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# Yield gap analysis of super hybrid rice between two subtropical environments

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**Abstract**

China's super hybrid rice breeding project has developed many new cultivars with great yield potential. However, rice yield depends not only on genotype but also on environment. In 2008 and 2009, field experiments were conducted to compare super hybrid rice grown in Changsha (normal-yielding) and Guidong (high-yielding), Hunan Province, China. Eight super hybrid rice cultivars, namely II-you 084, II-youhang 1, D-you 527, Liangyoupeijiu, Nei-2-you 6, Y-liangyou 1, Zhongzheyou 1 and Zhunliangyou 527, were evaluated in each site. Grain yield and some yield attributes were determined for each cultivar. On the average across cultivars, Guidong produced higher grain yield than Changsha by 18% in 2008 and 41% in 2009. The higher grain yields were mainly attributed to a simultaneous increase in sink and source. For the sink, Guidong had both more panicles per $m^2$ and larger panicle size (spikelets per panicle) than Changsha, which resulted in larger sink size (spikelets per $m^2$). For the source, Guidong produced greater biomass than Changsha. Longer growth duration, more tillers (panicles) per $m^2$ and higher biomass per unit tiller height were responsible for the greater biomass production in Guidong. Liangyoupeijiu and Zhunliangyou 527 performed well in both sites. Liangyoupeijiu was characterized by large panicle size, while Zhunliangyou 527 had high spikelet filling percentage and grain weight. Our study suggests that further improvement in both sink and source should be possible in the normal-yielding subtropical environments if new rice cultivars are to be bred by selection for tillering (tiller number and size), and developing cultivars with high spikelet filling percentage and grain weight may also be a feasible approach to achieve high rice yield.

**Keywords:** Biomass production, grain yield, sink size, super hybrid rice, tillering.
**Abbreviations:** BCPH - biomass per cm plant height, BCTH - biomass per cm tiller height, CGR - crop growth rate.

## Introduction

Rice is the staple food for about 65% of the population in China. Rice yield has experienced two quantum leaps in China since the 1950s. This happened primarily as the result of genetic improvement and increasing harvest index by reducing plant height using the semi-dwarf genes (Huang, 2001) and utilization of heterosis by producing hybrids (Yuan et al., 1994). However, rapid population growth and economic development have been posing a growing pressure for increased food production (Zhang, 2007). To further increase the yield potential of rice, China established a nationwide mega-project in 1996 on the development of super rice based on the ideotype concept (Cheng et al., 1998). In 1998, Prof. Longping Yuan proposed a strategy for developing super hybrid rice by combining an ideotype approach with the use of inter-subspecific heterosis (Yuan et al., 2001). Up to 2011, 56 hybrid cultivars with great yield potential were approved as super hybrid rice by the Ministry of Agriculture of China. It was reported that super hybrid rice cultivars have increased yield potential by 12% compared with ordinary hybrid and inbred cultivars under subtropical conditions (Zhang et al., 2009).

Grain yield of rice is determined by sink size (spikelets per unit land area), spikelet filling percentage and grain weight. Sink size is considered as the primary determinant of the rice yield, and it can be increased either by increasing panicle number or panicle size (spikelets per panicle) or both (Kropff et al., 1994, Ying et al., 1998). Zhang et al. (2009) reported that super hybrid rice had significantly larger panicle size than ordinary hybrid and inbred rice, which resulted in an increase sink size and a consequent increase in grain yield. However, Huang et al. (2011a) stated that panicle number ought to be emphasized in super hybrid rice production. On the other hand, rice yield increase can be achieved either by increasing biomass production or harvest index or both. Evans et al. (1984) reported that rice yield difference between traditional and modern rice cultivars was due to difference in harvest index. But when comparison was made among the modern rice cultivars, high grain yield was achieved by increasing biomass production (Akita, 1989). Recently, Zhang et al. (2009) compared super hybrid rice cultivars with ordinary hybrid and inbred cultivars. Their results showed that high biomass production was responsible for the high grain yield of super hybrid cultivars.

Biomass production can be increased either by growth duration or crop growth rate (CGR) or both (Yoshida, 1983). Growth duration is strongly influenced by temperature. CGR is determined mainly by canopy gross photosynthesis and crop respiration losses, both of which are sensitive to temperature (Evans, 1993). In another approach, biomass production is a function of plant height and biomass per unit plant height, and the latter can be divided into two sub-components, namely tiller number and biomass per unit tiller height. However, association of high biomass production with high plant height is considered as unfavorable in grain production due to plant lodging potential. Grain yields over 13 t $ha^{-1}$ have been reported for irrigated rice in high-yielding subtropical environments

(Amamo et al., 1996, Ying et al., 1998). However, it is still difficult to achieve such a high grain yield in normal-yielding subtropical environments, even using the super hybrid rice cultivars. Currently, limited information is available on the critical factors that elaborate on the yield gap between high-yielding and normal-yielding subtropical environments. Such information would be useful for understanding the constraints of rice yield potential in the normal-yielding subtropical environment and for determining the plant characteristics that contribute to high yields.

This study aimed to (1) compare the grain yield of super hybrid rice between a normal-yielding and a high-yielding subtropical environment and (2) identify the key factors that contribute to the yield gap between the two environments.

