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ORIGINAL PAPER

Spatial Patterns of Relationship Between Wheat Yield and Yield Components in China

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Abstract
The considerable plasticity of wheat (*Triticum aestivum* L.) in reaching final yield is dynamically determined by three yield components: spike number m^{-2} (SN), kernel number spike^{-1} (KN) and 1000-kernel weight (KW). Understanding the contribution of yield components to the variation of grain yield under different production environments is essential for designing breeding programs and increasing grain production. This study analyzed 2 years of experimental data from the Chinese Variety Evaluation Program to explore the relationship between grain yield and yield components in four main winter wheat production regions. Correlation and path analysis were the main methods used in this paper. Yield and yield components were restricted by high temperature and lower sunshine hours at southern regions (Upper Yangtze Valleys, UY and Middle and Lower Yangtze Valleys, MLY). No relationship between yield and climate elements was found at northern region (Yellow and Huai Valleys, YH and Northern Land, NL). Yield in the YH region was the greatest with both higher SN and KN, and SN had strong negative relationships with KN and KW. SN was the main factor correlated the variation of yield, especially in low yielding regions (UY and NL), suggesting breeding efforts should emphasize increasing SN in these environments. The role of KW and KN became increasingly important in high yielding region (YH), indicating that all yield components should be considered in breeding for high yielding environments.

Keywords Wheat yield · Yield components · Spike number · Kernel number · Kernel weight · Climate elements

Introduction

Wheat yield was frequently analyzed in terms of yield components, which were spike number m^{-2} (SN), kernel number spike^{-1} (KN), and kernel weight (KW) respectively. The three yield components were not independent but related in complex ways (Mohsin et al. 2009; Gambín and Borrás 2010), and the relationships often changed under various production conditions (García del Moral et al. 2003; Ferrante et al. 2017). The three yield components dynamically interact during the life cycle of wheat (McMaster 2005; Sadras and Slafer 2012). Compensations among components were main barriers to understand the relationships. Understanding which yield components determined yield changes and relationships among yield components would be helpful for wheat yield increase and wheat breeding.

Major climatic elements influenced SN and KN were solar radiation and mean temperature during spike growth (Fischer 2007; Miralles and Slafer 2007; Reynolds et al. 2009). KW was strongly affected by the daily mean air temperature during grain-filling period (Wardlaw and Wrigley 1994), and also had

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a weak positive relation with solar radiation (Fischer 1984). The first aim of this paper was to analyze the relationships between yield, yield components and climate elements of different production environments in China.

Grain number per m^2 (GN, SN multiplied KN) as the main component determining yield was recognized by many studies (Zhang et al. 2007; Fischer 2011). The variation of GN was the main reason for the changes of wheat yield. Slafer et al. (2014) further reported that large changes of GN were mainly attributed to changes of SN. The competitive relationship probably be found between SN and KN as the growth stage of which were all from emergence to anthesis and overlapped a lot. The formation of KW is mainly from anthesis to maturity growth stage. KW was more heritable and less variable than GN (Sadras and Denison 2009; Sadras and Slafer 2012). KW and KN had the significant negative genotypic correlation in most populations (Fischer 2007). While the relationships between yield and yield components were strong influenced by environment, genotype and growth progress. Analysis the relationship between yield and yield components under different production environment in China was the second aim of this paper.

China is the largest wheat producer and consumer in the world. Wheat production in China can be divided into ten major agro-ecological zones according to different geographical positions, wheat types, growth season, cultivar responses to temperature and photoperiod (Fig. 1; Jin 1996; Zhang et al. 2008). The Northern China Plain winter wheat zone (Zone I) and the Yellow and Huai River Valleys winter wheat zone (Zone II) contribute about 56% of annual wheat production in China; the Middle and Lower Yangtze River Valleys winter wheat zone (Zone III) and the Southwestern winter wheat zone (Zone V) contribute about 26%; less than 20% is produced in the other six wheat agro-ecological zones. Production conditions (e.g. climate, soil, irrigation conditions) of the Yellow and Huai River Valley are the best of China, so per unit wheat yield of this zone is always greater. This paper focus on the spatial patterns of relationship between wheat yield and yield components in four main winter wheat production zones (I, II, III and V).

The objectives of this paper were to: (i) evaluate the influence of climate elements on yield and yield components in different production environments of China, and, (ii) evaluate the spatial patterns of relationship between grain yield and the three yield components in four main winter wheat production zones of China.

