Reduction in Fertilizer Input's Has No Significant Affect on Yield or Performance of Early- and Late-season Indica Hybrid Rice

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Original article

Keywords: hybrid rice, heterosis, main yield trait, restorer lines, double-cropping rice

Posted Date: July 7th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-40038/v1>

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Abstract

Increasing rice production by using genetically improved rice cultivars and fertilizer application has been the main objective of rice farming. The double rice-cropping system has been an important rice production system in the middle and lower reaches of the Yangtze River in China since the 1950s. It is of great significance to determine whether hybrid vigor can make a substantial contribution to early- and late-season rice production, and how the heterosis expression of hybrid rice functions under different level of fertilization application. The objective of this study was to evaluate the grain yield and associated plant traits of popular hybrid and inbred rice varieties with large-scale promotion under conditions of customary (high) and combined (low) fertilization in the early and late seasons of 2017-18 in Changsha County, Hunan Province, central Southern China. We found that hybrid rice varieties displayed their respective advantages in the early- and late-rice seasons, but the advantages in their relative yield traits varied. The main advantages of early-season rice were effective panicle number per hill (EPN), 1000-grain weight (KGW), harvest index (HI), yield, and nitrogen use efficiency (NUE). Whereas in late-season rice, the major advantages were grain number per panicle (GNP), HI, yield, and NUE. The EPN was the main advantage of early-season hybrid rice with a short-growth period, and the GNP was the main advantage of late-season hybrid rice with a long-growth period. The main yield advantage of hybrid rice was stronger under combined (low) fertilization than under customary (high) fertilization. Hence, high yield can be achieved by selecting good hybrid rice varieties and by using combined fertilization (lower fertilizer use with higher efficiency). This work is contributive for rice growers, extension specialists, and fertilizer producers, as it provides data that can be used to maximize yields with reduced fertilizer and pesticide inputs.

Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops, accounting for 25% of China's total planted area and 37% of its national cereal production. China will require approximately 20% more rice production by 2030 to meet its domestic needs if rice consumption per capita is maintained at its current trends (Cai and Chen, 2000). As such, there are two primary intensification options: (1) increasing rice yield through management optimization and genetic improvement (Neumann et al, 2010); and (2) using existing cropland more frequently each year through multiple cropping (Ray and Foley, 2013). In China, rice systems can be divided into single-season and double-season rice systems, with early- and late-season rice. The planting area depends on ambient agro-climatic resources. An important way to make full use of agricultural climatic resources is to double crop rice system using scientifically proven methods to increase the multiple cropping index. For obtaining a steady increasing in cropping areas and grain production capacity (Zhang and Yang, 2016), a huge portion of the rice planting area has been dominated by the double rice cropping system, especially in the middle and lower reaches of the Yangtze River in China, where early-season rice is generally grown from April to July and late-season rice from July to October (Wu et al, 2013). With the development of increased rice yield, varieties have also experienced the transformation from tall stem to dwarf and from inbred rice to hybrid rice (Zou, 2011). For example, Hunan Province is the main hybrid rice-producing province in China, the use of heterosis has long been considered a significant way to improve rice yield potential (Yuan, 2014). It is well documented that hybrid rice cultivars possess the advantage of a 15 % or more greater yield over improved inbred lines (Peng et al, 2009, Cheng et al, 2007, Yuan, 1994). Early-season hybrids still accounted for 31.4–39.7% of the whole planting area in the middle-lower reaches of the Yangtze River from 2015 to 2017 (Chen et al, 2019). It is of great importance to determine whether hybrid vigor could substantially contribute to early- and late-season rice production and how the heterosis expression of hybrid rice functions under different fertilization conditions.

However, rice production faces many challenges in China. The greatest challenge occurs in regions in which smallholder farming dominates the agricultural landscape (Cui et al, 2018). High labor input and low economic returns have reduced the enthusiasm of farmers to grow double-season rice (Peng et al, 2004). Further, excessive use of chemical fertilizers causes many negative environmental impacts, such as water pollution, eutrophication, high NO_3^- in underground water, and air pollution (Zhou et al, 2016, Norse and Ju, 2015, Liu et al, 2013, Carpenter, 2008). China produces 19% of the world's food supply; however, over the last decade, it has used chemical fertilizers equivalent to 30% of that used in the annual food consumption worldwide (West et al, 2014, Jiao et al, 2016). A campaign of the Chinese government aimed at capping the use of chemical fertilizers below 1% of the use from 2015 until 2019, without any yield losses and further increase slated for 2020 (Hvistendahl, 2010, Ju et al, 2009). In China, 200–300 million households farm having a few hectares of land, relies heavily on high-to-excessive fertilizer inputs in crop production system. For example, nitrogen application averages $305 \text{ kg N ha}^{-1}\text{yr}^{-1}$ in China as compared to $74 \text{ kg N ha}^{-1}\text{yr}^{-1}$ worldwide (Cui et al, 2018). High labor input in the traditional double-cropping system is primarily because of raising seedlings, transplanting twice a year (Xu et al, 2018), and controlling weeds, diseases, and insect pests. The diseases and insect pests of early- and late-season rice usually need to be controlled by the young and middle-aged rural labor force more than two or three times. To reduce labor costs in China, recently