## Results

### *Growing season temperature*

Temperatures during the rice-growing season in Changsha were higher than those in Guidong (Fig. 1). Seasonal average maximum temperatures were 32.2 °C and 27.4 °C in 2008 and 31.5 °C and 27.1 °C in 2009 for Changsha and Guidong, respectively. For minimum temperatures, seasonal mean values of Changsha vs. Guidong were 24.6 °C vs. 18.7 °C in 2008 and 23.8 °C vs. 19.0 °C in 2009.

### *Grain yield*

The difference in grain yield was significant between the two sites in both years (Table 1 and 2). Averaged across eight cultivars, grain yield was higher in Guidong than in Changsha by 18% in 2008 and 41% in 2009. The effect of cultivar and the interactive effect of site and cultivar on grain yield were significant in 2008 but insignificant in 2009. In 2008, Liangyoupeijiu and Zhunliangyou 527 produced over 10 t ha$^{-1}$ of grain yield in Changsha, while in Guidong all cultivars had more than 10 t ha$^{-1}$ of grain yield except for II-you 084. The difference in grain yield between the two years was inconsistent across sites. In Changsha, grain yield was higher in 2008 than in 2009 for all cultivars except for Y-liangyou 1. In Guidong, all cultivars produced lower grain yields in 2008 than in 2009. In all four experiments, the highest grain yield of 12.59 t ha$^{-1}$ was produced by Zhunliangyou 527 in Guidong in 2009.

### *Yield components*

Panicle number per m$^2$ was generally higher in Guidong than in Changsha (Table 1 and 2). Differences in panicle number per m$^2$ between the two sites were 13% in 2008 and 11% in 2009. The cultivar difference in panicle number per m$^2$ was significant in 2008 but not in 2009. In 2008, mean panicle number per m$^2$ across two sites was the highest in Zhongzheyou 1 and the lowest in D-you 527. There was a significant difference between the two sites in spikelets per panicle, which were 8% and 7% higher in Guidong than Changsha in 2008 and 2009, respectively. A significant difference in spikelets per panicle was observed across cultivars in both years. Averaged across all four experiments, spikelets per panicle was the highest in Liangyoupeijiu and lowest in Zhunliangyou 527. Sink size (spikelet number per m$^2$) in Guidong was 22% and 19% greater than in Changsha in 2008 and 2009, respectively. Among all cultivars, Liangyoupeijiu had the highest sink size except for Changsha in 2009, while the lowest sink size was observed in Zhunliangyou 527 in all four experiments.

Spikelet filling percentage was variable across environments and cultivars (Table 1 and 2). There was no significant difference in spikelet filling percentage between the two sites in 2008, whereas in 2009 spikelet filling percentage in Guidong was 8% higher than in Changsha. Among all cultivars, Zhunliangyou 527 had the highest spikelet filling percentage except for Changsha in 2009, while the lowest spikelet filling percentage was recorded in Nei-2-you 6 in 2008 and in D-you 527 in 2009. There was no consistent difference in grain weight between the two sites. In 2008, grain weight was 6% lower in Guidong than in Changsha, whereas in 2009 it was 5% higher in Guidong than in Changsha. The difference in grain weight across cultivars was larger than across sites. Averaged across four experiments, variability in grain weight was 27% between cultivars with highest grain weight in Zhunliangyou 527 and lowest in Liangyoupeijiu.

### *Biomass production*

Biomass accumulation in each growth period was significantly greater in Guidong than in Changsha (Table 3 and 4). Total biomass accumulation was 13% and 37% higher in Guidong than in Changsha in 2008 and 2009, respectively. There was no significant cultivar difference in biomass accumulation in each growth period. Guidong had slightly but significantly higher harvest index than Changsha. The difference in harvest index across cultivars was significant in 2008 but not in 2009. In 2008, a maximum harvest index of 0.55 was observed in Zhunliangyou 527 in Guidong.

Duration of each growth period in Guidong was generally longer than in Changsha (Table 3 and 4). Total growth duration was longer in Guidong than in Changsha by 17–31 d in 2008 and 20–27 d in 2009, depending on cultivars. Within sites, the difference in total growth duration was relatively small across cultivars. There was no consistent difference in CGR during pre-heading between the two sites. In 2008, CGR during pre-heading was 6% higher in Changsha than in Guidong, whereas in 2009 it was 18% lower in Changsha. The cultivar difference in CGR during pre-heading was insignificant in 2008 but significant in 2009. In 2009, average CGR during pre-heading across two sites was the highest in D-you 527 and the lowest in Nei-2-you 6. There was no significant difference in CGR during post-heading between the two sites in both years. The difference in CGR during the whole growth period between the two sites was not significant in 2008 but significant in 2009. Guidong had 16% higher CGR during the whole growth period than Changsha in 2009. The differences in CGR during post-heading and the whole growth period across cultivars were not significant in both years.

There was no consistent difference in plant height between the two sites (Table 3 and 4). Plant height was 16% lower in Guidong than in Changsha in 2008, whereas it was similar between the two sites in 2009. A significant cultivar difference in plant height was observed in 2008 but not in 2009. In 2008, average plant height across two sites was the highest in Zhunliangyou 527 and the lowest in Nei-2-you 6. Guidong generally had higher BCPH than Changsha. Differences in BCPH between the two sites were 35% in 2008 and 40% in 2009. An insignificant difference in BCPH was observed across cultivars in both years. BCTH was also higher in Guidong than in Changsha. Differences in BCTH between the two sites were 20% in 2008 and 10% in 2009.

