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Effects of Weak- and Semi-Winter Cultivars of Wheat on Grain Yield and Agronomic Traits by Breaking through Traditional Area Planting

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Abstract: Global warming has changed the suitability of areas traditionally planted with crops, raising concerns about cereal security. To investigate the possibilities and constraints of increasing yields by breaking through traditional area plantings of wheat cultivars, a two-year field experiment was conducted in southern and northern locations in the Yangtze River basin (YRB), China (separated by approximately 180 km), with seven weak-winter types and six semi-winter types, respectively, bred for the two regions. The movement of weak-winter-type cultivars to the north increased or did not change grain yield and their grain yields were not significantly higher than those of local semi-winter-type cultivars. The movement of semi-winter-type cultivars to the south significantly decreased their yields. Thus, breaking through traditional area plantings did not significantly increase grain yields compared with those of local wheat cultivars. Grain yield of wheat planted in the northern YRB was higher by 5 to 20% than that in the southern YRB because of an increase in spikes that resulted from a longer spike formation phase. In addition, the post-anthesis leaf area declined more slowly in the northern YRB because of higher main stem and tiller survival. High-yielding cultivars always had more spikes and larger photosynthetic areas after anthesis than those of low-yielding cultivars regardless of the planting locations, which led to increases in post-anthesis biomass. However, the grain yield of different cultivars was highly variable under different environmental conditions. The coefficient of variation (CV) of grain yield in different cultivars was significantly positively correlated with the CV of spike number and post-anthesis biomass, implying that flexibility spike number and post-anthesis biomass in response to environmental changes can maximize release of yield potential. Therefore, improving main stem and tiller survival can increase spike number and maintain post-anthesis photosynthetic areas and help to establish a large, highly stable, and productive population with a high level of suitability and production through effectively utilizing the resources during the late growth phase. Valuable suggestions for breeding high-yield and -stability cultivars and confirming their planting range in the future are given.

Keywords: biomass; grain yield; enlarging planting area; stem and tiller survival; weak- and semi-winter cultivars; Yangtze River basin

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1. Introduction

The mean global surface temperature increased approximately 1.0 °C in 2017 compared with the mean temperature from 1850 to 1900 [1]. Global warming decreased cold damage and expanded the planting area of wheat in mid and high latitudes [2], but it also increased soil water evapotranspiration and aggravated drought stress in arid and semiarid regions [3]. In low latitude regions, precipitation and its intensity have increased [4,5], resulting in increased frequency of waterlogging stress. To respond to changes in regional climate, some countries and regions, including Spain [6], Poland [7], the Mediterranean [8], and Norway [9], have adjusted the appropriate planting ranges of wheat cultivars to adapt to growth conditions and reduce possible stress damage and thereby maintain stable production. In the US, the adjustment of planting acreage can also increase wheat grain yields [10]. Therefore, the adjustment of planting regions has been a quick and efficient approach to address environmental changes caused by global warming.

Vernalization is an important biological character of wheat that is directly related to grain yield because it influences spike development and flowering time [11,12]. According to the duration of low-temperature exposure for flowering, winter wheat cultivars are divided into strong-winter, semi-winter, and weak-winter types [13]. The weak-winter type cultivars can adapt to a warm growth condition, but with a low low-temperature tolerance. Low-temperature stress can damage spikes and spikelets as well as reduce their numbers in weak-winter-type cultivars [14]. For semi- and strong-winter-type cultivars, the breeding climate is colder than that for weak-winter types and therefore, they experience less cold damage but also require long vernalization. When semi-winter-type cultivars are planted in a warm environment, the flowering time is delayed, which causes poor grain filling because of high-temperature stress during the late growth phase [15]. In addition, warm winters and frequency precipitation favor disease development [16], semi-winter-type cultivars are susceptible to the general diseases of weak-winter-type cultivars, which negatively affect grain yields of semi-winter-type cultivars [17]. These results indicate that the yield potential and stability of wheat cultivars bred for specific environments are affected when they are planted in other environments.

In China, the Yangtze River basin (YRB) is the main wheat production region, with winter wheat accounting for 25% of the area [18]. The YRB is in the north–south interface zone of China and the climate is very different between northern and southern regions. The mean temperature of the northern YRB (-5 to -1 °C) in the coldest month is lower than that of the southern YRB (2 to 6 °C) [19]. To avoid the negative effects of low-temperature stress on wheat growth, semi-winter-type cultivars are selected by breeders in the northern YRB, whereas weak-winter-type cultivars are planted in the southern YRB [19]. However, with the warming of the climate, the planting zoning division of wheat has become indistinct [10] and farmers now plant semi-winter-type cultivars in the southern YRB to pursue high grain yields. The semi-winter-type cultivars have a shorter vernalization time than that of the previous cultivars bred under low-temperature growing conditions in order to reduce high-temperature damage after the anthesis stage [15]. In addition, the yield potential of the semi-winter-type cultivars is considered to be higher than that of the weak-winter types [12,20]. Additionally, gibberellic disease, a common disease in the southern YRB, has moved northward [21]. To reduce economic losses from the disease, farmers in the northern YRB select cultivars with high gibberellic disease resistance, which are mostly bred in the southern YRB and are weak-winter types [21]. Although farmers are currently practicing breaking through traditional area planting of wheat cultivars in the YRB, information on its effects on yield components, biomass production, and their stability is lacking.

In the present study, a two-year field experiment was conducted at Suining (northern YRB, China) and Yangzhou (southern YRB, China) with the same 13 winter wheat cultivars, composed of seven weak-winter-type and six semi-winter-type cultivars. The objectives of this study were to (1) quantify the differences in grain yield and associated traits among different wheat cultivars and vernalization types, (2) determine the changes in grain yield and associated traits by breaking through traditional area planting, and (3) examine the possibility of breaking through traditional area planting to increase yields and the key constraints.