some companies have developed “medicinal fertilizers” for farmers. The term “medicinal fertilizer” usually refers to a mixture of pesticides and fertilizers in a given proportion, produced via a special process, which has the integrated function of both the pesticide and the fertilizer. The pesticide can be a herbicide, insecticide, or bactericide; the fertilizer can be either a simple or multi-nutrient compound fertilizer. Consequently, the medicinal fertilizer could be used for killing / inhibiting insects, bacteria, and weeds, regulating crop growth, and providing nutrition for crops, or improving the fertilizer utilization rate. Farmers can combine the frequently used fertilizer with the medicinal fertilizer to solve the issue of labor shortage. In addition to the maintenance of agricultural growth and increase in yield and harvest, combined fertilization has advantages of convenience of use and reduced environmental pollution (Li, 2018). On the other hand, many farmers select hybrid rice to increase yield, but the performance of early- and late-season hybrid rice has not been clarified under different fertilization conditions. To address this gap the present investigation was conducted to find the outcome of using different fertilizer regimens, we explored differences in the performance of hybrid and inbred rice lines under customary (high) and combined (low) fertilization treatments across the 2017 and 2018 rice growing seasons. Our study objectives were to (1) evaluate the performance of hybrid rice in double-cropping seasons and (2) identify the effects of different fertilization regimens on heterosis expression in hybrid versus inbred lines for the purpose of reducing fertilization inputs. We compared the yield relative traits, such as biomass accumulation, main yield traits, grain yields, and nitrogen use efficiency (NUE), between tested early- and late-season hybrid and inbred rice varieties under two fertilization treatments. This work provides valuable data for growers, extension specialists, and fertilizer producers that can be used to maximize yields with reduced fertilizer and pesticide inputs..

Materials And Methods

1.1 Experimental Design and Operation

The field experiments were conducted at the Hunan Hybrid Rice Research Center experimental base, Changsha County, Hunan Province, China (28°12'N, 112°59'E) in 2017-18. The early-season and late season hybrid rice varieties tested in this study were ZLY89 and LLY268, TY390 and CLY7 and inbred varieties were ZZ39 and XZX45 and HHZ and X2 respectively. A detailed description of each variety is given in **Table 1**. The experimental field covered an area of 0.2 ha. Customary fertilization (CUF: high fertilizer use) and combined fertilization (COF: low fertilizer use) treatments were used. Customary fertilization of early- and late-season rice in 2017 and 2018 included a basal fertilizer application before transplanting, and topdressing about one week after transplanting. The fertilizer application amounts are listed detailed in **Table 2**. The combined fertilization of early- and late-season rice in 2017 and 2018 included a basal fertilizer application before transplanting, two topdressings with medicinal fertilizer application about one week after transplanting, and during the booting and heading stages, as shown in **Table 2**. The total fertilizer amount ($N-P_2O_5-K_2O$) used for customary fertilization of early-season rice was 350.84 and 399.82 kg ha⁻¹ in 2017 and 2018, respectively, and the total fertilizer amount ($N-P_2O_5-K_2O$) used for combined fertilization of early-season rice was 221.67 and 305.34 kg ha⁻¹ in 2017 and 2018, respectively. The total fertilizer ($N-P_2O_5-K_2O$) amount of customary fertilization used for late-season rice was 443.25 and 399.82 kg ha⁻¹ in 2017 and 2018, respectively, and the total fertilizer ($N-P_2O_5-K_2O$) amount of combined fertilization used for the late-season rice was 221.67 and 291.67 kg ha⁻¹ in 2017 and 2018, respectively (**Table 2**). The medicinal fertilizer XSL (N 16%, bensulfuron 0.032%, butachlor 0.608%, China Patent No: ZL201410082830.3) was developed by Hunan Shenlong High Tech Co., Ltd, Changsha city, Hunan province, China, for use as a topdressing fertilizer to control the growth of weeds at the rice tilling stage. The medicinal fertilizer SAK (N 20%, furosemide 0.1%) was developed by Hunan Shenlong High Tech Co., Ltd. Changsha city, Hunan province, China to control insects in the paddy field. The date of sowing and transplanting and the specifications for transplanting, number of transplanted seedlings per hill, and maturity of each variety are provided in **Table 3**. According to the local farmer field management practice, under customary fertilization conditions, the paddy rice was sprayed with pesticides 2–3 times during the entire growth period, but under combined fertilization conditions, the paddy rice was not sprayed with pesticides. Each treatment area was approximately 30 m², and the treatments were replicated three times.

1.2 Sampling and measurements

Biomass accumulation was investigated at different stages. After the maturity stage, 20 hills of each variety were sampled for EPN and plant height (PH). Six hills of each variety were investigated for GNP, seed set rate (SSR), 1000-grain weight (KGW), and harvest index (HI) . The panicles of every hill were hand-threshed, and the filled grains were separated from unfilled grains by winnowing. The GNP was calculated as the total number of grains divided by the EPN. The SSR was $100 \times \text{total filled grains} / \text{number of total grains per hill}$, and the KGW was $1000 \times \text{total filled grains' weight} / \text{number of filled grains per hill}$. The total above ground biomass was calculated as the summation of dry weight of leaves, stems, rachis, and filled, half-filled, and empty spikelet' s. The biomass of six hills for each

variety was measured after plants were heated at 70 °C for 48 h to a constant weight. The HI (filled grains' weight / total above ground biomass) was calculated separately (Miao et al, 2011). The yield was determined from more than 300 hills in each plot using a combine harvester when grains had adjusted to a moisture content of 12%. The HI was calculated as the ratio of the filled grain dry weight to the total aboveground biomass. The NUE, defined as the yield produced per unit of N applied (Chen et al, 2018, Ju et al, 2016), was approximated using N partial factor productivity (PPF_N , kg rice grain per kg N applied) because it integrates fertilizer input, inherent soil N supply capacity, and achieved yield, and as such is the broadest measure of NUE (Cassman et al, 1996, Xie et al, 2020). $PPF_N = \text{Grain yield with N application} / \text{N application rate}$. Standard heterosis (HCK) was calculated according to the following formula:

$$HCK = (F1 - CK) / CK \times 100$$

Where F1 is the performance of yield traits of the hybrid rice, CK is the performance of yield traits of the inbred control variety of early and late-season rice.

