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Full Length Research Paper

Morphological and yield responses of winter wheat (*Triticum aestivum* L.) to raised bed planting in Northern China

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Six winter wheat (*Triticum aestivum* L.) varieties (Jimai 19, Jimai 20, Jimai 21, Yannong 19, Jining 12 and Jining 16) were grown in 8 crop seasons/site combinations to investigate the effect of raised bed planting as compared to the conventional flat planting on wheat plant morphology, grain yield and associated yield components in Northern China. Raised bed planting produced a more ideal plant structure composed of larger basal leaves with smaller top leaves. Crop canopy analysis indicated that raised bed planting produced more durable dry matter weight of green leaves from the top of the canopy to the bottom as compared to conventional flat planting. In addition, raised bed planting shortened the basal first and second internodes and reduced plant height, leading to less crop lodging when compared with conventional flat planting. Under bed planting, the spike number per unit area was decreased, but the number of grains per spike and the 1000-grain weight of wheat were significantly increased in comparison with flat planting. Ultimately, raised bed planting produced more grain yield than flat planting through the integrative effect of these yield components. It is concluded that raised bed planting can optimize wheat morphological traits, enhance plant lodging resistance, and thereby increase the wheat productivity and yield difference between two planting systems varied from 6.6 to 12% over 5 locations in favour of raised bed planting.

Key words: Winter wheat, conventional flat planting, raised bed planting, plant morphology, grain yield.

INTRODUCTION

In Northern China, wheat is the first most important of the irrigated crops in terms of area. In 2005, the wheat-growing area in China reached 22.50 million ha and total wheat production reached 96.34 million tons representing an increase of 46% in area and 604% in production, respectively, as compared to 1949. The technological breakthroughs in wheat cultivation are represented by two new crop management strategies being used by farmers. They are: (i) use of leaf number and leaf stage of development to determine the timing for fertilizer and irrigation applications and (ii) use of uniform seed distribution with reduced seed to enhance/control wheat planting technology (Wang et al., 2009). These have greatly accelerated the promotion of wheat production (Yu et al., 1993; Zhu et al., 1993). However, both technologies have been successfully applied only in conventional flat planting and flood irrigation conditions which can be associated with inefficient use of irrigation water. In China, 1 m^3 of water produces a 1.2 to 1.4 kg of grain in well water irrigated areas or 0.8 to 1.0 kg of grain on average in the areas irrigated by the Yellow River water irrigated using flood irrigation practices, much too low compared to 2.32 kg of grain in some developed countries (Kang and Li, 1997; Dai and Li, 2000). With the increase in population combined with the rapid economic development in China, strong demand for farm products has increased.

On the other hand, competition for the water supplied for agricultural, industrial, and municipal uses, including

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household drinking water, has become more and more severe and the percentage of agricultural water to total water consumption has gradually decreased. In many areas, poor management of flood irrigation in conventional flat planting conditions has resulted in land degradation and soil erosion, damage to ecosystems and reduction of crop productivity (Janes et al., 2001; Elmi et al., 2002; Lichter et al., 2008). At present, further growth in agricultural production will depend more on increasing agricultural productivity with respect to both land and water. Therefore, improving water use efficiency (WUE) and developing water-saving, sustainable agriculture remain the biggest challenges (Dai and Li, 2000). In recent years, with the increase of fertilizer inputs and improvement of soil fertility by crop residue retaining, wheat density and plant height had been gradually increased and thus leading to high humidity in canopy. Consequently, lodging and occurrence of wheat sharp eye spot and wheat powdery mildew are becoming more common with intensively managed crops (Wang et al., 2004; Tripathi et al., 2005). An accumulating body of evidence has verified that the bed planting with 2 to 5 rows of wheat on a raised bed 70 to 90 cm wide offers better weed control, water and fertilizer management, thus leading to the lower inputs of water and fertilizers, higher stress-resistance and grain yield (Wang et al., 2004; Tripathi et al., 2005; Singh et al., 2009; Kong et al., 2010). From the initial introduction of this system through cooperation with CIMMYT in 1998, experiments on bed planting have been conducted in China, especially in Shandong, Henan, Inner Mongolia and Ningxia provinces (Wang et al., 2009). Results from these experiments have further demonstrated that the adoption of this planting practice can reduce irrigation water requirement by 30 to 40% (Wang et al., 2004; Kong et al., 2010). As compared with conventional flat planting, the bed planting could increase grains per spike and improve grain yield significantly, while the spike per squared meter was almost the same (no significance). Bed planting has been, therefore, considered to be an attractive technology for irrigated wheat producers (Tripathi et al., 2005) and which is now fully recognized by farmers and policy-makers in China.

