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Belt Uniform Sowing Pattern Boosts Yield of Different Winter Wheat Cultivars in Southwest China

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Abstract: The relationship between the sowing patterns and yield performance is a valuable topic for food security. In this study, a novel belt uniform (BU) sowing pattern was reported, and a field experiment with four winter wheat cultivars was carried out over three consecutive growing seasons to compare the dry matter accumulation, harvest index (HI), grain yield and yield components under BU and line and dense (LD) sowing patterns [BU sowing with narrow (15 cm) spacing; BU sowing with wide (20 cm) spacing; LD sowing with wide (33.3 cm) row spacing; LD sowing with narrow (16.6 cm) row spacing]. Four cultivars produced a higher mean grain yield (GY), above-ground biomass (AGB) and spike number (SN) per m² under the BU sowing patterns than the LD sowing patterns in all three growing seasons. However, yield stability under the BU sowing patterns did not increase with the improved grain yield. The HI did not change with sowing patterns, and the contribution of above-ground biomass to grain yield (84%) was more than 5-fold higher than that of HI (16%). Principal component and correlation analyses indicated that the grain yield was positively correlated with the aboveground biomass and SN, while the HI and 1000-grain weight were not correlated with grain yield. We concluded that (1) the novel BU sowing patterns achieved a higher yield potential in winter wheat but did not further improve yield stability; (2) increasing the dry matter accumulation without changing the HI drove improvements in the SN and grain number per spike, thus increasing grain yield.

Keywords: sowing pattern; winter wheat; biomass; grain yield; harvest index

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1. Introduction

Wheat is one of the most important cereal crops grown worldwide [1] and the third most important staple crop in China. The yield improvement in winter wheat was realized by improving the harvest index (HI) [2–4], dry matter accumulation and radiation use efficiency [5–9]. Increasing the HI is the main driver of yield improvements through wheat breeding [5,7,10]. Although the theoretical limit of the HI is 0.62 for wheat [11], HI values have not progressed since the 1990s when they reached ~0.50–0.55 [5]. Thus, it is difficult to further improve yield by raising the HI, because this has reached a realistic limit of ~0.5 [5,7]. Future yield improvement should rely on achieving greater above-ground biomass (AGB), while at least maintaining present HI levels [7]. The relative contribution of the AGB and HI to the grain yield was not well known.

Most studies concentrated on the role of fertilizer schemes and planting density in yield performance [12,13], but previous studies showed new sowing patterns such as raised-bed sowing [14] and furrow sowing [15] could increase the yields of winter wheat [16,17] and other crops [18,19]. Li et al. [15,20] reported a wide and narrow furrow planting

which could increase the winter wheat grain yield in the North China Plain. Recently, a new sowing method-wide-precision planting pattern (sowing width was 6–8 cm) was reported; the author proposed that this new method, combined with deficit irrigation, could maximize winter wheat production in the North China Plain [20]. Thus, the development of new cultivation measures contributes hugely to increasing winter wheat yields. Moreover, previous studies have shown yield improvements associated with increases in radiation use efficiency [6], biomass [8,9] and spike number (SN) per square meter [20,21].

South China is one of the three main winter wheat production areas in China [10]. In this study, we reported a novel sowing pattern and the yield; yield components and biomass accumulation were compared among four sowing patterns and identified the related contribution of the HI and AGB to yield performance. The following hypotheses were tested: (1) the novel sowing pattern could improve the winter wheat grain yield, which was associated with the increasing of AGB not HI; (2) the yield improvement was associated with the increasing of the spike number m^{-2} (SN), grain number per spike (GN) or 1000-grain weight (TGW).

2. Materials and Methods

2.1. Materials and Growth Conditions

A field experiment was conducted in the Guiyang, Guizhou province, China. The mean temperatures were 10.2, 9.5 and 11.0 °C, whereas the precipitation was 377, 316 and 367 mm for the 2017–2018, 2018–2019 and 2019–2020 growing seasons, respectively (Figure 1). The soil in the field was classified as yellow soil according to the Chinese soil classification system. The soil organic matter and soil available P, N and K were 6.60 g kg^{-1} , 4.85 mg kg^{-1} , 31.50 mg kg^{-1} , and 141.69 mg kg^{-1} in 2017, respectively.