2. Materials and Methods

2.1. Experimental Design and Treatments

The field experiments were conducted at two sites in China during the wheat seasons of 2016 to 2017 (2017) and 2017 to 2018 (2018). The sites were the Agricultural Experiment Station of Yangzhou University (32°23′ N, 119°25′ E,) in Yangzhou University, China and the Morden Agricultural Center of Suining (33°59′ N, 117°56′ E) in Suihe village, Suining, China, which are about 180 km between the Yangzhou (southern YRB) and Suining (northern YRB), the altitude of Yangzhou and Suining were 12 and 23 m, respectively. The soil at the two sites is a loamy clay mix and nutrient contents in the 0 to 20 cm soil layer were collected before sowing each year (Table 1), the organic matter content was detected based on the potassium dichromate volumetric method, the available nitrogen, phosphorus, and potassium were measured alkali diffusion method, molybdenum blue method, and NH_4OAc extraction–flame photometric method, respectively [22,23]. The precipitation and mean temperatures during the wheat growing seasons are shown in Figure 1.

Table 1. Soil nutrient contents in experimental winter wheat fields in the southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Site	Season	Organic Matter (g kg^{-1})	Available Nitrogen (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})
Yangzhou	2017	21.82	77.67	76.47	114.50
	2018	18.41	77.25	98.98	58.26
Suining	2017	15.29	71.09	16.03	103.00
	2018	15.17	66.07	44.31	69.65

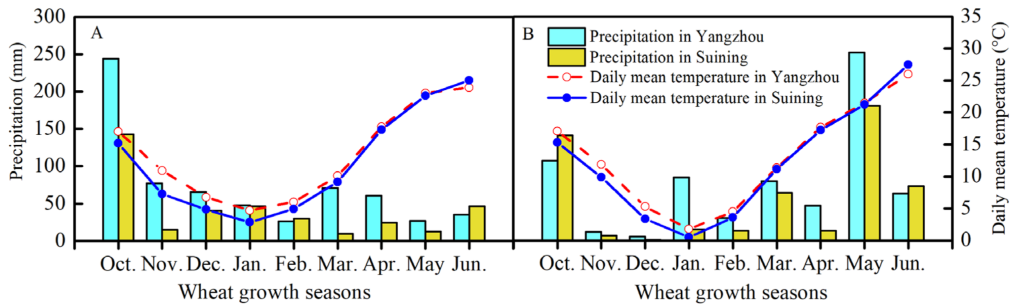

Figure 1. Precipitation (mm) and daily mean temperature (°C) during the wheat growth period in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2016 to 2017 (**A**) and 2017 to 2018 (**B**).

The cultivars included seven weak-winter types released in the southern YRB and six semi-winter types released in the northern YRB. The year of release and genealogy of the cultivars are shown in Table S1. According to the statistics of the China National Seed Association [24], Ningmai 13, Yangmai 16, and Yangmai 20 were sown cumulatively over 1.5, 2.5, and 5.2 million hectares, respectively, in the southern YRB, and Zhengmai 9023, Emai 596, and Jimai 22 were sown cumulatively over 15 million hectares in the northern YRB. The other cultivars were released after 2010 and their sown area increased quickly.

In the two sites in the two years, all cultivars were planted randomly in three blocks (three replications). In each plot, the 13 wheat cultivars were randomly assigned to subplots, with each subplot 18 m^2 (6 m × 3 m). Seeds were sown by hand into rows at a depth of approximately 3 cm and a spacing of 25 cm. In 2016, all cultivars were sown on 16 November at Yangzhou and on 17 November at Suining, and in 2017 on 1 November at Yangzhou and on 28 October at Suining. At the three-leaf stage (Zadoks stage, GS13), seedlings were removed or transplanted manually to the density of 225 plants m^{-2}. In both sites and years, each plot received 120, 24, 48, and 48 kg of nitrogen per hectare at the pre-sowing, four-leaf (GS14), stem elongation (GS32), and booting (GS45) stages, respectively.

Phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied twice at 60 kg ha^{-1} at the pre-sowing and elongation stages. Herbicides, pesticides, and fungicides were used according to the local standard practices and diseases, insects, and weeds did not affect the yield in the experiments.

2.2. Measurements and Data Analysis

2.2.1. Phenological Development

The anthesis and maturity dates of each cultivar were recorded. The anthesis date was the date on which 50% of wheat ears were flowering in a plot. The maturity date was the date on which grain could not be dented by thumbnail.

2.2.2. Yield and Yield Components

Wheat within 1 m^2 (four 1 m long rows spaced at 25 cm) in the middle of each subplot was harvested by hand and the area was not sampled before harvesting. The grains were threshed, air-dried, and weighed. The number of spikes was counted before harvesting at the maturity stage (GS92) in the harvest area. The spike yield was calculated as single grain weight multiplied by the number of kernels per spike and the single grain weight was calculated as the mean of 1000 random grain weights from harvested grain. The number of kernels per spike was determined as described by Ding et al. [25]. The grain moisture was measured using a Grain Analyzer (Infratec™ 1241, Foss, Denmark) and the grain yield and single grain weight were adjusted to a standard 13% moisture content.

2.2.3. Maximum Stem and Tiller Number, and Main Stem and Tiller Survival

To determine the maximum stem and tiller number, the stem and tiller number within 1 m^2 was recorded at the elongation stage (GS30). Main stem and tiller survival was calculated by dividing the spike number at the maturity stage by the maximum stem and tiller number and expressed as a percentage.