For example, the government extended the bed planting technology with subsidy by 450 Yuan RMB (64 USD) in Zoucheng county, wheat planting area for bed planting was 400 ha in 2004, 8000 ha in 2005 and 13400 ha in 2006. The most recent estimate by the Shandong Academy of Agricultural Sciences indicates that approximately 30000 ha of wheat are now seeded on raised beds with furrow irrigation in Shandong province. However, little is known about the unique morphological traits in wheat under raised bed planting system and how these traits contribute to yield component formation and final grain yield. This research was therefore carried out over an 8-year period using six wheat cultivars in Shandong province, North China, with the objectives of investigating plant growth dynamics under raised bed planting system and determining how the variations in plant morphology contributed to the formation of appropriate yield components and yield outputs.

MATERIALS AND METHODS

Site description and experimental layout

In order to compare the performance of the raised bed planting technology with conventional planting on the flat, a series of trials that included six different winter wheat varieties were conducted under irrigated conditions in five locations during the winter cropping seasons from 2003 to 2010 in Shandong province. The five sites in Shandong province were chosen to represent different growing conditions as follows (soil samples for all measured parameters in all five sites were taken from 0 to 20 cm) (Table 1). The long-term annual rainfall in Shandong province varies from 670 to 750 mm over the different sites. Approximately 30% of total rainfall occurs during the winter wheat growing season (early October to early June). The field experiments consisted of the two planting systems (raised bed and conventional on the flat) with one of the five winter wheat varieties (Jimai 19, Jimai 20, Jimai 21, Yannong 19, Jining 12 and Jining 16) seeded each cropping season/site in a randomized complete block design with a plot of 6 × 6 m with three replications.

Every variety was sown at a seeding rate of 112.5 kg ha^{-1} for both the raised bed planting and conventional flat planting in each site and each cropping season and the planting date varied with different years from October 2nd to 12th. The varieties chosen for each cropping season/site were those most widely used by farmers in each site. For raised bed planting, the beds had an average width of 75 cm (center furrow to center furrow) on which three rows of wheat were seeded 15 cm apart and the height of the bed was 15 to 20 cm above bottom furrow. Beds were planted with a 2BFL-3 drill manufactured specially for planting wheat on top of a bed. For conventional flat planting, the soil was well-leveled and the wheat was planted at a row spacing of 24.3 cm. Before tillage, 112.5 kg N ha^{-1}, 37.5 kg P_2O_5 ha^{-1} and 112.5 kg K_2O ha^{-1} were applied to all plots. The same amount of N was applied at jointing stage as top dressing and incorporated through irrigation. During the whole growth period, the wheat was irrigated three times in furrows between the raised beds or by flooding for the flat planting at early winter, jointing and grain-filling stages.

Measurement of green leaf dry matter and area

The field layer cutting method was used to determine dry matter of functional leaves. The leaves at every 10-cm level on the stems, including main stems and tillers, were collected from 1 m^2 at mid-grain-filling stage (20th to 25th May). Leaf area was determined with a LICOR LI-3000A area meter (LI-COR, Lincoln, USA). The samples were dried in a fan-aided oven to a constant weight at 60°C and then weighed to estimate the leaf dry matter.

Determining internode length and plant height

Plant height (from the surface of the soil to the ear tip of the spike not including the awns) and internode length were measured at twenty days after anthesis, when full plant height had been reached. At least ten plants were randomly sampled from each plot for these measurements. To identify leaves and internodes, we utilized the system that starts with the uppermost leaf (the top leaf) or the uppermost internode as the reference and the numbering proceeds basally.

Table 1. Experiment site characteristics.

Site	Latitude (°N)	Longitude (°E)	Altitude (m)	OM[†] (%)	AHN (mg kg^{-1})	RAP (mg kg^{-1})	RAK (mg kg^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Jining	35.396	116.586	31	1.02	68	19	98	250	120	150
Qingzhou	36.768	118.603	40	1.32	74	25	125	180	125	130
Qufu	35.558	116.982	61	1.14	63	23	76	220	150	120
Wenshang	35.720	116.486	34	1.16	78	20	84	180	130	120
Jinan	36.667	117.000	27	1.21	65	21	110	225	138	126

[†] OM, Organic matter; AHN, alkali-hydrolyzable nitrogen; RAK, rapidly available potassium; RAP, rapidly available phosphorus.