1.3 Data Analysis

The data for rice attributes, i.e., biomass accumulation per hill (BPH), PH, EPN, GNP, SSR, KGW, HI, yield, and NUE were subjected to an analysis of variance using the SPSS 17.0 (IBM) software. Means of varieties were compared based on the least significant difference test (LSD) at $P \leq 0.05$ probability levels under different fertilization treatments during different seasons. The figures were prepared using Microsoft Excel.

Results

2.1 BPH and PH are independent of fertilizer regimen and cultivar across seasons

Source capacity is typically expressed as units of biomass production, which is directly related to the photosynthetic capacity of plants (Zhang et al, 2009). The most common approach for increasing productivity in rice is to increase biomass production (Peng et al, 2009, Yuan, 2012). To evaluate differences in biomass production related to low-versus high-fertilizer treatments, we compared the total BPH of different cultivars of early- and late-season rice. It was found that early-season rice accumulated more biomass in its late growth stages, whereas late-season rice accumulated more biomass after full heading (Table 4 and, Fig. 1). Compared with the inbred varieties, the HCK for BPH of early-season hybrid rice was largely negative. The difference in BPH for these hybrids was inconsistent between the two fertilization treatments. Specifically, the HCK for BPH of late-season hybrid rice at the booting and mature stages showed an increase over the inbred cultivars in 2017, but was lower than that of inbred cultivars in 2018 (Table 5 and S2, Fig. 2). Furthermore, the hybrid rice varieties did not exhibit consistent differences in BPH at different growth stages. Similarly, differences in BPH between fertilization treatments were also non-significant in 2017. However, among late-season rice, COF led to lower biomass accumulation than that of CUF during the full heading and full-ripening stages.

Plant height (PH) was relatively lower among early-season rice than late-season rice, averaging 70–80 cm. The PH of early-season rice was 83.06 and 84.89 cm in 2017 and 78.43 and 79.76 cm in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). The average HCK for PH of early-season hybrid rice varieties was 0.05% and 1.65% in 2017, and 3.12% and 2.63% in 2018 under the CUF and COF treatments, respectively, indicating better performance of the hybrid rice. Under the COF treatment, the average PH of early-season hybrid rice varieties was higher than that under the CUF treatment (Table 7 and S4, Fig. 4).

In contrast, the PH varied widely among late-season rice varieties. The PH of inbred rice variety X2 was the highest, reaching 110 cm, whereas that of other varieties averaged 90–100 cm (Table S3). The PH of late-season rice was 101.79 and 100.86 cm in 2017 and 103.49 and 105.80 cm in 2018 under CUF and COF treatments, respectively. Thus, PH was 0.93 cm and 2.31 cm higher under CUF treatments in 2017 and 2018, respectively (Table 6 and S3, Fig. 3). Compared with late-season inbred rice, the HCK for PH of late-season hybrid rice was -3.07% and -1.55% in 2017 and -6.58% and -4.94% in 2018 under CUF and COF treatments, respectively, indicating a decrease in heterosis (Table 7 and S4, Fig. 4). Under the COF treatment, the average PH among late-season hybrid rice varieties was higher on an average than that under the CUF treatment, suggesting that higher fertilizer application did not significantly affect plant height as a function of biomass production.

2.2 Low fertilization increased EPN per hill in early-season hybrids and GNP in late-season hybrids

Tiller number is also an informative and quantitative agronomic trait in rice because it is positively correlated with panicle number per m² (Ao et al, 2010, Wu et al, 1998, Miller et al, 1991). EPN represents the tillering ability of varieties and contributes to other yield related traits. The average EPN of early-season rice varieties was 13.22 and 13.99 in 2017, and 10.50 and 11.21 in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with early-season inbred varieties, the average HCK for EPN of early-season hybrid rice was 13.27% and 14.1% in 2017 and 9.07% and 7.45% in 2018 under CUF and COF treatments, respectively (Table 7 and S4, Fig. 4). Taken together, these data indicate that the early-season hybrids produced higher EPN than that of inbred lines; however, the higher fertilizer application did not affect EPN.

The average EPN of late-season rice varieties was 12.31 and 12.4 in 2017 and 15.32, and 16.34 in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with late-season inbred lines, the average HCK for EPN of late-season hybrid rice varieties was 1.86% and 0.08% in 2017 and 2.62% and -0.29% in 2018 under CUF and COF treatments, respectively (Tables 7 and S4, Fig. 4). These results showed that the EPN of early-season hybrids were higher than that of inbred lines, but lower in late-season hybrids; further, CUF generally led to greater EPN, although not consistently (e.g., COF improved EPN in 2017 early-season rice).

Several field studies have reported that higher grain yields among hybrid rice varieties are associated with a large sink size (spikelets per m²) because of large panicles (GNP) (Huang et al, 2011, Zhang et al, 2009). The average GNP of early rice was 69.87 and 77.48 in 2017 and 82.67 and 82.2 in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with early-season inbred varieties, the average HCK for GNP in the early-season hybrid was -19.89% and -5.28% in 2017 and -7.71% and -6.58% in 2018 under CUF and COF treatments, respectively (Table 7 and S4, Fig. 4). Given the primarily negative trends in GNP for hybrid varieties, these results indicated that the early-season hybrids did not exhibit strong heterosis through GNP and were not affected by lower fertilizer application.

The average GNP of late-season rice was 80.58 and 87.32 in 2017 and 113.18 and 113.34 in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with late-season inbred rice varieties, the average HCK for GNP of the late-season hybrids was 16.83% and 11.68% in 2017 and 2.31% and 6.28% in 2018, under CUF and COF treatments, respectively, indicating positive heterosis (Table 7 and S4, Fig. 4). Thus, the HCK for GNP in late-season hybrid varieties was higher under CUF applications than under COF, suggesting that this trait was positively affected by higher fertilizer application in the late-season hybrids.