2.2.4. Leaf Area Index

Twenty plants were selected from each plot at the anthesis and milk-ripe (GS75) stages. The green leaf area was measured using a leaf area meter (LI-3000, Li-Cor Inc., Lincoln, NE, USA) and the leaf area index (LAI) was defined as the green leaf area per ground surface area [26]. The decrease in LAI from anthesis to the milk-ripe stage was calculated as follows:

$$\text{Decrease in LAI (\%)} = (\text{LAI at anthesis} - \text{LAI at milk-ripe})/\text{LAI at anthesis} \times 100. \quad (1)$$

2.2.5. Biomass

Twenty plants were harvested from each plot at the anthesis (GS65) and maturity stages and then separated into stems and sheaths, leaf blades, and spikes. All samples were oven-dried at 80 °C until constant weight and then weighed to determine biomass. The biomass at anthesis was the pre-anthesis biomass and the difference in biomass between anthesis and maturity stages was the post-anthesis biomass. To determine the maximum stem and tiller number, the stem and tiller number within 1 m^2 was recorded at the elongation stage (GS30). Main stem and tiller survival was calculated by dividing the spike number at the maturity stage by the maximum stem and tiller number and expressed as a percentage.

2.2.6. Coefficient of Variation

The coefficient of variation (CV) indicates the degree of variation in an agronomy trait under different treatments [27]. The CV was calculated as follows:

$$\mathrm{CV} = \mathrm{a}/\overline{\mathrm{b}} \times 100 \quad (2)$$

where a is the standard deviation of a trait in the two years at the two sites and $\bar{b}$ is the average of the trait.

2.3. Statistical Analyses

All data were analyzed with ANOVA in each year using SPSS 19.0 (SPSS, Inc., Chicago, IL, USA). The ANOVA model was based on a split-plot design with site (S) as the main-plot factor, cultivar (C) as the subplot factor, and replicate as the random factor. Considering that two types of cultivars were examined, i.e., weak-winter and semi-winter types, a second ANOVA was conducted according to a completely random design to compare the differences between the types. The differences between the planting sites were also compared separately for weak-winter and semi-winter types using the ANOVA with a completely random design. The least significant difference (LSD) at the 5% level was used to compare the differences in agronomy traits among different cultivars in each year.

3. Results

3.1. Phenology

The growth period of wheat was different between years and sites with a longer period in 2018 than in 2017 (Table 2). The growth period of wheat was longer at Suining than at Yangzhou in both years, mainly because of a longer phase from sowing to anthesis, even though the duration from anthesis to maturity was shorter. A lower accumulated temperature before anthesis (in late April) at Suining could lead to a slower plant development at Suining than at Yangzhou (Figure 1), resulting in a later date of anthesis. However, the temperature from April to June increased rapidly and was similar between the two sites, accelerating maturation at Suining. The cultivars planted at the same site showed similar total growth periods with a difference of at most five days. The total growth period of the weak-winter types was close to that of the semi-winter types when they were planted at Yangzhou, with a difference of less than one day. However, at Suining, the growth period of weak-winter types was shorter by two to three days than that of semi-winter types because of a shorter duration before anthesis.

Table 2. Days in growth phases from sowing (SD) to anthesis (AS), anthesis to maturity (MS), and total phases of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Cultivar	Days of Growth Phase											
	Yangzhou 2017			Suining 2017			Yangzhou 2018			Suining 2018		
	SD–AS	AS–MS	Total	SD–AS	AS–MS	Total	SD–AS	AS–MS	Total	SD–AS	AS–MS	Total
Weak-winter type												
Annong 1124	151	41	192	163	35	198	163	45	208	180	37	217
Sumai 188	151	41	192	163	35	198	161	47	208	178	37	215
Yangmai 23	149	40	189	163	35	198	161	47	208	177	37	214
Yangmai 20	152	40	192	163	35	198	164	44	208	177	37	214
Ningmai 13	151	40	191	163	35	198	160	48	208	178	37	215
Haomai 1	151	41	192	163	35	198	160	48	208	178	37	215
Yangmai 16	151	41	192	163	35	198	161	47	208	178	37	215
Average	150.8	40.6	191.4	163.0	35.0	198	161.4	46.6	208	178.0	36.8	214.8
Semi-winter type												
Zhengmai 9023	152	40	192	164	35	199	160	48	208	180	37	217
Emai 596	151	40	191	165	35	200	160	48	208	180	37	217
Annong 0711	155	38	193	167	34	201	168	42	210	185	34	219
Emai 580	150	40	190	165	35	200	161	47	208	180	37	217
Huaimai 35	153	39	192	166	35	201	164	45	209	182	35	217
Jimai 22	157	37	194	167	34	201	168	42	210	185	34	219
Average	152.6	39.5	192.1	165.6	35.0	200.6	163.5	45.3	208.8	182.0	35.0	217

3.2. Grain Yield

Grain yield was significantly higher at Suining (by 20% in 2017 and by 5% in 2018) than that at Yangzhou in both years and there were large differences among cultivars (Table 3). Grain yields of different cultivars were variable between the two planting sites. Compared with other cultivars, Huaimai 35 had the highest grain yields in 2017. In 2018, Annong 0711 had the highest grain yield at both sites. The CV value of grain yield of different cultivars was highly variable across years and sites. Among the cultivars, Haomai 1, Zhengmai 9023, and Annong 0711 had relatively stable grain yields (CV < 10%).