The cultivar difference in BCTH was significant in 2008 but not in 2009. In 2008, mean BCTH across two sites was the highest in Nei-2-you 6 and the lowest in Zhongzheyou 1. Plant height was not related to total biomass accumulation (Fig. 2a). There was a strong positive relationship between total biomass accumulation and BCPH (Fig. 2b). Both panicle number and

**Table 1.** Grain yield and yield components of super hybrid rice cultivars grown in Changsha and Guidong, Hunan Province, China in 2008.

| Cultivar | Grain yield ($t\ ha^{-1}$) | Panicles $m^{-2}$ | Spikelets $panicle^{-1}$ | Spikelets $m^{-2}$ ($\times10^3$) | Spikelet filling (%) | Grain weight (mg) |
|---|---|---|---|---|---|---|
| Changsha | | | | | | |
| II-you 084 | 8.61 | 203 | 161 | 32.7 | 87.5 | 26.4 |
| II-youhang 1 | 8.01 | 201 | 182 | 36.6 | 85.3 | 26.6 |
| D-you 527 | 9.47 | 208 | 157 | 32.7 | 86.7 | 29.9 |
| Liangyoupeijiu | 10.69 | 226 | 186 | 42.1 | 84.6 | 25.2 |
| Nei-2-you 6 | 9.94 | 201 | 160 | 32.3 | 80.7 | 31.7 |
| Y-liangyou 1 | 9.54 | 231 | 171 | 39.6 | 84.2 | 25.2 |
| Zhongzheyou 1 | 8.61 | 235 | 160 | 37.6 | 91.3 | 25.7 |
| Zhunliangyou 527 | 10.01 | 205 | 142 | 29.1 | 93.7 | 31.9 |
| Mean | 9.36 | 214 | 165 | 35.3 | 86.8 | 27.8 |
| Guidong | | | | | | |
| II-you 084 | 9.64 | 230 | 170 | 39.1 | 85.8 | 25.6 |
| II-youhang 1 | 11.15 | 231 | 178 | 41.1 | 90.8 | 26.4 |
| D-you 527 | 11.07 | 218 | 194 | 42.4 | 84.7 | 27.0 |
| Liangyoupeijiu | 11.90 | 246 | 189 | 46.4 | 88.4 | 23.6 |
| Nei-2-you 6 | 10.84 | 232 | 195 | 45.1 | 78.2 | 28.4 |
| Y-liangyou 1 | 10.64 | 246 | 188 | 46.2 | 88.2 | 24.1 |
| Zhongzheyou 1 | 11.80 | 281 | 164 | 46.3 | 91.0 | 24.8 |
| Zhunliangyou 527 | 11.19 | 254 | 148 | 37.5 | 93.8 | 29.9 |
| Mean | 11.03 | 242 | 178 | 43.1 | 87.6 | 26.2 |
| Analysis of variance | | | | | | |
| Site | ** | ** | ** | ** | NS | ** |
| Cultivar | ** | ** | ** | ** | ** | ** |
| Site ×Cultivar | ** | NS | ** | NS | * | * |

* Significant at 0.05 probability level. ** Significant at 0.01 probability level. NS denotes non-significance.

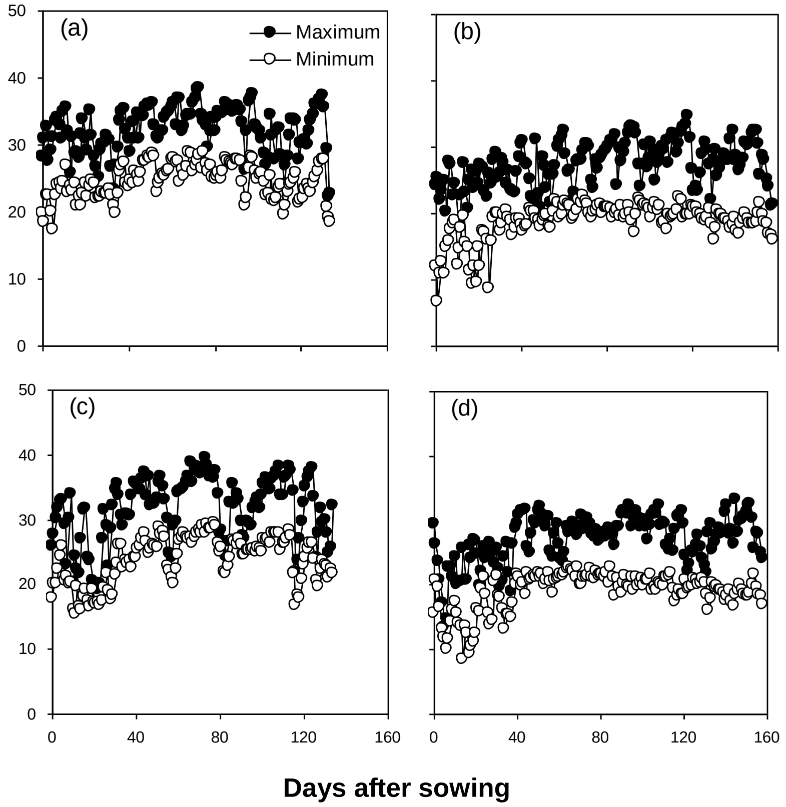


**Fig 1.** Daily maximum and minimum temperatures during rice-growing season in Changsha (a, c) and Guidong (b, d), Hunan Province, China in 2008 (a, b) and 2009 (c, d).