Figure 1. The daily mean, maximum and minimal temperature and daily precipitation during the experiment in (A) 2017–2018, (B) 2018–2019 and (C) 2019–2020.

Four sowing patterns (Line and dense (LD) sowing with wide (33.3 cm) row spacing (LDW, conventional sowing pattern); Line and dense (LD) sowing with narrow (16.6 cm) row spacing (LDN); Belt uniform (BU) sowing with narrow (15 cm) row spacing (BUN); and Belt uniform (BU) sowing with wide (20 cm) row spacing (BUW)) were used in this study (Figure 2). Four wheat cultivars (Guinong 19 (G19); Guinong 30 (G30); Guizi 1 (G1); and Guizi 4 (G4)) were used in three consecutive years during the winter wheat growing season. G19 and G30 were common cultivars; G1 and G4 were high anthocyanin (about 50 mg kg^{-1}) winter wheat cultivars. A completely random experimental design was used in this study and there were three replicates per cultivar per sowing pattern, the area of each plot was 4 m^2 ($2 \text{ m} \times 2 \text{ m}$). The plant density was 225 plants per m^2 . Before sowing, 160 kg N ha^{-1} , 35 kg P ha^{-1} and 35 kg K ha^{-1} were applied according to local practice. Pesticides were used when necessary and the weeds were controlled by hand. The sowing and harvest dates were November 5 in 2017 and May 11 in 2018 for the 2017–2018 growing season, November 19 in 2018 and May 18 in 2019 for the 2018–2019 growing season, and November 23 in 2019 and May 23 in 2020 for the 2019–2020 growing season.

Figure 2. The four sowing patterns (A): Line and dense sowing with wide (33.3 cm) row space (LDW). (B): Line and dense sowing with narrow (16.6 cm) row space (LDN). (C): belt uniform sowing with wide (20 cm) row space (BUN). (D): belt uniform sowing with narrow (15 cm) row space (BUW) used in this study. All sowing patterns have the same seed rate.

2.2. Harvest and Measurement of Parameters

When the winter wheat reached maturity, two rows in the center were harvested. The shoots were cut about 1 cm above the soil surface, placed in nylon bags, tagged and transported to the lab for further measurement.

The spikes were cut from the shoots, and the leaf and stem were combined and dried at 80°C for 48 h; then, the dry weights of the spike and the leaf + stem were evaluated. The dry weight was obtained by adding together the dry weights of the spike, leaf and stem. The number of spikes was counted for each sample in each plot; then, a subsample (ten representative spikes) was chosen to determine the grain numbers for each spike. The remaining spikes were threshed to obtain the grains and those were combined with the grains of the sub-samples to determine the grain yield for each plot. The grain yield (g m^{-2}) was obtained by dividing the grain yield for each sample for each plot by the harvested area. The harvest index ($\text{HI, \%}$) = $(\text{grain yield} \times 100) / \text{AGB}$.

2.3. Statistics Analysis

A two-way analysis of variance (ANOVA) for each year was conducted using GenStat 19.0 (VSN International Ltd., Rothamsted, UK) to analyze the effects of sowing patterns and cultivars and their interaction on the grain yield, yield components and biomass accumulation. Principal component analysis (PCA) was also conducted using GenStat 19.0, based on grain yield, yield formation traits and yield components. All figures were

generated using Origin 2020 (Origin Lab, Northampton, MA, USA); the elements of yield formation are presented using a histogram, the relationships are shown using a scatter plot and the stability of each cultivar in different sowing patterns is presented using a bubble chart.

The data for AGB, HI and grain yield were combined and used to evaluate the contribution of AGB and HI to winter wheat grain yield as follows:

$$A_1 = B_1 S_{X1} / S_Y; B_1 = B_2 S_{X2} / S_{GY} \quad (1)$$

$$C_{AGB} = (A_1 / (A_1 + B_1)) \times 100\%; C_{HI} = (B_1 / (A_1 + B_1)) \times 100\% \quad (2)$$

where A_1 and B_1 represent the standardized coefficients of AGB and HI; B_1 and B_2 represent the coefficients of AGB and HI in the partial regression equation; and S_{X1} , S_{X2} and S_{GY} represent the standard deviation of AGB, HI and grain yield, respectively. The contributions of AGB and HI to grain yield are represented by C_{AGB} and C_{HI} .