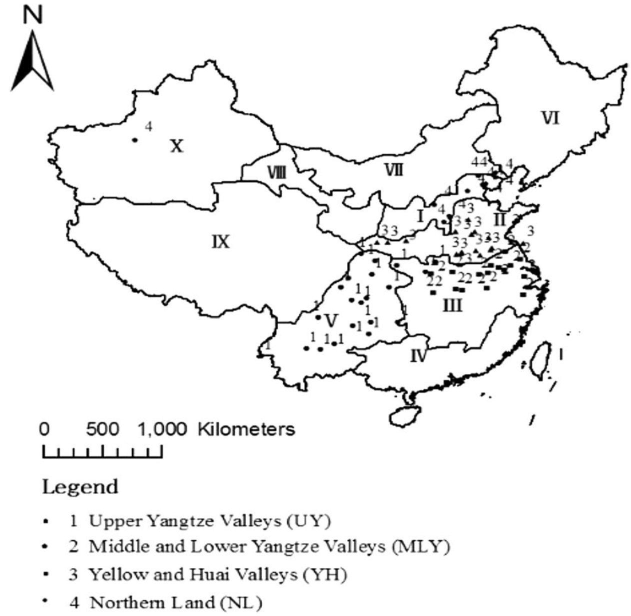

Fig. 1 Location of experimental sites within China used in the study. Ten major agro-ecological wheat production zones in China are denoted by Roman numerals, which were North China Plan winter wheat zone (I), Yellow and Huai River Valleys winter wheat zone (II), Middle and Lower Yangtze Valleys winter wheat zone (III), Southern winter wheat zone (IV), Southwestern winter wheat zone (V), Northeastern spring wheat zone (VI), Northern spring wheat zone (VII), Northwestern spring wheat zone (VIII), Qinghai-Tibetan Plateau spring and winter wheat zone (IX), and Sinkiang winter and spring wheat zone (X) respectively. Experimental sites were grouped according to four regional experiments, experimental sites belong to different experimental regions were denoted by 1, 2, 3 and 4 on the map

Materials and Methods

Data Source

The new wheat varieties need to be tested in designed experiments at a number of trial locations before being released. These trial locations were divided into several regions according to agro-ecological zones of wheat growth in China. Yield and yield component data for our study came from four regional experiments of new wheat varieties, which primarily located within four agro-ecological zones (I, II, III and V) and carried out in 2005–2006 and 2006–2007 growing seasons (Fig. 1, Table 1). The four regional experiments were named according to corresponding agro-ecological zone and geographical position. Each regional experiment included 4–6 varieties and 10–21 experimental sites (Table 2). The local popularized variety was used as check variety in each experimental region. Check variety was using for comparison with the performance of new varieties.

Table 1 Altitude, longitude and elevation ranges, emergence, heading and maturity dates, seeding density and soil texture of four experimental regions

	Upper Yangtze Valleys (UY)	Middle and lower Yangtze Valleys (MLY)	Yellow and Huai Valleys (YH)	Northern Land (NL)
Zone number[a]	V	III	II	I
Longitude	98–112°	112–120°	107–120°	81–119°
Latitude	24–34°	30–33°	33–36°	36–40°
Elevation (m)	90–1899	1–177	1–595	5–1016
Mean emergence date	2 Nov.	29 Oct.	18 Oct.	7 Oct.
Mean heading date	19 Mar.	4 Apr.	14 Apr.	7 May
Mean maturity date	11 May	23 May	1 Jun.	16 Jun.
Seedlings m^{-2}	200	229	173	322
Soil name	Red soil, yellow soil	Yellow–brown soil	Brown soil	Cinnamon soil
Soil texture	Silty clay, sandy loam	Sandy clay loam	Silty clay loam, sandy loam	Silty clay loam

[a] Agro-ecological zone number that experimental regions were located within

Table 2 Varieties and number of experimental/meteorological sites of four experimental regions in 2005–2006 and 2006–2007 wheat growing seasons

Experimental regions	Varieties			Experimental sites		Meteorological sites
	Check	2005–2006	2006–2007	2005–2006	2006–2007	
Upper Yangtze Valleys (UY)	Chuan Mai107	Mian2001-12, Chuan Yu64002, Chuan W5436	ML2651, XK027-4, D002	21	20	15
Middle and Lower Yangtze Valleys (MLY)	Yang Mai158	Zhen02166, Ning030119, Zhen02168	Nan Nong04Y10, Ning030119, Zhen02166	17	17	15
Yellow and Huai Valleys (YH)	Xin Mai18	Heng Guan35, Li Gao6, Xin Mai19	Zhou98165, Liu Hu98, Huai Mai0454	19	17	13
Northern Land (NL)	Jing Dong8	Gan4564, Lun Xuan1556, Jing Nong01-223, Chang Mai119, Chang6452	Jing Nong03-32, Lun Xuan1556, Jing Nong01-223, Chuang Mai119, Chang6452	12	11	8

The check variety listed was used in both years of each experimental region

Varieties with relatively stable characteristics and stable yield levels were chosen for this research. The same check varieties within a regional experiment were used in both growing seasons, although varieties within a regional experiment slightly differed between 2005–2006 and 2006–2007.

Daily climate data (including daily mean temperature, precipitation and sunshine duration) for most of the experimental sites (Table 2) were obtained from China Meteorological Administration. All meteorological sites were in the same city or county with the corresponding experimental sites. Mean temperature, precipitation and sunshine duration of each experimental region were calculated the average value of all experimental sites for each experimental region.

Experimental Regions

Longitude, altitude, emergence, heading and maturity dates, seeding density and soil texture of four experimental regions were listed in Table 1. Most experimental sites of the Upper Yangtze Valleys (UY) experimental regions located in the Southwestern winter wheat zone (V), all experimental sites of the Middle and Lower Yangtze Valleys (MLY) and the Yellow and Huai Valleys (YH) experimental regions located in the Middle and Lower Yangtze Valleys winter wheat zone (III) and the Yellow and Huai Valleys winter wheat zone (II) respectively (Fig. 1). Experimental sites of the Northern Land (NL) located in the North China Plan winter wheat zone (I) except one which located in the Sinkiang winter and spring wheat zone (X).