BCTH were significantly positive-related to BCPH (Fig. 2c and d). However, BCPH was related more closely to BCTH than panicle number; 62% and 38% of BCPH variation was explained by BCTH and panicle number, respectively.

## Discussion

In the present study, the highest grain yield of 12.59 t ha$^{-1}$ was produced by Zhunliangyou 527 in Guidong in 2009. Ying et al. (1998) reported that Guichao 2 (inbred cultivar) and Shanyou 63 (ordinary hybrid rice cultivar) yielded on average 15 t ha$^{-1}$ in a subtropical environment of at Taoyuan, Yunnan Province, China. Obviously, the yield potential is lower in Guidong than in Taoyuan. However, Guidong produced about 30% higher grain yield than Changsha across eight cultivars and two years. Analysis of yield components indicates that sink size was mainly responsible for the yield gap, because differences in spikelet filling percentage and grain weight between the two sites were relatively small and inconsistent across the two years. The importance of sink size in enhancing grain yield has been reported in many studies (Kropff et al., 1994, Ying et al., 1998, Zhang et al., 2009), and most of these studies demonstrated that large panicles contributed mostly to the great sink size. However, in this study, the difference in sink size between Guidong and Changsha was attributed to the differences in both panicles per m$^2$ and spikelets per panicle.

In cereal crops, the compensation among yield components always arises (Heinrich et al., 1983, Simane et al., 1993, Zeng and Shannon, 2000) from either the physiological competition or from the developmental allometry (Grafius et al., 1976). It has largely contributed to the failure in breeding efforts to improve yield potential through indirect selection for yield components in cereals (Li et al., 1998). In rice, a strong compensation mechanism always exists between panicles per m$^2$ and spikelets per panicle (Ying et al., 1998, Huang et al., 2011b). However, in the present study, Guidong had both higher panicles per m$^2$ and spikelets per panicle than Changsha, suggesting that the compensation between the two components can be detached.

In wheat, the way to detach the tight negative relationship between the two components is to increase biomass production during the critical phases of development when sink size is determined (Slafer et al., 1996). In the present study, Guidong had greater biomass accumulation during pre-heading than Changsha, indicating that increasing biomass production may also play an important role in detaching the compensation between panicle number and panicle size in rice.

The rice crops in Guidong had about 25% more total biomass accumulation than in Changsha. Harvest index was also higher in Guidong than in Changsha. These indicate that both source (biomass production) and flow (transport of assimilates to spikelets) were improved in Guidong. However, because the difference in harvest index between the two sites was relatively small, the higher grain yield in Guidong was mostly attributed to the improvement in source. There have been reports that high yield of rice is achieved by increasing biomass production under favorable conditions (Song et al., 1990, Yamauchi, 1994, Yang et al., 2008). In this regard, it was suggested that there is little scope to further increase harvest index (Evans and Fischer, 1999, Laza et al., 2003) and further improvement in rice yield might be driven from the increased biomass production rather than harvest index (Peng et al., 1999). Longer growth duration was mainly responsible for the greater biomass production in Guidong than in Changsha, because the difference in CGR between the two sites was inconsistent across the two years. Cool temperatures slow the development rate of crops and prolong growth duration (Sinclair and Bai, 1997). The long growth duration in Guidong was associated with the low temperatures. Although both shoot elongation and tillering are related to biomass production in rice (Samonte et al., 2006, Ao et al., 2010, Huang et al., 2012) but our results showed that the greater biomass production in Guidong was not achieved by increasing the plant height, instead by increasing tiller (panicle) number and especially the BCTH. To some extent, high BCTH is accompanied by a large stem size. Ansari et al. (2004) observed that larger stem size resulted in a higher stem transport rate and a consequent increase in panicle size in rice. This might also the reason why Guidong had larger panicle size than Changsha.

These findings suggest that further improvement in both sink and source should be possible in the normal-yielding subtropical environments if new rice cultivars are to be bred by selection for tillering (tiller number and size).

Liangyoupeijiu, the first super hybrid rice cultivar in China, performed well in both sites. Unexpectedly, most recently released cultivars did not perform better than Liangyoupeijiu. It shows that current effort did not contribute to increased rice yield. Consistently, over the last 10 years, rice yields have shown declining or stagnant trends in most rice production provinces and the average annual growth rate was –0.3% from 1998 to 2006 in China (Fan et al., 2009).

Zhunliangyou 527 also had a good performance in both sites. However, the yield-related traits of this cultivar were different from those of Liangyoupeijiu. Among all cultivars, Liangyoupeijiu had the highest sink size (except for Changsha in 2009). Large panicle size was mainly responsible for the large sink size in Liangyoupeijiu. Although Liangyoupeijiu did not show obvious superiority in panicle number and spikelet filling percentage, their values were relatively high. So that, the advantage of a large number of spikelets was not offset by other components of grain yield.