3. Results

3.1. Yield Performance

The HI was significantly related to the genotypes of the wheat, but its effect on the AGB and grain yield (GY) was irregular. The sowing pattern significantly affected the AGB, HI and grain yield, and the interaction with genotype significantly influenced the AGB, HI and grain yield during the 2017–2018 and 2018–2019 growing seasons (Table 1). Each cultivar produced the highest yield under the BU sowing conditions (Table 1; Figure 3A–C). Compared with the LDN sowing pattern, the average yield and AGB under the BU patterns was nearly double (Figure 3). The HI did not change with the sowing pattern but the AGB was significantly increased under the BU patterns (Figure 3). The contribution of AGB to yield (84%) was more than five-fold higher than that of HI (16%; Table 2).

Table 1. The above-ground biomass (AGB, g m^{−2}), harvest index (HI, %) and grain yield (GY, g m^{−2}) and their means of four wheat genotypes under four different sowing patterns during three consecutive growing seasons. LSD values at $p = 0.05$ are in parenthesis. n.s not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Genotype (G)	Sowing Pattern (SP)	2017–2018			2018–2019			2019–2020			Means of Three Years		
		AGB	HI	GY	AGB	HI	GY	AGB	HI	GY	AGB	HI	GY
G1	LDN	426	32.1	137	489	43.9	213	560	43.2	241	492	39.7	197
	LDW	846	41.6	351	611	49.1	301	1065	43.1	457	841	44.6	370
	BUN	1098	43.5	477	957	44.2	430	1119	45.6	510	1058	44.9	472
	BUW	914	40.9	374	1045	46.9	489	1241	44.5	552	1067	44.1	472
	G1-means	821	38.2	335	775	46.0	358	996	44.1	440	864	42.8	378
G19	LDN	486	49.2	239	538	48.8	263	538	45.9	249	521	48.0	250
	LDW	652	46.3	304	450	49.5	223	924	49.1	453	675	48.3	327
	BUN	774	47.3	365	868	50.6	439	1170	45.9	538	937	47.9	447
	BUW	871	49.4	431	1139	45.3	516	1140	47.8	545	1050	47.5	497
	G19-means	696	48.1	335	749	48.6	360	943	47.2	446	796	48.0	380
G30	LDN	542	46.9	255	718	44.8	322	465	43.5	203	575	45.1	260
	LDW	508	47.9	242	662	45.5	301	941	48.2	455	704	47.2	333
	BUN	833	46.5	395	986	42.0	413	1296	46.6	604	1038	45.1	471
	BUW	758	49.4	374	806	44.0	349	1199	46.5	558	921	46.6	427
	G30-means	660	47.7	317	793	44.1	346	975	46.2	455	809	45.9	373
G4	LDN	584	45.8	312	551	48.2	266	502	43.9	220	546	46.0	266
	LDW	760	45.9	349	635	46.7	295	1142	45.6	521	846	46.1	388
	BUN	962	45.2	434	916	42.4	390	1291	46.7	603	1056	44.8	476
	BUW	849	46.7	396	799	44.4	355	1308	48.1	629	985	46.4	460
	G4-means	789	45.9	373	725	45.4	327	1061	46.1	493	858	45.8	397
G		*** (74)	*** (1.6)	n.s	n.s	*** (1.4)	* (23)	n.s	*** (1.1)	n.s	*** (1.1)	*** (46)	
SP		*** (74)	** (1.6)	*** (41)	*** (56)	*** (1.4)	*** (23)	*** (95)	*** (1.1)	*** (46)	*** (46)		
G × SP		** (149)	*** (3.3)	** (83)	*** (111)	*** (2.9)	*** (46)	n.s	* (2.3)	n.s

Figure 3. The grain yield (A–C), shoot biomass (D–F) and harvest index (G–I) (HI) of four winter wheat cultivars under four sowing patterns during the growing seasons of 2017–2018, 2018–2019 and 2019–2020. Means $\pm$ SE ($n = 3$) with the different letters in each figure indicating a significant difference at $p = 0.05$.

Table 2. The variation in grain yield, above-ground dry biomass (AGB) and harvest index (HI) and the contribution of AGDM and HI to grain yield in winter wheat grown from 2017–2020. *** $p < 0.001$.