Table 3. Grain yield ($t\ ha^{-1}$) of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Cultivar	Grain Yield ($t \times ha^{1}$)				CV (%)
	Yangzhou 2017	Suining 2017	Yangzhou 2018	Suining 2018	
Weak-winter type (Weak)					
Annong 1124	7.37	7.97	5.60	5.38	19.5
Sumai 188	6.79	8.77	6.06	6.81	16.3
Yangmai 23	6.21	8.46	5.64	6.01	19.4
Yangmai 20	6.07	7.61	6.30	5.94	11.9
Ningmai 13	5.92	8.55	6.12	7.22	17.4
Haomai 1	5.81	6.24	6.29	5.98	3.7
Yangmai 16	5.58	8.36	6.82	6.33	17.3
Average	6.25 [b]	7.99 [a]	6.12 [a]	6.24 [a]	
Semi-winter type (Semi)					
Huaimai 35	7.54	8.81	6.49	7.41	12.6
Jimai 22	6.90	7.84	6.14	7.13	10.0
Zhengmai 9023	6.87	6.67	6.38	7.02	4.1
Emai 596	6.63	7.93	5.69	6.66	13.7
Annong 0711	6.30	7.20	7.32	7.70	8.3
Emai 580	5.99	7.62	6.95	6.55	10.1
Average	6.71 [b]	7.68 [a]	6.49 [b]	7.08 [a]	
ANOVA					
Site (S)	**		**		
Cultivar (C)	**		**		
S × C	**		**		
$LSD_{5\%\ (C)}$	0.59		0.51		
Weak vs. Semi	ns	ns	ns	*	

CV, coefficient of variation in grain yield across different sites and years. * $p < 0.05$; ** $p < 0.01$; ns, nonsignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. The grain yield of each cultivar indicated mean grain yield ($n = 3$).

Grain yield was not significantly different between semi- and weak-winter types under different sites, except for significantly higher (by 10%) average grain yield of semi-winter types than that of weak-winter types at Suining in 2018. The grain yield of the weak-winter types was significantly higher (by 28%) at Suining than at Yangzhou in 2017, but the difference was not significant in 2018. The grain yield of semi-winter types was significantly higher (by 15% in 2017 and by 9% in 2018) at Suining than at Yangzhou in both years.

3.3. Yield Components

As shown in Table 4, the spike number of cultivars was significantly higher (by 50%) and the spike yield was lower (by 20%) at Suining than at Yangzhou in 2017. In 2018, only the spike number was significantly higher (by 8%) at Suining and the spike yield was similar between the two sites. There were significant differences in spike number and spike yield among cultivars in both years and the interaction of sites and cultivars significantly affected spike yield in 2017 but not in 2018 (Table 5). According to correlation analyses (Table 6), grain yield of different cultivars was significantly positively correlated with spike number and spike yield at Yangzhou and Suining in 2017, whereas in 2018, grain yield and spike number at Suining were significantly positively correlated at both sites.

Spike number of semi-winter types was significantly higher than that of weak-winter types in Yangzhou and Suining only in 2018, but spike yield was similar between the two types at both sites in both years (Table 4). Spike number of weak-winter-type cultivars was higher (by 50% in 2017 and by 9% in 2018) at Suining than at Yangzhou and that of semi-winter-type cultivars was lower at Yangzhou (by 38% in 2017 and by 6% in 2018) than at Suining. Compared with Yangzhou, spike yield of weak-winter-type and semi-winter-type cultivars decreased by 14 and 18%, respectively, at Suining in 2017, whereas in 2018, differences were minor.

Table 4. Spike number and spike yield (g) of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Cultivar	Spike Number				Spike Yield (g)			
	2017		2018		2017		2018	
	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining
Weak-winter type (Weak)								
Annong 1124	384	528	401	406	1.92	1.57	1.62	1.51
Sumai 188	346	516	408	448	1.96	1.74	1.62	1.62
Yangmai 23	331	446	411	426	1.88	1.82	1.6	1.61
Yangmai 20	321	495	394	414	1.89	1.49	1.61	1.54
Ningmai 13	308	514	420	465	1.93	1.65	1.58	1.6
Haomai 1	300	451	434	428	1.94	1.4	1.47	1.49
Yangmai 16	308	480	408	422	1.81	1.76	1.73	1.54
Average	328 ^{b}	490 ^{a}	411 ^{a}	430 ^{a}	1.90 ^{a}	1.63 ^{b}	1.60 ^{a}	1.56 ^{a}
Semi-winter type (Semi)								
Huaimai 35	330	515	424	478	2.19	1.69	1.66	1.68
Jimai 22	336	464	442	484	2.06	1.61	1.55	1.58
Zhengmai 9023	328	417	424	477	2.1	1.61	1.59	1.6
Emai 596	330	488	421	440	2.01	1.67	1.52	1.62
Annong 0711	361	481	478	524	1.75	1.42	1.57	1.5
Emai 580	340	442	460	438	1.76	1.86	1.6	1.63
Average	338 ^{b}	468 ^{a}	442 ^{a}	474 ^{a}	1.96 ^{a}	1.64 ^{b}	1.58 ^{a}	1.60 ^{a}
ANOVA								
Site (S)	**		**		**		ns	
Cultivar (C)	**		**		**		**	
S × C	**		**		**		ns	
$LSD_{5\% (C)}$	49		33		0.18		0.18	
Weak vs. Semi	ns	ns	**	*	ns	ns	ns	ns

* $p < 0.05$; ** $p < 0.01$; ns, nonsignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. Spike number and spike yield of cultivars are means ($n = 3$).

Table 5. Correlations between grain yield and yield components, leaf area index (LAI) and biomass, of different cultivars in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Agronomic Trait	Grain Yield			
	Yangzhou 2017	Suining 2017	Yangzhou 2018	Suining 2018
Spike number	0.61 *	0.63 *	0.67 *	0.95 **
Spike yield	0.71 **	0.58 *	0.23	0.39
LAI at anthesis	0.64 *	0.76 **	0.57 *	0.77 **
LAI at milk-ripe	0.76 **	0.75 **	0.85 **	0.79 **
Pre-anthesis biomass	0.81 **	0.71 **	0.72 **	0.42
Post-anthesis biomass	0.90 **	0.74 **	0.85 **	0.84 **

* $p < 0.05$ and ** $p < 0.01$.