On the contrary, Zhunliangyou 527 had the lowest sink size. However, this cultivar displayed substantial advantages in spikelet filling percentage and grain weight, which could make up the low sink size. Moreover, Zhunliangyou 527 had the highest harvest index (except for Changsha in 2009), indicating that the flow was improved in this cultivar. This might also be partly responsible for the high spikelet filling percentage and grain weight in Zhunliangyou 527. Most previous studies attributed the high grain yield of super hybrid rice to its large panicle size (Zhu 2002, Zhang et al. 2009). Our study indicates that developing cultivars with high spikelet filling percentage and grain weight may also be a feasible approach to achieve high rice yield.

## Materials and methods

### *Sites and soils*

Field experiments were conducted in a normal-yielding environment at Changsha (28°11′ N, 113°04′ E, 32 m asl) and a high-yielding environment at Guidong (25°59′ N, 113°55′ E, 734 m asl), Hunan Province, China in 2008 and 2009. The soil of the Changsha site was a clay with the following properties: pH 6.15, 25.0 g kg$^{-1}$ organic matter, 1.47 g kg$^{-1}$ total N, 57.9 mg kg$^{-1}$ available P, and 55.6 mg kg$^{-1}$ available K. The soil of the Guidong site was a sandy loam with the following properties: pH 5.20, 52.7 g kg$^{-1}$ organic matter, 2.82 g kg$^{-1}$ total N, 44.7 mg kg$^{-1}$ available P, and 76.0 mg kg$^{-1}$ available K. The soil test was based on samples taken from the upper 20 cm of the soil.

**Table 2.** Grain yield and yield components of super hybrid rice cultivars grown in Changsha and Guidong, Hunan Province, China in 2009.

| Cultivar | Grain yield ($t\ ha^{-1}$) | Panicles $m^{-2}$ | Spikelets $panicle^{-1}$ | Spikelets $m^{-2}$ ($\times 10^3$) | Spikelet filling (%) | Grain weight (mg) |
|---|---|---|---|---|---|---|
| Changsha | | | | | | |
| II-you 084 | 8.09 | 239 | 182 | 43.3 | 72.7 | 23.1 |
| II-youhang 1 | 8.02 | 233 | 198 | 46.1 | 69.2 | 23.7 |
| D-you 527 | 7.77 | 244 | 157 | 38.4 | 62.8 | 26.4 |
| Liangyoupeijiu | 9.82 | 238 | 191 | 45.3 | 80.1 | 22.7 |
| Nei-2-you 6 | 8.60 | 241 | 155 | 37.1 | 72.6 | 27.9 |
| Y-liangyou 1 | 8.75 | 267 | 171 | 45.6 | 86.3 | 22.7 |
| Zhongzheyou 1 | 9.67 | 255 | 167 | 42.6 | 83.1 | 22.6 |
| Zhunliangyou 527 | 8.21 | 244 | 134 | 32.8 | 85.0 | 28.0 |
| Mean | 8.62 | 245 | 169 | 41.4 | 76.5 | 24.6 |
| Guidong | | | | | | |
| II-you 084 | 11.70 | 258 | 188 | 48.7 | 82.1 | 23.6 |
| II-youhang 1 | 12.51 | 254 | 208 | 52.7 | 78.6 | 25.1 |
| D-you 527 | 12.34 | 271 | 203 | 55.1 | 76.6 | 25.9 |
| Liangyoupeijiu | 11.99 | 279 | 200 | 55.9 | 88.1 | 22.8 |
| Nei-2-you 6 | 12.07 | 270 | 172 | 46.6 | 80.9 | 28.6 |
| Y-liangyou 1 | 12.17 | 282 | 169 | 47.7 | 89.4 | 25.9 |
| Zhongzheyou 1 | 12.02 | 287 | 159 | 45.6 | 87.7 | 24.4 |
| Zhunliangyou 527 | 12.59 | 265 | 150 | 39.8 | 90.5 | 29.7 |
| Mean | 12.17 | 271 | 181 | 49.1 | 84.2 | 25.8 |
| Analysis of variance | | | | | | |
| Site | ** | ** | * | ** | ** | ** |
| Cultivar | NS | NS | ** | ** | ** | ** |
| Site ×Cultivar | NS | NS | NS | NS | NS | NS |

* Significant at 0.05 probability level. ** Significant at 0.01 probability level. NS denotes non-significance.