2.3 Fertilizer regimen significantly affected neither SSR nor KGW for hybrid lines

Seed set rate (SSR) is also one of the main quantitative traits for assessing yield. We examined differences in SSR to determine the effects of reduced fertilizer application on yield. It was found that the SSR of early-season rice was 73.5% and 77.57% in 2017 and 91.64% and 91.02% in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). The SSR of early-season rice varieties was higher than 90% in 2018, with negligible differences between varieties but larger differences between years. Compared with early-season inbred varieties, the HCK for SSR of early-season hybrid rice varieties was -9.44% and -5.23% in 2017 and -1.07% and -0.2% in 2018 under conditions of CUF and COF treatments, respectively (Table 7 and S4, Fig. 4). Although all hybrids showed negative heterosis, the early-season hybrid rice varieties had a higher SSR under the COF than under the CUF treatment.

In the late-season hybrids, the average SSR was 72.01% and 77.19% in 2017 and 87.41% and 83.89% in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with late-season inbred varieties, the HCK for SSR in late-season hybrid rice varieties was -6.9% and 0.51% in 2017 and -6.07% and -7.73% in 2018 under CUF and COF treatments, respectively (Table 7 and S4, Fig. 4). These results showed that SSR was not the main yield heterosis trait in either early-season or late-season hybrid rice, and notably, heterosis of SSR is unaffected by fertilizer treatments.

Several previous studies have shown that increasing the spikelet size (grain weight) is a feasible approach for increasing rice yield (Huang et al, 2011, Zhang et al, 2009). To measure this trait, we examined 1000-grain weight (KGW) and compared the trait between varieties and across fertilizer treatments to determine if lower fertilization negatively impacted yield. The KGW of early-season rice was 23.36 and 23.63 g in 2017 and 25.74 and 25.68 g in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). Compared with early-season inbred varieties, the average KGW of early-season hybrid rice varieties was -1.02% and 2.02% higher in 2017 and 6.62% and 4.41% higher in 2018 under CUF and COF treatments, respectively (Table 7 and S4, Fig. 4). Hence, the early-season hybrid rice varieties exhibited an advantage in terms of KGW as compared to the early-season inbred rice varieties.

The KGW of late-season rice was 29.43 and 30.06 g in 2017 and 28.55 and 26.87 g in 2018 under CUF and COF treatments, respectively (Table 6 and S3, Fig. 3). However, in comparison with the late-season inbred varieties, the HCK for KGW of late-season

hybrid rice varieties was -3.41% and -6.96% in 2017 and -5.0% and -4.92% in 2018 under CUF and COF treatments, respectively, thus exhibiting poor heterosis for KGW, regardless of fertilizer treatment (**Table 7** and **S4, Fig. 4**). These data showed that, in terms of KGW, differences in fertilizer treatment did not lead to significant improvement of yield of hybrid rice over that of inbred rice.

2.4 Decreasing fertilizer inputs did not affect HI, grain yield, or NUE for either early- or late-season hybrids

The degree of source-to-sink translocation is often assessed by measuring the harvest index (Sinclair, 1998), which is determined by the rate of transient photosynthesis during grain formation and the remobilization of stored reserves into the growing grain (Blum, 1993). It is generally accepted that the HI (harvest index) of modern high-yielding rice cultivars is approximately 0.5 (Zhong et al, 2006). Here, we found that the HI of early-season rice was 0.32–0.63, with HI values being 0.36 and 0.38 for CUF and COF treatments, respectively, in 2017, and 0.58 and 0.57 for CUF and COF treatments, respectively, in 2018 (**Table 6** and **S3, Fig. 3**). Thus, the difference in HI between fertilization conditions was small, and it was greater among varieties and years also. Specifically, compared with the early-season inbred varieties, the average HCK for HI in early-season hybrids was -8.96% and 3.38% in 2017 and 5.32% and 4.99% in 2018 under CUF and COF treatments, respectively (**Table 7** and **S4, Fig. 4**).

In contrast, the HI for late-season rice was 0.43–0.57, with HI values being 0.47 and 0.49 for CUF and COF treatments, respectively, in 2017, and 0.52 and 0.50 for CUF and COF treatments, respectively, in 2018 (**Table 6** and **S3, Fig. 3**). Similarly, the differences were small between the fertilization conditions, but significant between rice varieties. In the comparison of heterosis in late-season inbred varieties, the HCK for HI of late-season hybrid rice varieties was higher than that of inbred varieties by 4.55% and 7.21% for CUF and COF treatments, respectively, in 2017 and by 5.25% and 7.42% for the respective treatments in 2018. Thus, there was positive heterosis for this trait (**Table 7** and **S4, Fig. 4**). In the case of HI, late-hybrid rice performed better under the low fertilizer COF treatment than under the CUF treatment.

The final metric for performance was yield, and we found that early hybrid varieties yielded between 5.61–7.69 t ha⁻¹ (tons per hectare). The average yield of early-season rice was 6.59 and 6.19 t ha⁻¹ in 2017 and 6.32 and 7.11 t ha⁻¹ in 2018 under CUF and COF treatments, respectively (**Table 6** and **3, Fig. 3**). The average HCK for yield among early-season hybrids was higher by 2.57% and 16.11% than that of inbred lines in 2017 and by 15.25% and 14.44% than that of inbred lines in 2018 under CUF and COF conditions, respectively (**Table 7** and **S4, Fig. 4**). This indicated a better performance by early-season hybrids than that of the inbred varieties, under COF conditions.