Table 6. Maximum stem and tiller number and main stem and tiller survival of weak-winter-type and semi-winter-type cultivars planted in southern (YZ, Yangzhou) and northern (SN, Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Cultivar	Maximum Stem and Tiller Number ($\times 10^4$ ha^{-1})				Main Stem and Tiller Survival (%)			
	2017		2018		2017		2018	
	YZ	SN	YZ	SN	YZ	SN	YZ	SN
Weak-winter-type (Weak)								
Annong 1124	913	1084	1258	1345	40.96	48.71	31.88	30.19
Sumai 188	861	1074	1307	1410	40.19	48.04	31.22	31.77
Yangmai 23	812	958	1346	1361	37.07	49.69	30.53	31.30
Yangmai 20	796	1033	1300	1293	40.33	47.92	30.31	32.02
Ningmai 13	778	1071	1293	1402	39.59	47.99	32.48	33.17
Haomai 1	768	972	1325	1342	44.27	46.40	32.75	31.89
Yangmai 16	800	1021	1261	1238	38.50	47.01	32.36	34.09
Average	818 [b]	1030 [a]	1298 [a]	1341 [a]	40.13 [b]	47.97 [a]	31.65 [a]	32.0 [a]
Semi-winter-type (Semi)								
Huaimai 35	829	1072	1315	1386	39.81	48.04	32.24	34.49
Jimai 22	815	968	1399	1397	41.23	47.93	31.59	34.65
Zhengmai 9023	848	1090	1377	1437	38.68	38.26	30.79	33.19
Emai 596	847	989	1368	1291	38.96	49.34	30.77	34.08
Annong 0711	832	882	1416	1301	43.39	54.54	33.76	40.28
Emai 580	824	1046	1426	1254	41.26	42.26	32.26	34.93
Average	833 [b]	1007 [a]	1384 [a]	1344 [a]	40.55 [b]	46.73 [a]	31.90 [b]	35.2 [a]
ANOVA								
Site (S)	**		ns		**		**	
Cultivar (C)	**		ns		*		*	
S × C	**		ns		**		ns	
$LSD_{5\% (C)}$	98		257		4.61		3.40	
Weak vs. Semi	ns	ns	**	ns	ns	ns	ns	*

* $p < 0.05$; ** $p < 0.01$; ns, insignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. Maximum stem and tiller number and main stem and tiller survival of cultivars are means ($n = 3$).

3.4. Maximum Stem and Tiller Number and Main Stem and Tiller Survival

Maximum stem and tiller number of cultivars was significantly higher (by 23%) at Suining than at Yangzhou in 2017, but the difference was not significant in 2018 (Table 6). Main stem and tiller survival was significantly higher at Suining than at Yangzhou in both years. Maximum stem and tiller number of cultivars were significantly different only in 2017. However, the difference in main stem and tiller survival was significant in both years. Spike number of cultivars was significantly positively correlated with main stem and tiller survival under different environmental conditions, but it was significantly positively correlated with maximum stem and tiller number only at Yangzhou, in both years (Figure 2).

In both sites and both years, there were no significant differences between weak-winter and semi-winter types in maximum stem and tiller number or main stem and tiller survival, with two exceptions (Table 6). Maximum stem and tiller number of semi-winter types was significantly higher than that of weak-winter types at Yangzhou in 2018 and main stem and tiller survival of semi-winter types was significantly higher than that of weak-winter types at Suining in 2018. When weak-winter-type cultivars were planted at Suining, maximum stem and tiller number was significantly higher than at Yangzhou in 2017, whereas in 2018, the difference was not significant. Maximum stem and tiller number of semi-winter types was significantly higher at Suining than at Yangzhou in 2017, but the difference was not significant in 2018. Main stem and tiller survival of the two types was significantly higher at Suining than at Yangzhou in both years.

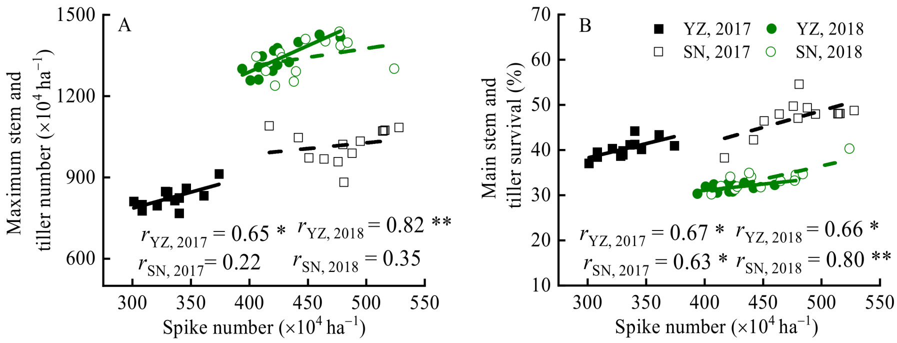

Figure 2. Correlations between spike number and (**A**) maximum stem and tiller number and (**B**) main stem and tiller survival of different cultivars in southern (YZ, Yangzhou) and northern (SN, Suining) areas of the Yangtze River basin, China, in 2017 and 2018. * $p < 0.05$; ** $p < 0.01$; ns, nonsignificant.

3.5. Leaf Area Index

The LAI at anthesis of different cultivars was significantly lower at Suining than at Yangzhou in 2017 and 2018, whereas the LAI at the milk-ripe stage and the decrease in LAI were significantly higher at Suining in both years (Tables 7 and 8). This result indicated a slower reduction in the photosynthetic area after anthesis at Suining than at Yangzhou. The LAI at anthesis and milk-ripe stages was significantly different among cultivars. However, the decrease in LAI was not significantly different among cultivars. Grain yield of different cultivars was significantly positively correlated with LAI at anthesis and milk-ripe stages at Yangzhou and Suining in both years (Table 5).