Table 2. Comparison of wheat leaf area under different planting methods.

Variety	Cropping season/site	Planting method	Leaf area (cm^{-2})					
			1st	2nd	3rd	4th	5th	Sum
		Bed planting	24.16	30.31	25.96	17.72	11.12	109.17
Jimai 21	2003-2005/Jining	Flat planting	26.24	32.42	25.03	16.84	9.06	109.59
		$LSD_{0.05}$	1.57	2.07	ns	ns	1.73	ns
		Bed planting	24.32	31.03	26.17	17.68	11.96	111.16
Yannong 19	2005-2006/Qingzhou	Flat planting	26.47	33.16	24.42	17.18	9.87	111.10
		$LSD_{0.05}$	1.94	2.07	ns	ns	1.43	ns
		Bed planting	22.17	28.76	24.32	16.62	10.14	102.11
Jining 12	2006-2007/Qufu	Flat planting	24.64	30.67	22.61	15.78	7.76	101.46
		$LSD_{0.05}$	2.04	1.41	ns	ns	1.85	ns
		Bed planting	23.18	25.74	23.67	18.94	10.96	102.49
Jining 16	2007-2008/Wenshang	Flat planting	25.42	27.86	24.01	17.12	8.86	103.27
		$LSD_{0.05}$	2.13	1.54	ns	ns	1.87	ns
		Bed planting	23.12	29.02	25.31	15.94	10.28	104.67
Jimai 19	2008-2010/Jinan	Flat planting	25.67	31.41	24.56	15.32	7.30	104.26
		$LSD_{0.05}$	2.12	1.34	ns[†]	ns	2.34	ns
Variety (V)			4.27	31.13	12.72	6.63	14.05	17.19
Planting method (PM)			44.55	42.59	0.79	0.72	30.37	7.05
V × PM			0.07	0.05	0.03	0.28	2.24	0.20

Statistical evaluation

The data of internode length, grain yield, yield components, and other traits were subjected to analysis of variance with SAS (SAS Institute Inc., Cary, NC). Significance of each source of variation was determined by application of the Duncan's multiple range tests. Least significance difference (LSD) tests were performed to determine variation between individual means at the 0.05 level of probability.

RESULTS

Leaf area and profile distribution

Marked variations in the area of first, second, and fifth leaves occurred in bed planted wheat as compared with flat planted wheat, even though the total leaf area per plant was similar for both planting methods (Table 2). The areas of top and second leaf were significantly shorter ($p \leq 0.05$), whereas the area of fifth leaf was significantly larger ($p \leq 0.05$) in wheat plants grown under raised bed planting as compared to flat planting.

Analysis on the profile distribution of functional leaves within the wheat canopy showed that the dry matter of functional leaves at 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm above the ground, were significantly higher in bed planted wheat (reaching a total increase of 26.05% green weight or 32.81 g m^{-2}) when compared to the same leaf intervals for flat planting (Figure 1). The change in leaf