The yield for late-season rice ranged from 7.05 to 9.9 t ha⁻¹. The yield of late-season rice was 8.52 and 8.37 t ha⁻¹ in 2017 and 8.90 and 8.61 t ha⁻¹ in 2018 under CUF and COF conditions, respectively (**Table 6** and **S3, Fig. 3**). The average HCK for yield of late-season hybrid varieties was 3.44% and 5.85% higher than that of inbred lines in 2017 and 9.24% and 15.45% higher than that of inbred lines in 2018 under CUF and COF treatments, respectively (**Table 7** and **S4, Fig. 4**). Both the early- and late-season hybrid varieties had higher yields than that of the inbred lines, and yields of hybrids were more stable and consistently higher under the COF treatment than under the CUF treatment.

PFP_N (kg rice grain per kg N applied) is used as the broadest measure of NUE. The average PFP_N of early-season rice was 37.82 and 42.24 kg kg⁻¹ in 2017 and 26.06 and 38.34 kg kg⁻¹ in 2018 under CUF and COF conditions, respectively (**Table 5** and **S3, Fig. 3**). The average HCK for PFP_N of early-season hybrids was 2.36% and 4.12% higher than that of the inbred lines in 2017 and 15.19 % and 9.62% higher than that of inbred lines in 2018 under CUF and COF conditions, respectively (**Table 6** and **S4, Fig. 4**).

The average PFP_N of late-season rice was 51.85 and 60.49 kg kg⁻¹ in 2017 and 36.73 and 49.14 kg kg⁻¹ in 2018 under CUF and COF conditions, respectively (**Table 5** and **S3, Fig. 3**). The average HCK for PFP_N of early-season hybrids was 3.44% and 5.79% higher than that of the inbred lines in 2017 and 9.23% and 15.37% higher than that of inbred lines in 2018 under CUF and COF conditions, respectively (**Table 6** and **S4, Fig. 4**). Both the early- and late-season hybrid varieties had higher PFP_N than that of the inbred lines, and the PFP_N values were higher under the CUF treatment than under the COF treatment, except for early-season 2018. Most of the PFP_N of early and late-season hybrid varieties corresponded to their yields under the CUF treatment rather than the COF treatment.

Discussion

Source capacity is usually expressed as the amount of biomass production, which is achieved through the plant's photosynthetic capacities. Sink capacity is a function of the number of spikelets per unit land area and their potential size. Source-to-sink

translocation degree is often assessed by measuring harvest index, which is determined by the transient photosynthesis during grain formation and the remobilization of stored reserves into the growing grain (Zhang et al, 2009, Mae et al, 2006, Sinclair, 1998, Blum, 1993). Rice yield is determined by the sink-source capacity, i.e., the degree of source-to-sink translocation, it is a function of total biomass and harvest index (HI). (Khush, 2013). Hybrid rice yielded approximately 7–19 % more grain than that of inbred cultivars. The higher grain yields observed for hybrid rice cultivars were attributed to high grain weight and biomass accumulation, with longer crop duration to make full use of the heat-light resources in the growing season (Jiang et al, 2016, Bueno and Lafarge, 2009, Yang et al, 2007, Katsura et al, 2007). The attainable early-season rice yield under double rice-cropping systems is characterized by a relatively lower grain yield of 5–6 t ha⁻¹ and superiority in sink size (sink capacity, such as spikelets per m²) and biomass production (Wu et al, 2013, Zhong et al, 2006). A recent investigation by Chen et al. 2019 showed that the highest yield of early-season hybrid rice was 7.60 t ha⁻¹ and 7.49 t ha⁻¹ in 2017 and 2018, respectively, with the yield advantage of early-season hybrids typically being less than 5.00% over that of inbred varieties; further, hybrids were shown to produce more panicles per plant but less grains per panicle (Chen et al, 2019). In this study, it was shown that the average yield of early-season rice was 6.39 t ha⁻¹ and 6.71 t ha⁻¹ in 2017 and 2018, respectively (Table S3). Compared with inbred lines, the average yield of early-season hybrid rice increased by 9.34% and 12.46% in 2017 and 2018, respectively (Table S4). Early-season rice hybrids had advantages in terms of EPN, KGW, HI, yield, and NUE (Fig. 5a), with the EPN advantage being hugely evident for them. The results of this study were consistent with those reported by Chen et al. (2019), but, in our study, the yield advantage of early-season hybrid rice was greater and not limited as compared to inbred rice.

A previous study showed that GNP and EPN traits were the main reasons for yield superiority in the two-line super high-yielding hybrid rice varieties with long growth duration. The GNP and EPN had super-parental advantages (Li et al, 2016). The highest yield of late-season hybrid rice was 9.64 t ha⁻¹, which produced a 6–26% higher grain yield than that of the other cultivars because the higher grain yield was driven by improvements in sink-source capacity (biomass production, panicles and spikelets per m⁻², and grain weight) (Huang et al, 2017b); In this study, it was shown that the average yield of late-season rice was 8.44 t ha⁻¹ and 8.75 t ha⁻¹ in 2017 and 2018, respectively (Table S3). Compared with the inbred lines, the average yield of late-season hybrid rice increased by 4.65% and 12.35% in 2017 and 2018, respectively (Table S4). The late-season hybrid rice had obvious advantages in GNP, HI, yield, and NUE (Fig. 5b and d). The GNP was an obvious advantage for late-season hybrid rice and different from early-season hybrid rice. This result has the similarity with Li et al. (2016).