Table 7. Leaf area index (LAI) and decrease in LAI of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017.

Cultivar	LAI at Anthesis		LAI at Milk-Ripe		Decrease in LAI (%)	
	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining
			Weak-winter-type (Weak)			
Annong 1124	4.66	3.22	2.13	2.19	54.29	31.99
Sumai 188	3.74	3.56	1.57	2.38	58.02	33.15
Yangmai 23	2.55	3.76	1.27	2.11	50.20	43.88
Yangmai 20	3.36	3.69	1.65	1.87	50.89	49.32
Ningmai 13	3.36	3.71	1.54	2.14	54.17	42.32
Haomai 1	3.74	2.97	1.48	1.75	60.43	41.08
Yangmai 16	3.74	3.73	1.50	2.12	59.89	43.16
Average	3.59 [a]	3.52 [a]	1.59 [b]	2.08 [a]	55.41 [a]	40.70 [b]
			Semi-winter-type (Semi)			
Huaimai 35	5.10	4.41	2.27	2.56	55.49	41.95
Jimai 22	3.07	3.03	1.55	1.85	49.51	38.94
Zhengmai 9023	4.85	3.09	2.07	1.57	57.32	49.19
Emai 596	4.2	3.49	1.80	2.04	57.14	41.55
Annong 0711	3.68	3.09	1.84	1.95	50.00	36.89
Emai 580	3.22	3.12	1.36	1.74	57.76	44.23
Average	4.02 [a]	3.37 [a]	1.82 [a]	1.95 [a]	54.54 [a]	42.13 [b]
ANOVA						
Site (S)	**		**		**	
Cultivar (C)	**		**		ns	
S × C	**		**		ns	
$LSD_{5\%\ (C)}$	0.58		0.31		12.71	
Weak vs. Semi	ns	ns	ns	ns	ns	ns

** $p < 0.01$; ns, nonsignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. The LAI at anthesis and milk-ripe stages and the decrease in LAI of cultivars are means ($n = 3$).

Table 8. Leaf area index (LAI) and decrease in LAI of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2018.

Cultivar	LAI at Anthesis		LAI at Milk-Ripe		Decrease in LAI (%)	
	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining
Weak-winter-type (Weak)						
Annong 1124	4.36	3.65	1.74	1.56	60.09	57.26
Sumai 188	5.06	5.78	2.14	2.59	57.71	55.19
Yangmai 23	5.12	4.13	2.07	1.89	55.66	54.24
Yangmai 20	3.91	3.75	1.73	1.73	55.75	53.87
Ningmai 13	4.25	4.83	1.91	2.28	55.06	52.80
Haomai 1	5.50	4.01	1.81	2.38	67.09	40.65
Yangmai 16	5.37	4.24	2.04	2.32	62.01	45.28
Average	4.80 [a]	4.34 [a]	1.93 [a]	2.11 [a]	59.33 [a]	51.33 [b]
Semi-winter-type (Semi)						
Huaimai 35	4.95	5.45	2.17	2.74	56.16	49.72
Jimai 22	4.88	4.05	2.17	2.24	55.53	44.69
Zhengmai 9023	4.32	4.86	2.00	2.51	53.70	48.35
Emai 596	5.10	4.10	2.11	2.08	58.63	49.27
Annong 0711	6.25	5.58	2.58	3.05	58.72	45.34
Emai 580	5.65	4.18	2.49	2.53	55.93	39.47
Average	5.19 [a]	4.70 [a]	2.25 [b]	2.53 [a]	56.45 [a]	46.14 [b]
ANOVA						
Site (S)	*		**		**	
Cultivar (C)	**		*		ns	
S × C	**		**		ns	
$LSD_{5\% (C)}$	0.95		0.31		12.36	
Weak vs. Semi	ns	ns	ns	ns	ns	ns

* $p < 0.05$; ** $p < 0.01$; ns, nonsignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. The LAI at anthesis and milk-ripe stages and decrease in LAI of cultivars are means ($n = 3$).

There were no significant differences in LAI at the anthesis and milk-ripe stages or in the decrease in LAI between weak-winter and semi-winter types of cultivars at the same site in the two years (Tables 7 and 8). Planting site did not affect the LAI of the same cultivar type at anthesis, but caused significant differences in the LAI at the milk-ripe stage. The decrease in LAI of the same cultivar type was significantly lower at Suining than at Yangzhou.

3.6. Biomass

Planting site did not significantly affect pre-anthesis biomass in either year, but post-anthesis biomass was higher at Suining (by 15% in 2017 and 11% in 2018) than at Yangzhou, although the difference was significant only in 2017 (Table 9). Pre-anthesis and post-anthesis biomass of cultivars were highly variable in 2017, but in 2018, there was a significant difference only in post-anthesis biomass. Moreover, the interaction of cultivar and site had a significant effect on pre-anthesis and post-anthesis biomass. Grain yield of different cultivars was significantly positively correlated with pre-anthesis and post-anthesis biomass at Yangzhou and Suining in both years, except for a nonsignificant correlation with pre-anthesis biomass at Suining in 2018 (Table 5).

Table 9. Pre-anthesis and post-anthesis biomass (t ha^{-1}) of weak-winter-type and semi-winter-type cultivars planted in southern (Yangzhou) and northern (Suining) areas of the Yangtze River basin, China, in 2017 and 2018.