Latitude of UY, MLY, YH and NL experimental regions were increased in turn. The emergence date was earlier in turn as the latitude increased, heading and maturity date were later in contrast. The results indicated that the growth period was longer in turn as the latitude increased. Seedling density of YH experimental region was the least, which of NL experimental region was the highest.

Field Experimental Plan

Uniform experimental design and measurements were used for the four experimental regions. The experimental design was a randomized complete block with three replicates. Management practices (e.g., tillage practices, planting dates and rates, fertilizer and irrigation management) were matched to normal production practices of the experimental region and site. There was no water and fertilizer stress across all the experimental sites. Weed control was by both chemical and hand cultivation methods.

Spike number m^{-2} (SN) was calculated by counting all spikes contained in 1 m of a central row in each plot just before maturity. Kernel number $spike^{-1}$ (KN) was determined by counting kernels of 50 spikes randomly selected in each plot before harvest. Kernel weight (KW) was determined by weighing 1000 kernels randomly selected from each plot. Grain yield was determined by harvesting the entire plot using hand and threshing the seed.

Statistical Analysis

Path analysis was a useful tool to clarify the complex interaction between yield components and improve crop yield (Güler et al. 2001; García del Moral et al. 2003; Cooper et al. 2012). Path coefficient analysis was performed to partition the correlation coefficient, r_{ij}, into direct and indirect effects among SN, KN, KW, and yield (Fig. 2). Subscripts indicated the yield components and yield, with 1, 2, 3 and 4 indicating SN, KN, KW and yield respectively. The following three sets of simultaneous equations were solved to determine the path coefficient, P_{ij}:

$$r_{14} = P_{14} + r_{12}P_{24} + r_{13}P_{34} \tag{a}$$

$$r_{24} = r_{12}P_{14} + P_{24} + r_{23}P_{34} \tag{b}$$

$$\mathrm{r}_{34} = \mathrm{r}_{13}\mathrm{P}_{14} + \mathrm{r}_{23}\mathrm{P}_{24} + \mathrm{P}_{34} \tag{c}$$

In the equation $r_{14} = P_{14} + r_{12}P_{24} + r_{13}P_{34}$, r_{14} *is* the correlation coefficient between 1 and 4, P_{14} is the direct effect of 1 on 4 (the path coefficient) while $r_{12}P_{24}$ is the indirect effect of 1 on 4 via 2. Similar definitions apply to the other equations.

Path analysis was performed using genotypic correlation considering grain yield as the dependent variable and SN, KN and KW as independent variables. To satisfy the assumption of additivity for the path-coefficient analysis, yield and yield components data were logarithmically transformed prior to analysis. Variance analysis and correlation coefficients of yield and its components were obtained using the Statistical Product and Service Solutions (SPSS 16.0).

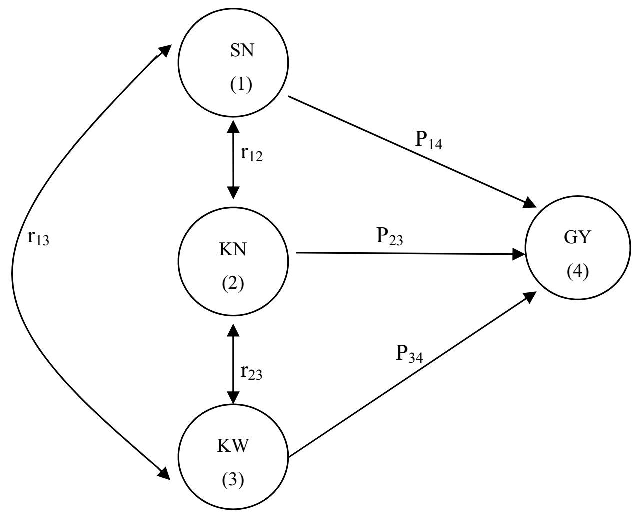

Fig. 2 Path coefficient diagram showing the interrelationships among (1) spike number m^{-2} (SN), (2) kernel number $spike^{-1}$ (KN), (3) kernel weight (KW), and (4) grain yield (GY). The single-headed arrows indicate path coefficients, and the double-headed arrows indicated simple correlation coefficients

Results

Climatic Conditions of Four Experimental Regions

Temperature, precipitation and sunshine duration of each month during wheat growing seasons of 2005–2006 (a, c and e) and 2006–2007 (b, d and f) in UY, MLY, YH and NL were shown in Fig. 3. Temperature of each month increased in accordance with the order of NL, YH, MLY and UY, this order of experimental regions also was from North to South on the map (Fig. 1). Temperature had a big difference among these four experimental regions on December, January, February and March, which were the formation stage of SN and KN.

Precipitation of MLY and NL were highest and lowest respectively (Fig. 3c), which were 497 and 71 mm during 2005–2006 wheat growth season and 489 and 106 mm during 2006–2007 wheat growth seasons. Sunshine duration of these four experimental regions were almost increased from South to North, UY may greater than MLY in some months during these two wheat growth seasons.