Grain Yield (g m^{-2})			AGB (g m^{-2})			HI			Contribution Rate to Yield (%)	
Range	Mean	CV (%)	Range	Mean	CV (%)	Range	Mean	CV (%)	AGB	HI
208–744	433	34.3	401–1630	960	34.7	0.40–0.62	0.46	9.9	83.7 ***	16.3 ***

The yield components were significantly affected by genotype, sowing pattern and their interaction (Table 3). All genotypes had higher SN per unit area in the BU sowing pattern with narrow or wide row spacing (Table 3; Figure 4A–C). The effects on grain number per spike of genotype and sowing pattern were not regular. The genotypes made a regular and significant difference to the 1000-grain weight, however (Figure 4). G4 had the highest 1000-grain weight, followed by G19 and G30, while that of G1 was the lowest (Table 3).

Table 3. The spike number (SN), grain number (GN) per spike and 1000-grain weight (TGW) of four wheat genotypes under four different sowing patterns during three consecutive growing seasons. LSD values at $p = 0.05$ are in parenthesis. n.s not significant, ** $p < 0.01$, *** $p < 0.001$.

Genotype (G)	Sowing Pattern (SP)	2017–2018			2018–2019			2019–2020		
		SN	GN	TGW	SN	GN	TGW	SN	GN	TGW
G1	LDN	138	32.7	30.1	159	44.3	30.8	157	48.4	31.6
	LDW	328	35.3	30.3	234	39.1	33.2	313	40.5	36.0
	BUN	398	39.2	30.9	381	36.3	31.1	248	65.8	31.3
	BUW	350	34.6	30.7	348	43.6	32.3	370	43.9	34.0
G19	LDN	177	38.4	35.2	253	29.3	35.4	158	43.9	35.4
	LDW	314	26.1	37.8	269	23.8	34.8	260	54.3	32.1
	BUN	380	27.9	34.4	279	45.7	34.4	350	47.2	32.5
	BUW	352	33.7	36.5	375	37.9	36.3	336	44.9	36.0
G30	LDN	169	44.9	33.3	214	42.3	35.6	166	32.2	37.9
	LDW	221	26.8	40.8	279	28.5	37.9	307	36.2	40.6
	BUN	276	42.4	33.0	390	31.6	33.8	371	47.2	34.6b
	BUW	366	31.4	33.0	376	25.5	36.2	364	38.7	39.4
G4	LDN	178	40.7	45.2	205	29.0	45.0	129	38.0	44.9
	LDW	304	28.3	40.8	243	29.1	41.8	261	46.6	42.8
	BUN	343	31.7	40.8	334	29.1	39.9	303	50.9	39.2
	BUW	268	36.8	42.9	316	27.2	41.3	311	51.1	39.7
G		** (26)	n.s	*** (0.3)	** (20)	*** (2.2)	*** (0.3)	*** (22)	*** (2.2)	*** (0.2)
SP		*** (26)	** (5)	*** (0.3)	*** (20)	*** (2.2)	*** (0.3)	*** (22)	*** (2.2)	*** (0.2)
G × SP		*** (52)	** (10)	*** (0.5)	*** (39)	*** (4.6)	*** (0.6)	*** (44)	*** (4.3)	*** (0.4)

Figure 4. The spike number (A–C), grain number per spike (D–F) and thousand-grain weight (G–I) in four winter wheat cultivars under four sowing patterns during the growing seasons of 2017–2018, 2018–2019 and 2019–2020. Means are $\pm$ SE ($n = 3$) with the different letters in each figure indicating a significant difference at $p = 0.05$.

3.2. Relationships between Yield and Its Components

The increase in grain yield was significantly positively correlated with the AGB under different sowing patterns ($r = 0.98$, $p < 0.001$). All genotypes produced a higher mean

AGB and grain yield under the BU sowing patterns than those planted under both the LDW and LDN sowing patterns (Figure 5A). The correlation between SN per unit area and grain yield was the same as between AGB and grain yield ($r = 0.69$, $p < 0.001$; Figure 5B). However, there was a positive correlation between grain yield and grain number per single spike ($r = 0.51$, $p < 0.001$); the grain number per spike under the BU patterns was not always higher than that under the other patterns and showed an irregular trend (Figure 5C). The HI and 1000-grain weight were not correlated with grain yield and the HI was not significantly different among the four sowing patterns (Figure 5D,E). The mean grain yield across the 3 years was significantly improved by using the new sowing methods, but the yield stability did not increase with the grain yield improvement, except in G9 (Figure 6).