Cultivar	Pre-Anthesis Biomass (t × ha^{-1})				Post-Anthesis Biomass (t × ha^{1})			
	2017		2018		2017		2018	
	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining	Yangzhou	Suining
				Weak-winter type (Weak)				
Annong 1124	11.12	10.50	9.82	10.08	5.29	5.93	3.71	3.04
Sumai 188	10.42	10.96	10.92	11.34	4.68	6.60	3.79	4.71
Yangmai 23	10.66	12.46	10.58	11.63	4.20	5.09	3.87	3.27
Yangmai 20	10.99	11.42	10.68	10.23	4.26	5.54	4.39	4.38
Ningmai 13	10.13	11.42	11.07	10.55	4.59	6.27	3.73	4.93
Haomai 1	9.69	9.33	11.01	10.36	3.95	4.12	3.84	3.82
Yangmai 16	9.00	11.27	10.61	11.78	4.35	6.69	5.34	4.46
Average	10.29 ^{a}	11.05 ^{a}	10.67 ^{a}	10.85 ^{a}	4.47 ^{b}	5.78 ^{a}	4.10 ^{a}	4.10 ^{a}
				Semi-winter type (Semi)				
Huaimai 35	11.56	11.56	10.77	11.99	5.46	5.91	4.28	5.35
Jimai 22	10.65	11.66	11.43	10.56	4.91	4.11	3.94	6.31
Zhengmai 9023	10.50	10.58	10.58	11.27	4.88	4.10	4.79	4.79
Emai 596	10.38	10.77	10.53	10.04	4.84	5.51	3.16	5.28
Annong 0711	10.16	10.69	12.15	11.81	4.75	5.47	5.28	5.46
Emai 580	9.57	10.28	11.52	9.24	4.25	5.47	4.55	4.15
Average	10.47 ^{a}	10.92 ^{a}	11.16 ^{a}	10.82 ^{a}	4.84 ^{a}	5.10 ^{a}	4.33 ^{b}	5.22 ^{a}
ANOVA								
Site (S)	ns		ns		*		ns	
Cultivar (C)	*		ns		**		*	
S × C	*		**		**		*	
$LSD_{5\% (C)}$	1.63		1.47		1.20		1.47	
Weak vs. Semi	ns	ns	ns	ns	ns	ns	ns	*

* $p < 0.05$; ** $p < 0.01$; ns, nonsignificant. Different lowercase letters indicate a significant difference between the sites for the same cultivar type at $p < 0.05$. The pre-anthesis and post-anthesis biomass values of cultivars are means ($n = 3$).

There were no significant differences in biomass between weak-winter and semi-winter types, except for significantly higher semi-winter post-anthesis biomass at Suining in 2018 (Table 9). Planting site did not affect pre-anthesis biomass of the two cultivar types. However, weak-winter types had significantly greater post-anthesis biomass at Suining than at Yangzhou in 2017, but the difference was not significant in 2018. Semi-winter types had significantly higher post-anthesis biomass at Suining than at Yangzhou in 2018, but the difference was not significant in 2017.

3.7. Relations between Coefficients of Variation of Grain Yield and Agronomic Traits at Different Sites

Planting year and site resulted in changes in grain yield and related agronomic traits of wheat, but the degree of variation depended on the cultivar (Figure 3). At different sites, the CV of grain yield in different cultivars was significantly positively correlated with the CV of spike number and post-anthesis biomass, but was significantly negatively correlated with the CV of spike yield. These results suggested that improving the changeability in spike number and post-anthesis biomass and lowering the variation in spike yield in response to environmental changes could increase grain yield of wheat cultivars.

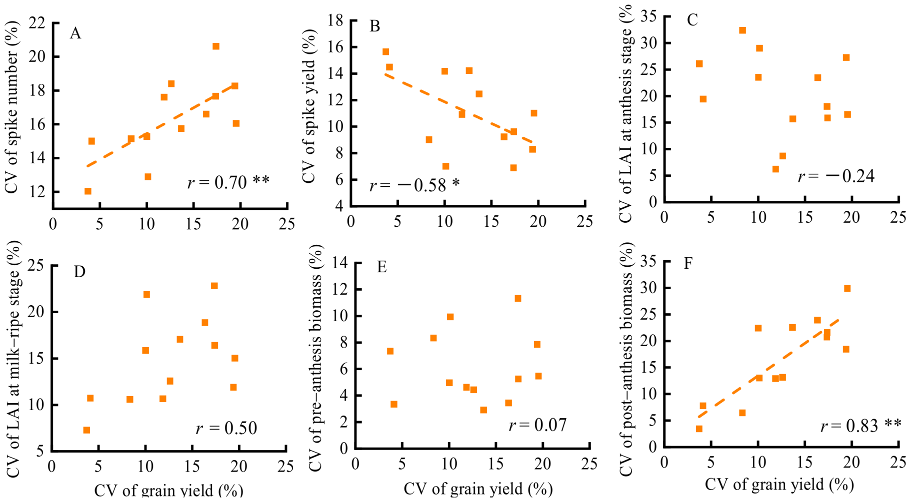

Figure 3. Correlations between the coefficient of variation (CV, %) of grain yield and the CV of (**A**) spike number, (**B**) spike yield, (**C**) leaf area index (LAI) at the anthesis stage, (**D**) LAI at the milk-ripe stage, (**E**) pre-anthesis biomass, and (**F**) post-anthesis biomass among cultivars. * $p < 0.05$; ** $p < 0.01$; ns, nonsignificant.