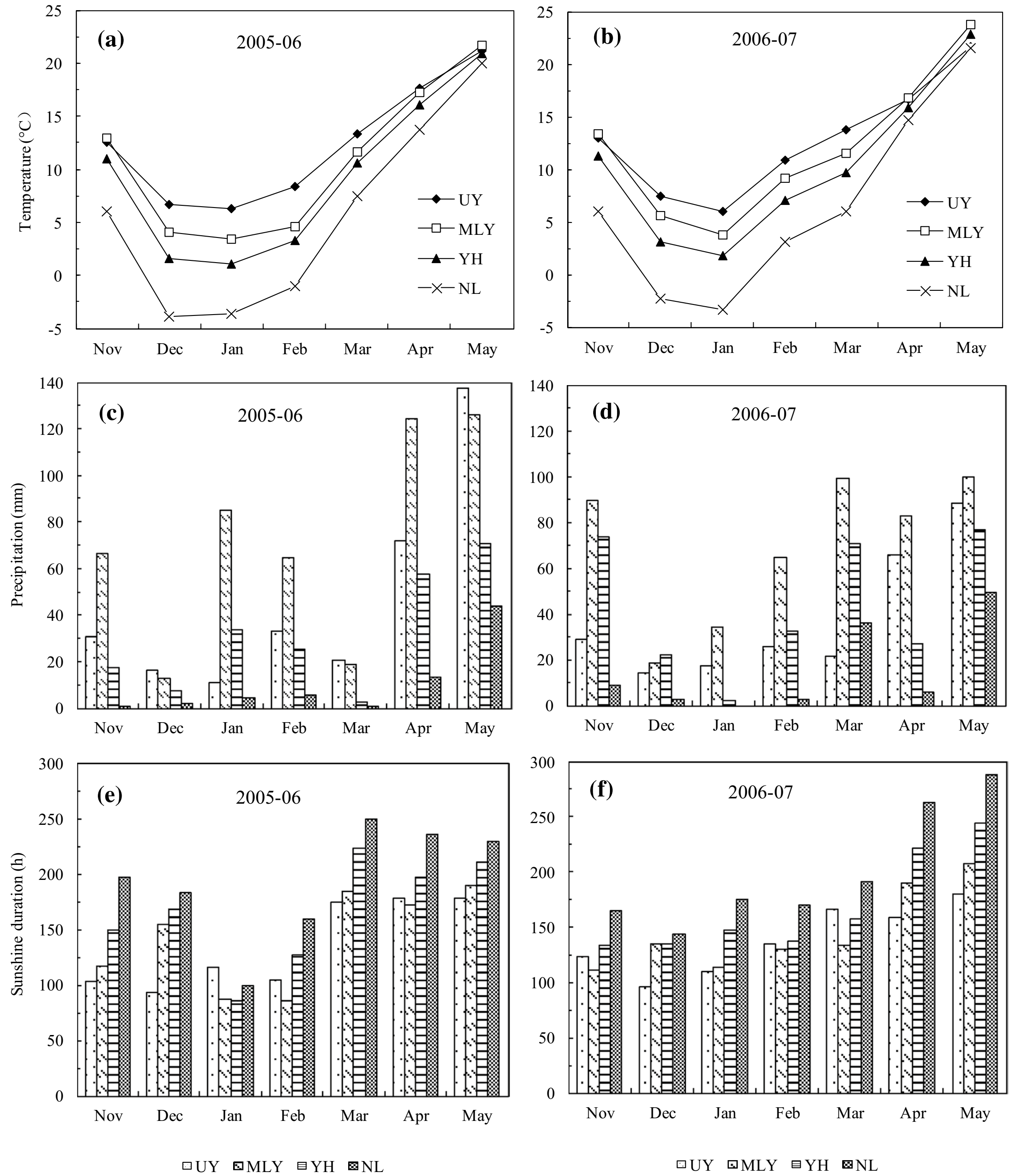

Fig. 3 Temperature, precipitation and sunshine duration of each month during wheat growing seasons of 2005–2006 (**a**, **c**, **e**) and 2006–2007 (**b**, **d**, **f**) in the Upper Yangtze Valleys (UY), the Middle and Lower Yangtze Valleys (MLY), the Yellow and Huai Valleys (YH) and the Northern Land (NL)

In summary, UY and MLY were warmer and moister than YH and NL experimental region, and sunshine hour of which were lower. YH and NL were relatively cooler and arid experimental regions with longer sunshine hour.