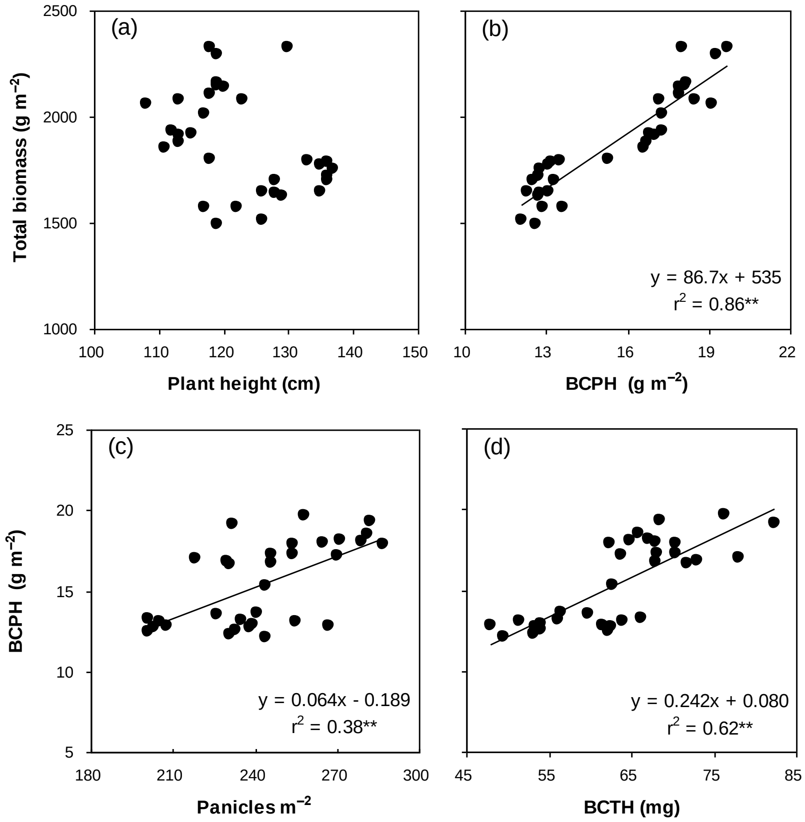


**Fig 2.** Relationships between total biomass accumulation with plant height (a) and biomass per cm plant height (BCPH) (b), and between BCPH with panicles per $m^2$ (c) and biomass per cm tiller height (BCTH) (d). Data were obtained from field experiments in which eight super rice cultivars were grown in Changsha and Guidong, Hunan Province, China in 2008 and 2009. ** Significance at 0.01 probability level.

**Table 3.** Biomass accumulation, harvest index, growth duration, crop growth rate (CGR), plant height, biomass per cm plant height (BCPH), and biomass per cm tiller height (BCTH) of super hybrid rice cultivars grown in Changsha and Guidong, Hunan Province, China in 2008.

| Cultivar | Biomass accumulation ($g\ m^{-2}$) | | | Harvest index | Growth duration (d) | | | CGR ($g\ m^{-2}\ d^{-1}$) | | | Plant height (cm) | BCPH ($g\ m^{-2}$) | BCTH (mg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre-heading | Post-heading | Total | | Pre-heading | Post-heading | Total | Pre-heading | Post-heading | Whole growth period | | | |
| Changsha | | | | | | | | | | | | | |
| II-you 084 | 1088 | 631 | 1719 | 0.50 | 93 | 38 | 131 | 11.7 | 16.6 | 13.1 | 136 | 12.7 | 62.6 |
| II-youhang 1 | 1052 | 651 | 1703 | 0.49 | 93 | 38 | 131 | 11.3 | 17.1 | 13.0 | 136 | 12.5 | 62.2 |
| D-you 527 | 1067 | 685 | 1752 | 0.49 | 97 | 35 | 132 | 11.0 | 19.6 | 13.3 | 137 | 12.8 | 61.5 |
| Liangyoupeijiu | 1133 | 660 | 1793 | 0.51 | 97 | 38 | 135 | 11.7 | 17.4 | 13.3 | 133 | 13.5 | 59.7 |
| Nei-2-you 6 | 1068 | 629 | 1697 | 0.50 | 95 | 36 | 131 | 11.2 | 17.5 | 13.0 | 128 | 13.3 | 66.2 |
| Y-liangyou 1 | 1037 | 612 | 1649 | 0.52 | 95 | 35 | 130 | 10.9 | 17.5 | 12.7 | 135 | 12.3 | 53.2 |
| Zhongzheyou 1 | 1101 | 684 | 1785 | 0.51 | 100 | 36 | 136 | 11.0 | 19.0 | 13.1 | 136 | 13.2 | 56.2 |
| Zhunliangyou 527 | 1074 | 698 | 1772 | 0.53 | 93 | 33 | 126 | 11.5 | 21.2 | 14.1 | 135 | 13.1 | 63.9 |
| Mean | 1078 | 656 | 1734 | 0.51 | 96 | 36 | 132 | 11.3 | 18.3 | 13.2 | 135 | 12.9 | 60.7 |
| Guidong | | | | | | | | | | | | | |
| II-you 084 | 1173 | 749 | 1922 | 0.47 | 110 | 48 | 158 | 10.7 | 15.6 | 12.2 | 115 | 16.8 | 73.0 |
| II-youhang 1 | 1154 | 699 | 1853 | 0.54 | 122 | 35 | 157 | 9.5 | 20.0 | 11.8 | 111 | 16.6 | 71.9 |
| D-you 527 | 1227 | 684 | 1911 | 0.54 | 116 | 38 | 154 | 10.6 | 18.0 | 12.4 | 113 | 17.0 | 78.0 |
| Liangyoupeijiu | 1200 | 683 | 1883 | 0.52 | 116 | 38 | 154 | 10.3 | 18.0 | 12.2 | 113 | 16.7 | 67.9 |
| Nei-2-you 6 | 1263 | 800 | 2063 | 0.50 | 110 | 43 | 153 | 11.5 | 18.6 | 13.5 | 108 | 19.1 | 82.3 |
| Y-liangyou 1 | 1205 | 728 | 1933 | 0.54 | 108 | 44 | 152 | 11.2 | 16.5 | 12.7 | 112 | 17.3 | 70.3 |
| Zhongzheyou 1 | 1269 | 808 | 2077 | 0.53 | 111 | 42 | 153 | 11.4 | 19.2 | 13.6 | 113 | 18.5 | 65.8 |
| Zhunliangyou 527 | 1259 | 754 | 2013 | 0.55 | 120 | 37 | 157 | 10.5 | 20.4 | 12.8 | 117 | 17.3 | 68.1 |
| Mean | 1219 | 738 | 1957 | 0.52 | 114 | 41 | 155 | 10.7 | 18.3 | 12.7 | 113 | 17.4 | 72.2 |
| Analysis of variance | | | | | | | | | | | | | |
| Site | ** | * | ** | ** | – | – | – | * | NS | NS | ** | ** | ** |
| Cultivar | NS | NS | NS | ** | – | – | – | NS | NS | NS | ** | NS | * |
| Site ×Cultivar | NS | NS | NS | ** | – | – | – | NS | NS | NS | NS | NS | NS |