4. Discussion

In province-level studies, breaking through traditional area planting for a long distance (over 500 km) has a negative effect on wheat growth because of differences in temperature and water availability [6,7,9]. In the present study, experimental site and year significantly affected the growth period of wheat, which was most likely due to different temperatures between the two planting sites of Yangzhou and Suining (distance~180 km). Monthly mean temperature was lower at Suining than at Yangzhou before anthesis (in late April), which led to a longer vegetative period at Suining than at Yangzhou (Figure 1 and Table 2). A long vegetative period increases tillering capacity and spike number [28]. In the current study, grain yield was higher at Suining than at Yangzhou, primarily because of increases in spike number rather than increases in spike yield (Tables 3 and 4). High spike density can increase competition among spikes and decrease the assimilates partitioned into individual spikes after anthesis, limiting spike yield [29,30]. However, the post-anthesis period was longer at Yangzhou than at Suining, which favored spike yield formation. Therefore, we conclude that yield components of cultivars need to match local climate conditions.

In previous studies, contributions of spike number and spike yield to grain yield are inconsistent under different environmental conditions. In France and southern Spain, increases in grain yield of cultivars are highly correlated with increases in spike number [31,32]. However, in Ireland and on the Loess Plateau of China, spike yield is the key contributor to increases in grain yield [33,34]. At Yangzhou and Suining in both years, grain yield of cultivars was positively correlated with spike number (Table 5). In addition, an increase in spike yield led to an increase in grain yield in 2017, possibly because of low spike number that resulted from late sowing, which facilitated assimilate transport to spikes during the late growth phase [35]. Spike number is the result of the balance between tiller production and mortality [36]. Low temperatures prolong the vegetative period and increase tiller number and facilitate tiller development [28]. In this study, main stem and tiller survival was higher at Suining than at Yangzhou in both years, whereas maximum stem and tiller number was significantly higher at Suining than at Yangzhou only in 2017, with the difference not significant in 2018 (Table 6). To explain the lack of a difference, the vegetative period might have been long enough to reduce the difference in tiller number between the two sites. Moreover, spike number of cultivars was positively correlated with main stem and tiller survival in both sites and years, with maximum stem and tiller number in the southern YRB (Figure 2). An increase in number of effective tillers increases number of leaves per unit area and leaf area and thereby boosts biomass productivity and grain yield [37]. In this study, LAI and post-anthesis biomass were greater in high-yield cultivars (Tables 7–9). Thus, we conclude that the key to achieving high wheat yield in the YRB is to increase main stem and tiller survival.

Farmers and breeders are concerned about the potential and stability of grain yield [20]. The coefficient of variation (CV) reflects the degree of variation and is used as an index to measure the stability of grain yield under different growth environments [27,38,39]. In this study, the stability of grain yield of most cultivars was low across different sites and years and cultivars with high stability of grain yield (CV of grain yield <10%) were not high yielding (Table 3). In addition, the CV of grain yield under different growth conditions was positively correlated with CVs of spike number and post-anthesis biomass, but negatively correlated with the CV of spike yield (Figure 3). These results suggest that flexibility in spike number and post-anthesis biomass and stability in spike yield facilitate yield potential of wheat. Improving main stem and tiller survival potential and stabilizing spike yield are important targets for breeding wheat cultivars with high and stable yields in the future.

The semi-winter-type of wheat needs a lower temperature with a longer duration to complete vernalization than the weak-winter-type [13]. Therefore, semi-winter-type cultivars are usually planted in high-latitude areas and have a long vegetative growth phase. In the present study, the growth period of semi-winter and weak-winter types at the same site was similar (Table 2), suggesting that cultivars breaking through traditional area planting lengthened or shortened the developmental period to adapt to the local temperature. According to Searle et al. [40], temperature is the signal that provides the information to synchronize crop growth with season.

The potential and stability of grain yield of wheat cultivars bred for specific environments are limited under different environmental conditions [41]. In the southern YRB (Yangzhou), warm temperatures shorten the vegetative period and limit tiller formation. Therefore, the target in breeding high-yielding weak-winter-type cultivars is to increase spike yield [42]. In the present study, moving weak-winter-type cultivars to the northern YRB (Suining) had the potential to increase grain yields (Table 3). Yield increased primarily because spike number was higher at Suining than at Yangzhou, as a result of higher main stem and tiller survival (Table 4 and Figure 2). High survival of main stems and tillers of wheat is associated with high root surface area, which improves absorption of soil N and thereby slows the decrease in leaf area [43]. In this study, the decline in LAI after anthesis was significantly slower at Suining than at Yangzhou, which led to an increase in post-anthesis biomass (Tables 7–9).

In the northern YRB, semi-winter types with multiple spikes have been widely planted because low temperatures during the early growth phase facilitate tillering [28,42]. Grain yield of semi-winter types planted in the southern YRB was limited and was similar to that of local weak-winter types. This result could be largely explained by decreases in main stem and tiller survival and resulting decreases in spike number and photosynthetic area during post-anthesis.

5. Conclusions

In both years, grain yield of wheat cultivars planted in the northern YRB was higher than that in the southern YRB, because a longer vegetative period improved stem and tiller survival and therefore increased spike number. Compared with local wheat cultivars, breaking through traditional area planting did not increase grain yield, primarily because the increase of grain yield by environmental conditions could not overcome the limiting of cultivar potential in grain yield.

Compared with low-yield cultivars, high-yield cultivars always had higher main stem and tiller survival, which led to increases in spike number and productivity area and post-anthesis biomass. Correlation analyses between the CV of grain yield and the CVs of agronomic traits indicated that flexibility in spike number and post-anthesis biomass in response to environmental changes facilitated release of yield potential. Therefore, we conclude that improving main stem and tiller survival can increase spike numbers and maintain post-anthesis photosynthetic areas and help to establish large, highly suitable, and productive populations that can effectively use resources late in growth to achieve high grain yield.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy12010196/s1, Table S1: Year of release and pedigree of seven weak-winter-type and six semi-winter-type wheat cultivars planted in the Yangtze River basin, China.

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