Yield and Yield Components in Four Experimental Regions

Mean and coefficient of variation values for grain yield and yield components varied among the four experimental regions and two growing seasons (Table 3). Mean yields within experimental regions were similar for the

Table 3 Mean and coefficient of variation values of yield and yield components in four experiments regions during 2005–2006 and 2006–2007 wheat growing seasons

	Upper Yangtze Valleys (UY)		Middle and lower Yangtze Valleys (MLY)		Yellow and Huai Valleys (YH)		Northern Land (NL)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
Yield (t ha^{-1})								
Mean	5.7	6.0	6.0	6.4	8.1	8.1	6.3	6.7
CV	0.207	0.235	0.164	0.160	0.103	0.095	0.208	0.160
Spikes (m^{-2})								
Mean	365	369	465	444	574	580	603	624
CV	0.212	0.219	0.159	0.172	0.126	0.130	0.148	0.161
Kernels (spike^{-1})								
Mean	40	42	38	38	36	36	32	31
CV	0.132	0.138	0.134	0.212	0.104	0.136	0.152	0.157
1000-kernel weight (g)								
Mean	43.2	44.4	40.8	44.5	40.8	41.9	40.4	40.8
CV	0.131	0.090	0.093	0.098	0.073	0.113	0.145	0.118

two growing seasons (differences ranged from 13 to 396 kg ha^{-1}), with YH and UY having the highest and lowest yields, respectively, of the experimental regions. Mean yields increased from South to North except for a decrease in the NL experimental region. As observed for yield, mean yield components were quite consistent within the four experimental regions in the two growing seasons. Trends with latitude of the yield components showed that SN tended to increase, and KN tended to decrease, with increasing latitude. No consistent trend was noted for KW.

Coefficients of variation (CV) for grain yield in the YH experimental region were less than other regions for both growing seasons (Table 3). In almost all instances for both growing seasons, the CV of SN were greater than KN and KW, which indicated that the formation of SN was most sensitive to differences in environments. The CV of KW were the least during both growing seasons, indicated that the formation of KW was less sensitive to differences in environments. Coefficients of variation for grain yield, SN, KN and KW in YH were the lowest for all experimental regions, and this result might indicate that wheat production in YH is the most stable of four experimental regions.

Analysis of Variance (ANOVA) was conducted for yield and yield components in four experimental regions during 2005–2006 and 2006–2007 wheat growing seasons (Table 4). The ratios of sum of squares for varieties/

Table 4 Analysis of Variance (*ANOVA*) for yield and yield components in four experiments regions during 2005–2006 and 2006–2007 wheat growing seasons

Source	Upper Yangtze Valleys (UY)		Middle and lower Yangtze Valleys (MLY)		Yellow and Huai Valleys (YH)		Northern Land (NL)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
Yield (t ha^{-1})								
Varieties	0.7	2.3	3.1	1.6	5.3	5.6	3.3	6.9
Environment	89.7	91.9	87.4	89.1	83.2	70.2	85.7	82.5
Spikes (m^{-2})								
Varieties	3.2	5.1	19.4	9.3	6.3	30.0	4.6	4.0
Environment	83.7	88.3	61.6	75.9	66.6	46.7	68.0	74.4
Kernels (spike^{-1})								
Varieties	8.9	18.4	26.7	14.1	12.2	31.8	26.9	34.0
Environment	61.8	51.0	53.9	72.1	43.4	49.8	39.2	41.7
1000-kernel weight (g)								
Varieties	3.8	6.5	4.4	24.1	8.4	22.2	25.8	15.3
Environment	80.5	68.5	71.8	63.4	55.0	56.0	52.5	65.2

The ratios of sum of squares for varieties/environment to total sum of squares (%) were listed in this table environment to total sum of squares were calculated to analyze which was the main factor to influence the variation of yield and yield components. The ratios of varieties for yield changes from 0.7 to 6.9% across four experiment regions. The ratios of varieties for SN were mostly below 9.4% except MLY (2005–2006) and YH (2006–2007), and which for KN and KW mostly more than 10% while still lower than the ratios of environment. The results indicated that variations of yield and yield components for each experimental region mainly due to the changes of environments as the ratios of varieties were lower.

Developmental Phases and Relationship With Yield Components

The observed trend of the SN and KN with increasing latitude among experimental regions might be related to differences in the length of developmental phases among experimental regions (Fig. 4). If the growing season is divided into two developmental phases (emergence to heading and heading to physiological maturity), both the number of days from emergence to heading and emergence to maturity gradually increased with increasing latitude, while the number of days from heading to maturity was not related to latitude (or even slightly decreased). Lower temperature extended the length from emergence to heading of winter wheat, leading to longer growth period finally. Yield and yield components probably be impacted by the changes of growth period.

The relationships between yield, yield components and corresponding developmental phases of check variety for four experimental regions were shown in Fig. 5. SN increased with the days from emergence to heading increase, and KN decreased, which probably due to strong competition of resources with SN. Yield increased with the increase of emergence to maturity duration when the duration below about 240 days, and yield decreased when the duration greater than 240 days (NL region). The growth stage duration around 230 days (YH region) was appropriate for yield formation of winter wheat, with both higher SN and KN. 1000-kernel weight (KW) did not changed with the variation of heading to maturity duration.

Correlation Analysis Between Climate Elements and Yield/Yield Components

The relationship between yield, SN, KN and mean values of meteorological elements from emergence to heading were analyzed for four experimental regions (Table 5). Yield was significantly positively related with sunshine duration (SD), and significantly negatively related with precipitation (P) in UY and MLY. A significantly negative relationship was also found between temperatures (T) and yield in MLY. No significant relationships were found between yield and climate elements in YH and NL. Significant positive relationships were found between SN and SD in UY and MLY. The relationship between SN and T/P were significant negative in MLY. KN was significant negatively related with P in UY and YH, and the relationship with SD in MLY and T in NL was significant positive.