* Significant at 0.05 probability level. ** Significant at 0.01 probability level. NS denotes non-significance.

**Table 4.** Biomass accumulation, harvest index, growth duration, crop growth rate (CGR), plant height, biomass per cm plant height (BCPH), and biomass per cm tiller height (BCTH) of super hybrid rice cultivars grown in Changsha and Guidong, Hunan Province, China in 2009.

| Cultivar | Biomass accumulation (g m$^{-2}$) | | | Harvest index | Growth duration (d) | | | CGR (g m$^{-2}$ d$^{-1}$) | | | Plant height (cm) | BCPH (g m$^{-2}$) | BCTH (mg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre-heading | Post-heading | Total | | Pre-heading | Post-heading | Total | Pre-heading | Post-heading | Whole growth period | | | |
| Changsha | | | | | | | | | | | | | |
| II-you 084 | 1046 | 528 | 1574 | 0.47 | 96 | 35 | 131 | 10.9 | 15.1 | 12.0 | 122 | 12.9 | 54.0 |
| II-youhang 1 | 992 | 500 | 1492 | 0.47 | 96 | 35 | 131 | 10.3 | 14.3 | 11.4 | 119 | 12.6 | 54.1 |
| D-you 527 | 1123 | 680 | 1803 | 0.44 | 95 | 32 | 127 | 11.8 | 21.3 | 14.2 | 118 | 15.3 | 62.7 |
| Liangyoupeijiu | 1094 | 536 | 1630 | 0.48 | 100 | 35 | 135 | 10.9 | 15.3 | 12.1 | 129 | 12.7 | 53.4 |
| Nei-2-you 6 | 1052 | 524 | 1576 | 0.48 | 99 | 32 | 131 | 10.6 | 16.4 | 12.0 | 117 | 13.6 | 56.4 |
| Y-liangyou 1 | 1087 | 554 | 1641 | 0.51 | 99 | 32 | 131 | 11.0 | 17.3 | 12.5 | 128 | 12.8 | 47.9 |
| Zhongzheyou 1 | 1093 | 551 | 1644 | 0.48 | 99 | 32 | 131 | 11.0 | 17.2 | 12.5 | 126 | 13.1 | 51.4 |
| Zhunliangyou 527 | 988 | 523 | 1511 | 0.50 | 96 | 31 | 127 | 10.3 | 16.9 | 11.9 | 126 | 12.1 | 49.6 |
| Mean | 1059 | 550 | 1609 | 0.48 | 98 | 33 | 131 | 10.8 | 16.7 | 12.3 | 123 | 13.1 | 53.7 |
| Guidong | | | | | | | | | | | | | |
| II-you 084 | 1497 | 831 | 2327 | 0.50 | 114 | 44 | 158 | 13.1 | 18.9 | 14.7 | 118 | 19.7 | 76.4 |
| II-youhang 1 | 1424 | 719 | 2143 | 0.52 | 111 | 44 | 155 | 12.8 | 16.3 | 13.8 | 120 | 17.9 | 70.5 |
| D-you 527 | 1436 | 722 | 2158 | 0.52 | 106 | 44 | 150 | 13.5 | 16.4 | 14.4 | 119 | 18.2 | 67.2 |
| Liangyoupeijiu | 1398 | 747 | 2146 | 0.53 | 112 | 43 | 155 | 12.5 | 17.4 | 13.8 | 119 | 18.1 | 64.9 |
| Nei-2-you 6 | 1360 | 720 | 2080 | 0.48 | 109 | 44 | 153 | 12.5 | 16.4 | 13.6 | 123 | 17.2 | 63.7 |
| Y-liangyou 1 | 1519 | 772 | 2291 | 0.53 | 109 | 45 | 154 | 13.9 | 17.2 | 14.9 | 119 | 19.3 | 68.4 |
| Zhongzheyou 1 | 1354 | 755 | 2109 | 0.50 | 110 | 44 | 154 | 12.3 | 17.2 | 13.7 | 118 | 17.9 | 62.4 |
| Zhunliangyou 527 | 1490 | 837 | 2327 | 0.55 | 108 | 44 | 152 | 13.8 | 19.0 | 15.3 | 130 | 18.0 | 67.9 |
| Mean | 1435 | 763 | 2198 | 0.52 | 110 | 44 | 154 | 13.1 | 17.3 | 14.3 | 121 | 18.3 | 67.7 |
| Analysis of variance | | | | | | | | | | | | | |
| Site | ** | ** | ** | ** | – | – | – | ** | NS | ** | NS | ** | ** |
| Cultivar | NS | NS | NS | NS | – | – | – | * | NS | NS | NS | NS | NS |
| Site ×Cultivar | * | NS | NS | NS | – | – | – | * | NS | NS | NS | NS | NS |

