was lower in this paper because of the effect of other meteorological factors. Therefore, more research on temperature effects on wheat with longer time and broader scope, and the interaction between temperature and other meteorological factors should be considered to modify the correlation coefficient and enrich the conclusion.

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