The relationship between yield, KW and climate elements from heading to maturity of two growing seasons were also analyzed (Table 5). Yield was negatively related with P, and positively related with SD in UY. KW was positively related with T and SD in YH. The other relationships between yield/KW and climate elements were poor.

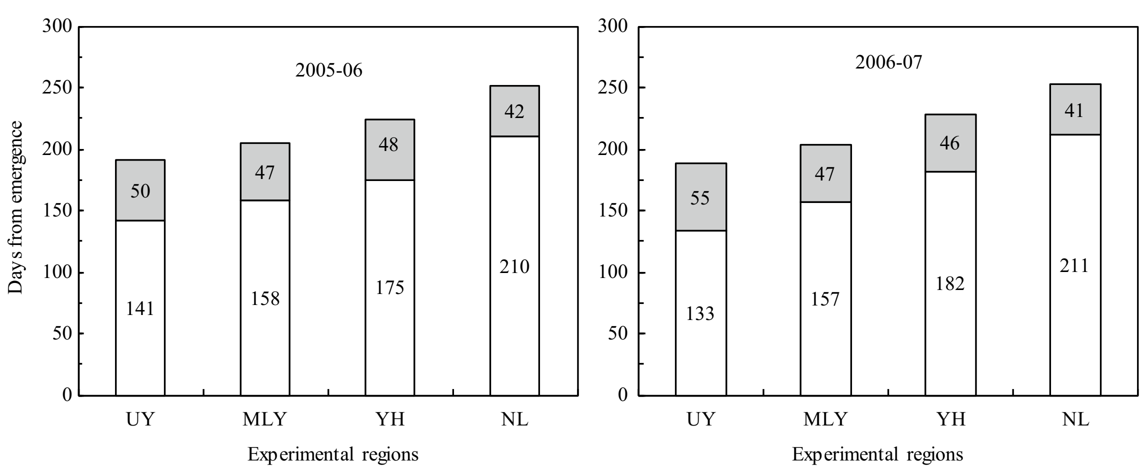

Fig. 4 Days from emergence to heading (white square) and heading to physiological maturity (grey square) of the check varieties in each experimental region for 2005–2006 and 2006–2007 growing season. The experimental regions are listed by increasing latitude, and denoted by UY (Upper Yangtze Valleys), MLY (Middle and Lower Yangtze Valleys), YH (Yellow and Huai Valleys) and NL (Northern Land) respectively

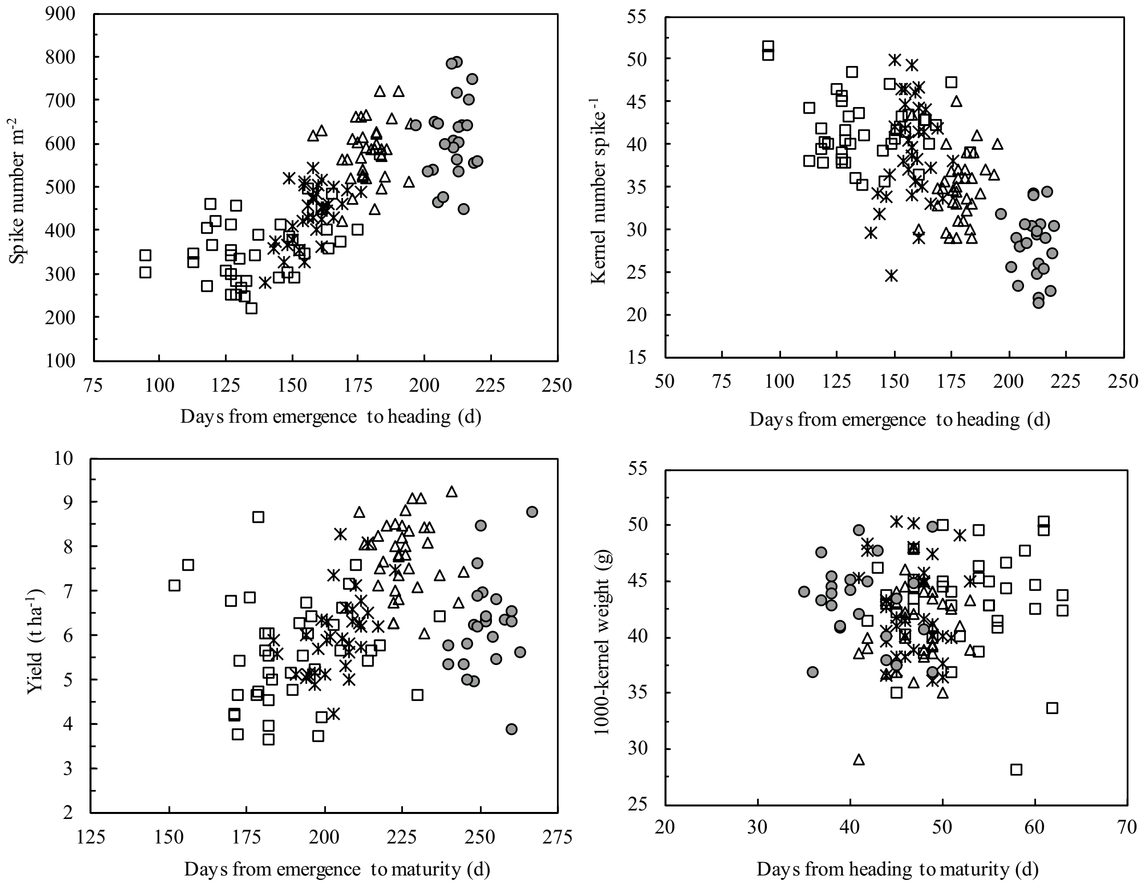

Fig. 5 The relationships between yield, yield components and developmental phases (involved emergence to maturity, emergence to heading and heading to maturity) of the check varieties in UY (white square; n = 30), MLY (asterisk; n = 30), YH (triangle; n = 26) and NL (black circle; n = 16)