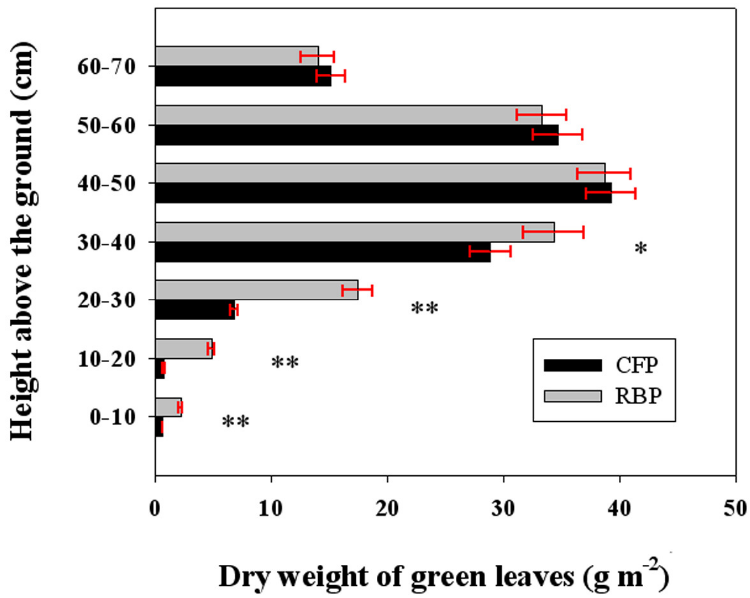

Figure 1. Comparison of dry weight of green leaves in raised bed planting and conventional flat planting wheat at mid-gain-filling stage. * and ** are significant at 0.05 and 0.01 probability levels, respectively.

area followed the same trend in all the sites with different varieties.

Internode lengths and plant height

In five cultivars planted in five sites, slight decrease in lengths of top internodes and significant decrease in lengths of the fourth and fifth internodes in raised bed planted wheat was consistently observed throughout the experiment in comparison with flat planted wheat. This directly resulted in the significant reduction of wheat plant height in raised bed planting ($p \leq 0.05$). The reduction of plant height in five cultivars was about 5.2 to 9.5% (Table 3). As a consequence of this, the lodging rate of wheat plants significantly decreased in raised bed planting as compared with flat planting.

Grain yield and yield components

The grain yield and yield components were significantly affected by different planting systems over years for the different cultivars at the several sites as presented in Table 4. The spike number per square meter in wheat planted on raised bed declined slightly, in comparison with flat planting. However, the grain number per spike and 1000-grain weight in bed planting system increased significantly at 0.05 level of probability, which compensated for the lower number of spikes per unit area. As a result, the grain yield increased in bed planting in comparison with flat planting (Table 4).

DISCUSSION

In wheat, major agronomic traits, such as plant height, lodging, and intemodes length have been extensively applied in selecting cultivars with superior performance and adaptation. In this study, results from several years' experiments for these diverse cultivars at several sites indicated that raised bed planting decreased significantly plant height by reducing the length of the fourth and fifth internodes. In a previous study, Wang et al. (2003) found that under the bed planting system, better field air circulation and stronger light penetration appeared to reduce the surface field moisture and canopy humidity. Probably due to these growth conditions in bed planting system, the plant height and length of lower internodes significantly decreased. The plant height and its components were closely associated with the lodging character of plants and could be used as a good indicator of lodging resistance in crops (Zhu et al., 2006; Zhu et al., 2008). In rice (*Oryza sativa* L.), basal internode lengths are particularly closely associated with plant lodging, because lodging often occurs at the lower internodes (Zhu et al., 2008). Significant inhibition of elongation of lower other than upper internodes by expression of the semidwarfing gene, *sd-1*, contributes to lodging resistance (Ogi et al., 1993). Given that bed planting decreases the length of the lower internodes and plant height and increases plant lodging resistance, consequently the raised bed planting system might be an alternative planting method in Northern China, because lodging resulting from excessive rainfall during grain filling is a severe problem there for wheat production.

Table 3. Comparison of internode length, plant height, PHCI, and lodging under different planting methods.

Variety	Cropping season/site	Planting method	Internode length 1st	2nd	3rd	4th	5th	Plant height (cm)	Lodging (%)
		Bed planting	26.6	15.7	11.7	8.4	4.7	76.1	0
Jimai 21	2003-2005/Jining	Flat planting	27.1	16.4	13.8	9.7	5.8	81.8	7
		$LSD_{0.05}$	ns†	ns	0.9	1.1	0.6	4.1	2
		Bed planting	25.2	15.6	10.2	7.9	4.3	72.2	2
Yannong 19	2005-2006/Qingzhou	Flat planting	25.4	16.1	12.0	8.6	5.6	76.7	15
		$LSD_{0.05}$	ns	ns	1.2	0.5	0.7	3.9	3
		Bed planting	26.1	18.2	13.1	8.7	4.8	79.9	0
Jining 12	2006-2007/Qufu	Flat planting	26.6	18.8	14.2	9.8	5.9	84.3	11
		$LSD_{0.05}$	ns	ns	ns	0.8	0.8	3.5	
		Bed planting	25.4	17.5	11.7	7.6	4.2	74.4	0
Jining 16	2007-2008/Wenshang	Flat planting	26.7	19.1	12.6	9.4	6.4	82.2	0
		$LSD_{0.05}$	ns	1.4	ns	1.6	0.9	2.8	
		Bed planting	25.4	15.6	11.2	6.1	4.6	70.8	2
Jimai 19	2008-2010/Jinan	Flat planting	25.8	16.4	12.1	7.3	5.5	75.1	13
		$LSD_{0.05}$	ns	ns	ns	0.9	0.7	3.9	3
Variety (V)			10.33	39.27	10.16	18.05	3.20	29.93	13.68
Planting method (PM)			11.42	19.38	24.08	33.12	17.73	79.33	90.35
V × PM			1.14	1.06	0.80	0.70	1.38	1.23	10.50