Figure 5. The relationship between the grain yield and (A) above-ground biomass (g m⁻²), (B) spike number per square meter, (C) grain number per spike, (D) harvest index and (E) 1000-grain weight under four sowing patterns. *** $p < 0.001$.

Figure 6. The grain yield and yield stability of four winter wheat cultivars (Guizi 1 (G1), Guizi 4 (G4), Guinong 19 (G19) and Guinong 39 (G30)) under four sowing patterns.

A PCA (Figure 7) based on yield formation traits and yield components indicated that the AGB and SN per m² highly correlated with PC1 were positively correlated with grain yield. PC2 was correlated with HI and 1000-grain weight, the inherent features of genotype. The scoring data obtained under the BU sowing patterns were closer to the SN, AGB and yield loadings than the LD conditions.

Figure 7. PCA based on yield formation and yield components of winter wheat grown under different sowing patterns during three consecutive growing seasons.

4. Discussion

In this study, a novel sowing pattern was reported and this largely improved 29.5% grain yield across all genotypes and years in Southern China, compared with other sowing methods such as raised bed-sowing (5.2%) [14], bed sowing (7.0%) [22] and wide-precision sowing (6.7–12.7%) [6]. These results not only highlighted the importance of developing

new sowing methods to increase grain yield but also indicated that the new sowing method implemented in this study vastly improved yield. Moreover, we found no significant differences in the yield obtained from the four winter wheat cultivars under the BU sowing pattern, indicating that these four cultivars had similar yield potentials and the proper sowing methods could help to realize this high yield potential. However, the yield stability did not improve with increases in grain yield in three of the four cultivars. Thus, more work, such as improved fertilizer management, will be required to improve the yield stability [13].

Previous studies showed that yield improvement was associated with increasing radiation use efficiency [6], biomass [8,9], leaf area index [23] and yield components [10,20]. However, in this study, we focused on the response of the biomass and yield components and their roles in yield performance under different sowing patterns. The AGB and HI are the two main factors that determine the grain yield, as indicated by the equation: grain yield = $(AGB \times HI)/100$ [24]. In this study, the biomass increased by 24–38%, while the grain yield increased by 25–34% under the new sowing patterns; however, the HI was almost the same between the four sowing patterns (0.45–0.48). Moreover, the contribution of the AGB to grain yield was more than five-fold higher than that of HI. These results clearly showed that (1) increasing the biomass was the main driver of grain yield improvement under the BU sowing patterns; (2) it was hard to increase GY by increasing the HI, which was almost 0.5. Solar radiation is essential for plant growth in field conditions and the leaf area index was the main factor determined the absorb of the solar radiation [6]. Thus, the large amount of biomass may have been a result of an increase in the leaf area index [23], a high radiation interaction ratio and use efficiency [6,25] and higher land use related to narrow row spacing. Reasonable line spacing can improve the space arrangement between the plants and help to increase the radiation interaction ratio and use efficiency [26,27].

Increases in yield components, such as TGW, SN and GN, have been significant in improving yields of winter wheat worldwide [7,10,28–30]. In this study, we found that variations in the 1000-grain weight were observed among the different winter wheat cultivars, but this did not contribute to the yield performance, indicating that the 1000-grain weight was a specific property of each cultivar and the sowing patterns had little effect on it. Both the SN per m² and grain number per spike were positively correlated with yield performance, indicating that these two traits could be altered through breeding and field management in winter wheat. Thus, developing new farming methods combined with the high yield potential winter wheat cultivar could further increase the grain yield [9]. Furthermore, we found that SN per m² was more important than grain number per spike in yield performance and a 51% variation in the SN per m² was explained by the high accumulation of biomass. Moreover, changing the row spacing also contributed to increasing the SN per m² [26,27].

5. Conclusions

In this study, the BU sowing patterns significantly increased the grain yield of winter wheat in three consecutive growing seasons; the increasing of aboveground biomass, not the harvest index, was the main driver for the improvement of the grain yield; the increasing of the aboveground biomass was associated with the improvement of the spike number per m². The fixed traits related to the wheat genotype, such as HI, the grain number per spike, and 1000-grain weight, did not change or had an irregular performance under different sowing patterns.

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