Table 5 Correlation coefficients among yield, spike number m^{-2} (SN), kernel number $spike^{-1}$ (KN), kernel weight (KW) and mean values of daily mean temperature (T), sunshine duration (SD) and precipitation (P) from emergence to heading and from heading to maturity of wheat in Upper Yangtze Valleys (UY, n = 30), Middle and lower Yangtze Valleys (MLY, n = 30), Yellow and Huai Valleys (YH, n = 26) and Northern Land (NL, n = 16)

	UY			MLY			YH			NL		
	T	SD	P	T	SD	P	T	SD	P	T	SD	P
From emergence to heading												
Yield	0.276	0.506**	− 0.551**	− 0.472**	0.566**	− 0.509**	0.165	0.214	− 0.002	0.106	− 0.45	− 0.155
SN	− 0.163	0.396*	− 0.216	− 0.523**	0.424*	− 0.493**	− 0.333	− 0.171	− 0.331	0.027	− 0.29	− 0.248
KN	0.353	0.154	− 0.371*	− 0.169	0.445*	− 0.125	− 0.306	0.079	− 0.403*	0.686**	− 0.207	− 0.307
From heading to maturity												
Yield	0.248	0.511**	− 0.494**	− 0.319	0.314	− 0.271	0.006	− 0.005	− 0.237	0.296	0.182	− 0.337
KW	0.112	0.212	− 0.344	0.316	− 0.228	− 0.019	0.500**	0.459*	0.116	0.194	0.189	− 0.215

** Significant $P < 0.001$ * significant $P < 0.05$

Correlation Analysis Between Yield and Yield Components

Correlation analysis was conducted among yield and three yield components across four experimental regions (Table 6). A highly significant positive relationship was found between grain yield and SN in UY and NL in the two growing seasons. KW was also significant positively related

Table 6 Correlation coefficients between yield and yield components in four experimental regions of China during 2005–2006 and 2006–2007 wheat growing seasons

Experimental regions	Spike number m^{-2} (SN)		Kernel number $spike^{-1}$ (KN)		Kernel weight (KW)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
Upper Yangtze Valleys (UY)						
Yield	0.658**	0.701**	0.096	0.300**	0.538**	0.329**
SN			– 0.401**	0.109	0.130	– 0.001
KN					0.127	– 0.127
Middle and lower Yangtze Valleys (MLY)						
Yield	0.225	0.181	0.015	0.422**	0.481**	– 0.379**
SN			– 0.322**	0.037	– 0.126	– 0.347**
KN					– 0.207	– 0.665**
Yellow and Huai Valleys (YH)						
Yield	0.290**	0.197	0.118	0.225	0.242*	0.17
SN			– 0.319**	– 0.429**	– 0.408**	– 0.412**
KN					0.002	– 0.092
Northern Land (NL)						
Yield	0.699**	0.517**	0.132	0.135	0.359**	0.139
SN			0.107	– 0.151	0.053	– 0.384**
KN					– 0.271*	– 0.079

** Significant P < 0.001 * significant P < 0.05

with yield in UY and NL except 2006–2007 growth season of NL, while the correlation coefficients were lower than SN. These results indicated that yield were mainly determined by SN in UY and NL region. KN Only had significant positive relationship with yield in UY and MLY region in 2006–2007 growing season, which indicated that the role of KN on yield was minor. The significant positive relationship only found between KN (2006–2007) and yield, KW (2005–2006) and yield in MLY region. All correlation coefficients of three yield components on yield were low in YH region. Inconsistent with other regions, strongly negative relationships between SN and KN, KW were found in YH region, which indicated that three yield components were strong competitive relationship during wheat growth.

Path Coefficient Analysis Between Yield and Yield Components

Path coefficient analysis (Table 7) was performed to obtain further information on the relationship between grain yield and yield components for the four experimental regions. The sequence for direct effects of three yield components on grain yield from high to low were SN, KW, and KN, except 2006–2007 growth season in MLY. SN was the main factor which determined the changes of yield, especially in UY and NL, which had the greatest direct effects and determination coefficients of SN on yield for four regions. Direct effects of KW and KN on yield in YH region were higher than other regions except KW of MLY (2005–2006), which indicated that the role of KW and KN became important in YH region. Although the direct effects of three yield components of YH region were all higher, the correlation and determination coefficients were all lower because of the negative indirect effect of SN via other yield components.