† Not significant at $LSD_{0.05}$.

Previous reports for flat planted wheat suggest that the configuration of crop leaves on the stems provided some information related to assimilate translocation in plants, considerably affecting the photosynthetic rate of plants, lodging resistance and the formation of yield components, all associated with crop productivity (Liu et al., 2000). In the present study, a significantly larger area of the lowest leaf and smaller area of the uppermost two leaves were observed in bed planted wheat than that in conventional flat planted wheat, even though no significant variations in total wheat leaf area were found between both planting conditions (Table 3). These changes are likely due to the fact that the lower leaves have been developed in early spring, when the highly differed day/night temperature in raised bed soil is beneficial for dry matter accumulation in bed planted wheat (Yang et al., 2005) and that the improved air and light conditions resulted from blank rows (furrows), in raised bed planting delayed leaf senescence and thus more leaves stayed green longer during grain filling (Wang et al., 2004), the reasons why the area of top leaves decrease remained to be elucidated. However, it is of interest to note that the difference in area change of upper and lower leaves constructs a “tower”-type plant architecture. The “tower”-type plant configuration is a potentially important contributor to improve light penetration into the crop canopy that can result in more efficient photosynthesis of wheat and higher grain yield. Additionally, longer duration of green leaves therefore plays an important role in wheat growth and yield component formation through more potential photosynp-thesis for a longer period.

As one of the important yield components, spike number per unit area decreased in raised bed planting, which might be caused by increased row spacing (Zhang et al., 2007) and lower soil temperature at the tillering stage (Kong et al., 2010). Better light reception and air circulation and optimized phenological pattern will increase the total assimilates available for spike growth, thereby increasing the potential for grain filling and permitting the maximum partitioning of the available assimilates to the spikes (Reynolds et al., 2009). Even though there was a reduction in spikes per unit area, the grains per spike and 1000-grain weight of wheat significantly increased under bed planting in comparison with flat planting, and the grain yield increased as a result of the integrative compensation between these yield components. Based on these data, we conclude that better development of wheat morphological traits in raised bed planting promotes the expression of the apparent “border effect” for wheat on the raised beds and

Table 4. Effects of planting methods on yield components and grain yield.

Variety	Cropping season/site	Planting method	Spikes per m^2	Grains per spike	1000-Grain weight (g)	Grain yield (kg ha^{-1})
		Bed planting	532	34.7	41.3	6481
Jimai 21	2003-2005/Jining	Flat planting	546	31.3	39.5	5737
		$LSD_{0.05}$	ns	2.7	1.3	319
		Bed planting	519	41.6	43.6	7518
Yannong 19	2005-2006/Qingzhou	Flat planting	559	35.8	42.1	6912
		$LSD_{0.05}$	ns	3.8	0.9	438
		Bed planting	543	37.8	42.4	7397
Jining 12	2006-2007/Qufu	Flat planting	587	33.7	41.3	6938
		$LSD_{0.05}$	ns	2.4	ns	367
		Bed planting	541	31.5	40.9	5925
Jining 16	2007-2008/Wenshang	Flat planting	569	29.8	38.4	5529
		$LSD_{0.05}$	ns	ns	2.3	334
		Bed planting	525	35.4	40.3	6366
Jimai 19	2008-2010/Jinan	Flat planting	567	31.3	38.6	5822
		$LSD_{0.05}$	ns†	3.4	1.4	274
Variety (V)			1.54	31.55	7.83	75.38
Planting method (PM)			17.38	61.59	13.46	61.09
V × PM			0.49	1.85	0.24	0.74

† Not significant at $LSD_{0.05}$.

optimizes the compensation of the yield components to increase wheat grain yield.

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