* Significant at 0.05 probability level. ** Significant at 0.01 probability level. NS denotes non-significance.

**Table 5.** List of super hybrid rice cultivars ($F_1$ hybrids) used in this experiment.

| Cultivar | Type | Release year | Female parent | Male parent |
|---|---|---|---|---|
| II-you 084 | Indica | 2001 | II-32A | Zhenhui 084 |
| II-youhang 1 | Indica | 2006 | II-32A | Hang 2 |
| D-you 527 | Indica | 2000 | D62A | Shuhui 527 |
| Liangyoupeijiu | Intermediate[a] | 1999 | Peiai64S | 9311 |
| Nei-2-you 6 | Indica | 2006 | Neixiang2A | R8006 |
| Y-liangyou 1 | Indica | 2006 | Y58S | 9311 |
| Zhongzheyou 1 | Indica | 2004 | ZhongzheA | Hanghui 570 |
| Zhunliangyou 527 | Indica | 2003 | ZhunS | Shuhui 527 |

[a] The intermediate type between indica and japonica.

### *Plant materials and experimental design*

Eight super hybrid rice cultivars ($F_1$ hybrids) were used in each site. Detailed information about them is given in Table 5. The experiments were laid out in a split-plot design with fertilizer treatments (fertilization and non-fertilization) as main plots and cultivars as subplots, with two replications and subplot size of 13 $m^2$. In this study, only data from the fertilized plots were used. Pre-germinated seeds were sown in a seedbed on 15 May 2008 and 6 May 2009 in Changsha and on 25 April 2008 and 23 April 2009 in Guidong, respectively. Transplanting was done at a hill spacing of 23 cm × 23 cm with two seedlings per hill at the 4–5 leaf stage (about 25 d after sowing). Nitrogen (210 kg urea $ha^{-1}$, 46% N) was applied equally at basal and top dressing (midtillering, panicle initiation and heading). Phosphorus (900 kg superphosphate $ha^{-1}$, 12% $P_2O_5$) was applied 1 day before transplanting. Potassium (90 kg potassium chloride $ha^{-1}$, 60% $K_2O$) was split equally at basal and panicle initiation. Water management adopted a strategy of flooding–midseason drainage–reflooding–moist intermittent irrigation. Weeds, insects and diseases were controlled as required to avoid yield loss.

### *Sampling and measurements*

Ten hills were sampled for each replication at heading. Plants were oven-dried at 70 °C to constant weight to determine biomass accumulation and crop growth rate (CGR) during pre-heading. At maturity, 20 hills were randomly selected for each replication to count panicle number. Ten hills were sampled for each replication to determine plant height, biomass accumulation and CGR during post-heading and the whole growth period, biomass per cm plant height (BCPH), biomass per cm tiller height (BCTH), harvest index, spikelet number per panicle, spikelet filling percentage and grain weight. Plant height was measured from the base of the stem to the tip of the tallest panicle. Plant samples were separated into straw and panicles. Straw dry weight was determined after oven-drying at 70 °C to constant weight. Panicles were hand-threshed and filled spikelets were separated from unfilled spikelets by submerging them in tap water. Three subsamples of 30 g of filled spikelets and all of unfilled spikelets were taken to count the number of spikelets. Dry weight of rachis and filled and unfilled spikelets were determined after oven-drying at 70 °C to constant weight. Total biomass accumulation was the total dry weight of straw, rachis, and filled and unfilled spikelets. Biomass accumulation during post-heading, CGR during pre-heading, post-heading and the whole growth period, BCPH, BCTH, harvest index, spikelet number per panicle, spikelet filling percentage, and grain weight were calculated as following:

$$\mathrm{CGR} = \frac{\text{Biomass accumulation}}{\text{Growth duration}}$$

$$\mathrm{BCPH} = \frac{\text{Total biomass accumulation}}{\text{Plant height}}$$

$$\mathrm{BCTH} = \frac{\mathrm{BCPH}}{\text{Panicles per m}^2}$$

Grain yield was determined from a 5-$m^2$ area in each plot and adjusted to standard moisture content of 0.14 g $H_2O$ $g^{-1}$. Daily maximum and minimum temperatures during rice-growing season in each site were collected from local weather station.

### *Statistical analysis and figure preparation*

Statistical analyses were performed using analysis of variance and linear regression (Statistix 8, Analytical software, Tallahassee, FL, USA). Figures were plotted by Excel software 2003 (Microsoft Inc., Redmond, Washington, USA).


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