Nitrogen (N) is the most important nutrient element in irrigated rice production, and current high yields of irrigated rice are associated with large applications of fertilizer (Cassman et al, 1998). To fulfill the yield potential of the super hybrid rice, N input of more than 350 kg N ha⁻¹ was needed (Wang and Peng, 2017). The yield of hybrid rice increased by 59–71% when the N application rate increased from 150 to 210 kg ha⁻¹. The results of grain yield, NUE, and apparent N balance (ANB) indicated that the 180 kg ha⁻¹ rate of N application was the most effective (Yousaf et al, 2016). The average yield of hybrid cultivars LYPJ and YLY1 was 22% and 16% higher than that of inbred cultivars HHZ and YXYZ, the higher grain yield with N fertilizer in hybrid rice was driven more by a higher yield without N fertilizer than by increases in grain yield with N fertilizer under moderate to high soil fertility conditions (Huang et al, 2017a). The grain yield of super hybrid rice was higher than that of inbred rice by 3.33–7.41% at N0 (0 kg N ha⁻¹) and 5.94–19.87% at N90 (90 kg N ha⁻¹) (Huang et al, 2018). Another study showed that N2 (125–176 kg N ha⁻¹) had higher agronomic NUE, whereas the difference in grain yield between N1 (225 kg N ha⁻¹) and N2 (125–176 kg N ha⁻¹) was relatively small (Jiang et al, 2016). In this study the total N fertilizer application of early-season rice was 174.17 and 138.34 kg ha⁻¹ in 2017 and 242.32 and 185.34 kg ha⁻¹ in 2018 under conditions of CUF and COF respectively; the average yield of early-season rice was 6.59 and 6.19 t ha⁻¹ in 2017 and 6.32 and 7.11 t ha⁻¹ in 2018 under conditions of CUF and COF, respectively. Compared with the inbred varieties, the HCK for yield of early-season hybrid rice was 2.57% and 16.11% higher than that of inbred varieties in 2017 and 15.25% and 14.44% higher than that of inbred varieties in 2018 under conditions of CUF and COF, respectively. The total N fertilizer application of late-season rice was 164.25 and 138.34 kg ha⁻¹ in 2017 and 242.32 and 175.1 kg ha⁻¹ in 2018 under conditions of CUF and COF, respectively. Compared with the inbred varieties, the HCK of late-season hybrid rice was 3.44% and 5.85% in 2017 and 9.24% and 15.45% in 2018 under conditions of CUF and COF, respectively. The yield of late-season rice was 8.52 and 8.37 t ha⁻¹ in 2017 and 8.90 and 8.61 t ha⁻¹ in 2018 under conditions of CUF and COF, respectively (Table S3 and S4, Fig. 5c and 5d). It was shown that the yield advantage of hybrid rice under COF was higher than that under CUF.

Farmers in China usually over-apply synthetic N fertilizer to maximize grain yield, resulting in a steep decline in NUE (Miao et al, 2011, Ju et al, 2009). A PFP_N of 41.1 kg kg⁻¹ of irrigated rice was reported previously on a national scale in China (Xu L et al, 2018). PFP_N values of 50 kg kg⁻¹ and above are generally considered to be achievable with good management (Xie et al, 2020, Dobermann and

Fairhurst, 2000). In this study, the PFP_N s of early-season rice were 37.82 and 42.24 kg kg⁻¹ in 2017 and 26.06 and 38.34 kg kg⁻¹ in 2018 under CUF and COF treatments, respectively, whereas the PFP_N s of late-season rice were 51.85 and 60.49 kg kg⁻¹ in 2017 and 36.73 and 49.14 kg kg⁻¹ in 2018 under CUF and COF treatments, respectively. NUE under COF treatment was much higher than that under CUF treatment. This result provided an important clue for the molecular mechanism of the interaction between yield advantage and NUE in hybrid rice, which could be of use in the future. Previous studies have suggested that a small farm size and smallholder management are key causes of low agricultural productivity worldwide (Ju et al, 2016). In China, the rice planting area per household was an average of 0.33 ha, and 60% of farmers had <0.3 ha of planting area (Xie et al, 2020). Most farmers lacked the knowledge of required application of N-fertilizer to obtain optimal amounts of grain production. Consequently, they supposed that applying more N, regardless of how much a crop needed, was an “insurance” strategy against low yields (Jiao et al, 2018, Zhang and Yang, 2016, Vitousek et al, 2009). The combined fertilization can reduce N fertilizer and total fertilizer application, still achieve high yield, and further improve NUE when used on hybrid rice, while being convenient for elderly farmers to use against weeds and insect pests.

Conclusion

Rice grain yield is determined by four factors: EPN, GNP, SSR, and KGW (Gravois and Helms, 1992); it is also greatly affected by climate and cultivation conditions. The EPN was the main advantage of early-season hybrid rice with a short-growth period, whereas the GNP was the main advantage of late-season hybrid rice with a long-growth period. The main yield characteristic advantage of hybrid rice was stronger under combined (low) fertilization than under customary (high) fertilization. In summary, high yield can be achieved by selecting excellent hybrid rice varieties and using combined fertilization (low fertilizer). Additionally, combined fertilizer can reduce the amount of fertilizer used, pesticide spraying times, and labor costs as well as production cost and more economic returns to rice growers

List Of Abbreviations

HCK: standard heterosis

CUF: customary fertilization

COF: combined fertilization

EPN: effective panicle number

GNP: grain number per panicle

SSR: seed set rate

KGW: the 1000-grain weight

HI: harvest index

PFP_N : Grain yield with N application / N application rate.

Declarations

Ethics approval and consent to participate

This study complied with the ethical standards of China, where this research was carried out.

Consent for publication

Not applicable.

Availability of data and material

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interest.

Funding

This work was the Key Research and Development Program of China (Grant number 2017YFD0301504)

Authors' contributions

ZY, LH designed the research. ZY, QM performed the experiments. ZY analyzed the data. ZY wrote the paper. All authors read and approved the final manuscript.