Discussion

Temperature and solar radiation were the key weather factors that caused yield changing from year to year (Fischer 2007; Yang et al. 2013). Precipitation during the vegetative stage had significant relationship with yield in Australia (Yu et al. 2014), especially in the arid area in China (Zhang and Zhang 2016; Zhang et al. 2016). Our research showed that yield, SN and KN were negatively influenced by higher temperature and lower sunshine hour from emergence to heading growth stage at warmer and humid production regions (UY and MLY). Li et al. (2010) also reported that the variability of precipitation had a negative impact on wheat yield in parts of southeast China. Most of relationships between yield and climate elements were poor at cooler and arid production regions (YH and NL), which showed that climate conditions of YH and NL were probably more proper for wheat growth and yield formation. Yield and yield components would also be influenced by management and soil except climate, which were not considered in this research due to lack of data.

The relationship between yield components were commonly negative as the competition for resources during growth process (Slafer et al. 2014), especially the relationship between SN and KN. García del Moral et al. (2003) reported that negative effects of SN on KN and KW of durum wheat were found under warmer conditions, while

Table 7 Path coefficient analysis between grain yield and yield components in four experimental regions during 2005–2006 and 2006–2007 wheat growing seasons

Pathway	Upper Yangtze Valleys (UY)		Middle and lower Yangtze Valleys (MLY)		Yellow and Huai Valleys (YH)		Northern Land (NL)	
	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007	2005–2006	2006–2007
Spike number m^{-2} vs. grain yield								
Direct effect	0.744	0.672	0.382	0.133	0.582	0.625	0.662	0.728
Indirect effect via								
Kernel number $spike^{-1}$	− 0.138	0.03	− 0.083	0.013	− 0.096	− 0.231	0.017	− 0.042
Kernel weight	0.052	0	− 0.073	0.035	− 0.195	− 0.197	0.019	− 0.169
Correlation	0.658	0.702	0.225	0.181	0.29	0.197	0.699	0.517
Determination coefficient (%)	43.3	49.3	5.0	3.3	8.4	3.9	48.8	26.7
Kernel number $spike^{-1}$ versus grain yield								
Direct effect	0.343	0.275	0.259	0.35	0.302	0.538	0.16	0.28
Indirect effect via								
Spike number m^{-2}	− 0.298	0.073	− 0.123	0.005	− 0.186	− 0.268	0.071	− 0.11
Kernel weight	0.05	− 0.048	− 0.121	0.067	0.001	− 0.044	− 0.099	− 0.035
Correlation	0.095	0.3	0.015	0.422	0.117	0.226	0.131	0.135
Determination coefficient (%)	0.9	9.0	0	17.8	1.4	5.1	1.7	1.8
Kernel weight versus grain yield								
Direct effect	0.397	0.375	0.583	− 0.101	0.479	0.478	0.367	0.44
Indirect effect via								
Spike number m^{-2}	0.097	0	− 0.048	− 0.046	− 0.237	− 0.258	0.035	− 0.28
Kernel number $spike^{-1}$	0.044	− 0.035	− 0.054	− 0.233	0.001	− 0.05	− 0.043	− 0.022
Correlation	0.537	0.339	0.481	− 0.379	0.242	0.171	0.359	0.138
Determination coefficient (%)	28.9	11.5	23.2	14.4	5.9	2.9	12.9	1.9

negative effects were absent in the cooler environments. Acreche and Slafer (2006) reported that competitive relationship between grain number and grain weight of wheat were minor in a Mediterranean area. Significantly negative relationships between SN and KN, KW were only found in experimental region with high and stable yield (YH) during two growth seasons for this research. There were strong trade-offs between three yield components when grain yield was high and stable.

Grain number was strongly source-limited and grain weight was limited by its own sink-strength. So grain number was more variable than grain weight (Peltonen-Sainio et al. 2007; Sadras 2007; Sadras and Slafer 2012). Spike number per m^2 accounted for most of the variation in grain number (Slafer et al. 2014; Kennedy et al. 2017). Agreed with the results of previous studies, we found the variations of SN and KN were significant greater than KW across four experimental regions and two growth seasons. Yield changes were mainly determined by grain number (Slafer 2003; Fischer 2011) or head number (Cooper et al. 2012). While García del Moral et al. (2003) reported that grain yield under warmer conditions was mostly determined by SN, whereas KW predominantly influenced grain production in the cooler environments. Our research results showed that SN was the main factor which determined yield changes, especially in the regions with low yield level (UY and NL). The number of spike was guarantee of yield, increasing SN would be more effective in improving grain yield under source-limited conditions (Cooper et al. 2012). KW and KN became important for yield in YH region with high yield level, confirms previous report by Peltonen-Sainio et al. (2007), the role of grain weight became increasingly important at a high yield condition. Yield components should be balanced development when yield level increase (Duggan and Fowler 2006).

Conclusions

SN was the main factor to determine the variation of yield, the second one was KW, the influence of KN on yield was mainly via the negative relationship with SN. Yield increased with the increase of SN from South to North until SN reached a certain level which led to KN decrease a lot, and then yield corresponding decreased. Yield in the YH region was the greatest with both higher SN and KN, which probably due to proper climate conditions. SN was the main factor influencing yield, especially at low yield level regions. The role of KW and KN became important when yield level increase.

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