Acknowledgements

We thank Mr. Zhibin Luo and Mrs.Zhulian Xie for the field work and management.

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Tables

Table 1 Rice varieties used for yield comparison tests

Variety name	Type	Male sterile line	Restorer line	Approval status ^a	Main traits
ZZ39	Early-season inbred rice			National approved 2012015	High yield
XZX45	Early-season inbred rice			Hunan approved 2007002	High yield
ZLY819	Early-season hybrid rice	Zhu 1S	Hua819	Hunan approved 2007002	High yield
LLY268	Early-season hybrid rice	Xiangling 628S	Hua268	National approved 2008008	High yield
HHZ	Late-season inbred rice			Hunan approved 2007002	High yield
X2	Late-season inbred rice			Hunan approved 2007002	High quality
TY390	Late-season hybrid rice	TaifengA	Guanghui390	Hunan approved 2007002	High quality
CLY7	Late-season hybrid rice	C815S	R777	Hunan approved 2007002	High yield

^aApproval for release by year and by the Crops Variety Approval Committee at or above the provincial level in China.
(<http://www.ricedata.cn/>)

N.A., not available

Table 2 Different fertilization treatments of early-season and late-season rice

Year-Season-Fertilization	BF:Amount(Kg/ha)	TF (TS): Amount(Kg/ha)	TF(BHS): Amount(Kg/ha)	Total N (kg/ha)	Total P ₂ O ₅ (kg/ha)	Total K ₂ O (kg/ha)	Total fertilization (kg/ha)
2017-ESR-CUF	CF(20%-8%-12%) : 583.33	UR (N46%)+PF(K ₂ O60%) 125+100		174.17	46.67	130	350.84
2017-ESR-COF	CF(22-8%-12%) + RSC :416.67 and 450	COF1(16-0.032-0.608):166.67	COF2(20%-0.1%):100	138.34	33.33	50	221.67
2018-ESR-CUF	CF(18%-4%-9%): 750	UR (46%) + PF(K ₂ O60%):233.3+100		242.32	30	127.5	399.82
2018-ESR-COF	CF(22-8%-12%) +RSC:600 +450	CO1(16-0.032-0.608):166.67	COF2(20%-0.1%):100	185.34	48	72	305.34
2017-LSR-CUF	CF(15%-15%-15%) 750	UR (46%)+PF(60%):112.5+90		164.25	112.5	166.5	443.25
2017-LSR-COF	CF(22-8%-12%) + RSC:416.67+450	CO1(16-0.032-0.608):166.67	COF2(20%-0.1%):100	138.34	33.33	50	221.67
2018-LSR-CUF	CF(18%-4%-9%): 750	UR (46%)+PF(60%):233.3+100		242.32	30	127.5	399.82
2018-LSR-COF	CF(22-8%-12%) + RSC:583.63+450	CO1(16-0.032-0.608):166.67	COF2(20%-0.1%):100	175.1	46.67	70	291.67

ESR: early-season rice, LSR: later-season rice,CUF: customary fertilization, COF: combined fertilization, BF: base fertilizer, TF: topdressing fertilizer, TS: tilling stage, BHS:booting and heading stage, CF: compound fertilizer (N:P₂O₅:K₂O), COF1: combined fertilizer 1 (N 16%, bensulfuron 0.032%, butachlor 0.608%), COF2: combined fertilizer 2 (N 20%, furosemide 0.1%)

Table 3 Transplanting specifications for different rice varieties

Variety name	Transplanting specifications	Plant number per hill	Sowing date	Transplanting date	Full-ripe stage date	Growth duration (days)
ZZ39	16.5cm×19.8cm	3-5	2017/3/25	2017/4/23	2017/7/16	113
ZZ39	16.5cm×19.8cm	3-5	2018/3/25	2018/4/19	2018/7/17	114
XZX45	16.5cm×19.8cm	3-5	2017/3/25	2017/4/23	2017/7/16	113
XZX45	16.5cm×19.8cm	3-5	2018/3/25	2018/4/19	2018/7/17	114
ZLY819	16.5cm×19.8cm	3-5	2017/3/25	2017/4/23	2017/7/16	113
ZLY819	16.5cm×19.8cm	3-5	2018/3/25	2018/4/19	2018/7/17	114
LLY268	16.5cm×19.8cm	3-5	2017/3/25	2017/4/23	2017/7/16	113
LLY268	16.5cm×19.8cm	3-5	2018/3/25	2018/4/19	2018/7/17	114
HHZ	19.8cm×19.8cm	3-5	2017/6/18	2017/7/28	2017/11/6	141
HHZ	19.8cm×19.8cm	3-5	2018/6/20	2018/7/19	2018/11/1	134
X2	19.8cm×19.8cm	3-5	2017/6/18	2017/7/28	2017/11/10	145
X2	19.8cm×19.8cm	3-5	2018/6/20	2018/7/19	2018/11/5	138
TY390	19.8cm×19.8cm	3-5	2017/6/18	2017/7/28	2017/11/6	141
TY390	19.8cm×19.8cm	3-5	2018/6/20	2018/7/19	2018/11/1	134
CLY7	19.8cm×19.8cm	3-5	2017/6/18	2017/7/28	2017/11/1	136
CLY7	19.8cm×19.8cm`	3-5	2018/6/20	2018/7/19	2018/11/3	136

Table 4 The average biomass accumulation between different fertilization conditions

Year-season-fertilization	Booting stage2017/6/8	Yellow maturity (2017/7/11	Full-ripe stage2017/7/15
	Biomass per hill (g)	Biomass per hill (g)	Biomass per hill (g)
	(Mean±SE)	(Mean±SE)	(Mean±SE)
2017-ESR-CUF	18.34±1.72	34.83±1.79	49.52±1.76
2017-ESR-COF	19.42±1.51	33.52±1.28	49.96±1.45
	Booting stage2018/6/7	Yellow maturity2018/6/27	Full-ripe stage2018/7/12
	Biomass per hill (g)	Biomass per hill (g)	Biomass per hill (g)
	(Mean±SE)	(Mean±SE)	(Mean±SE)
2018-ESR-CUF	22.12±1.06	30.01±0.38a	41.46±1.36
2018-ESR-COF	21.64±0.74	35.18±0.85b	41.41±1.64
	Booting stage2017/8/30	Yellow maturity (2017/10/10)	Full-ripe stage2017/10/30
	Biomass per hill (g)	Biomass per hill (g)	Biomass per hill (g)
	(Mean±SE)	(Mean±SE)	(Mean±SE)
2017-LSR-CUF	25.7±1.08	53.58±1.78	50.28±0.45
2017-LSR-COF	23.6±0.52	54.72±1.06	50.35±2.37
	Booting stage2018/8/31	Full Heading stage2018/9/18	Full-ripe stage2018/10/31
	Biomass per hill (g)	Biomass per hill (g)	Biomass per hill (g)
	(Mean±SE)	(Mean±SE)	(Mean±SE)
2018-LSR-CUF	51.56±2.87	80.09±2.58	44.75±3.83
2018-LSR-COF	53.58±2.01	76.7±2.87	43.26±3.78
	(Mean±SE)	(Mean±SE)	(Mean±SE)

ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization, Within a column, the same lowercase letters for biomass among each variety under different fertilization conditions in each season and year, indicate non-significant differences according to the least significant difference test (LSD, $P \geq 0.05$).

Table 5 Standard heterosis (HCK) for biomass accumulation in early-season and late-season rice under different fertilization conditions

Year-season-fertilization	Booting stage2017/6/8	Yellow mature stage2017/7/11	Full-ripe stage (2017/7/15
	HCK (biomass per hill %)	HCK (biomass per hill %)	HCK (biomass per hill %)
2017-ESR-CUF	17.79±15.56	-10.65±4.93	-11.1±1.39
2017-ESR-COF	29.85±4.07	-2.47±5.24	8.83±2.30
	Booting stage2018/6/7	Yellow mature stage2018/6/27	Full-ripe stage (2018/7/12
	HCK (biomass per hill %)	HCK (biomass per hill %)	HCK (biomass per hill %)
2018-ESR-CUF	-4.31±5.94	-4.09±0.43	7.02±3.92b
2018-ESR-COF	-4.47±4.33	-0.77±3.4	-10.17±3.05a
	Booting stage2017/8/30	yellow mature stage2017/10/10	Full-ripe stage (2017/10/30
	HCK (biomass per hill %)	HCK (biomass per hill %)	HCK (biomass per hill %)
2017-LSR-CUF	15.54±1.12b	8.87±1.50	1.12±1.21
2017-LSR-COF	3.93±2.85a	0.94±2.87	-13.35±2.45
	Booting stage2018/8/31	Full Heading stage2018/9/18	Full-ripe stage (2018/10/31
	HCK (biomass per hill %)	HCK (biomass per hill %)	HCK (biomass per hill %)
2018-LSR-CUF	-6.79±6.88	-10.23±1.0	-21.42±4.87
2018-LSR-COF	5.4±5.33	-6.67±4.14	-16.05±7.21

ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization,

Within a column, the same lowercase letters for biomass among each variety under different fertilization conditions in each season and year, indicate non-significant differences according to the least significant difference test (LSD, $P \geq 0.05$).

Table 6 Performance of main traits of different varieties

Year-Season-Fertilization	PH(cm)	EPN	GNP	SSR(%)	KGW(g)	HI	Yield	PFP _N (kg/kg)
2017-ESR-CUF	83.06	13.22	69.87	73.50	23.36	0.36	6.59	37.82
2017-ESR-COF	84.89	13.99	77.48	77.57	23.63	0.38	6.19	42.24
2018-ESR-CUF	78.43	10.50	82.67	91.64	25.74	0.58	6.32	26.06
2018-ESR-COF	79.76	11.21	82.24	91.02	25.68	0.57	7.11	38.34
2017-LSR-CUF	101.79	12.31	80.58	72.01	29.43	0.47	8.52	51.85
2017-LSR-COF	100.86	12.40	87.32	77.19	30.06	0.49	8.37	60.49
2018-LSR-COF	103.49	15.32	113.18	87.41	28.55	0.52	8.90	36.73
2018-LSR-CUF	105.80	16.34	113.34	83.89	26.87	0.50	8.61	49.14

ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization,

PH: plant height, EPN: effective panicle number per hill, GNP: grain number per panicle, SSR: seed set rate, KGW:1000-grain weight, HI: harvest index, PFP_N: grain yield with N application.

Table 7 Performance of standard heterosis (HCK)for main traits of early-season and late-season rice under different fertilization conditions

Year-Season-Fertilization	HCK (PH%)	HCK (EPN%)	HCK (GNP%)	HCK (SSR% ¹)	HCK (KGW%)	HCK (HI%)	HCK (Yield%)	HCK (PFP _N %)
2017-ESR-CUF	0.05	13.27	-19.89	-9.44	-1.02	-8.96	2.57	2.36
2017-ESR-COF	1.65	14.10	-5.28	-5.23	2.02	3.38	16.11	4.12
2018-ESR-CUF	3.12	9.07	-7.71	-1.07	6.62	5.32	15.25	15.19
2018-ESR-COF	2.63	7.45	-6.58	-0.20	4.41	4.99	14.44	9.62
2017-LSR-CUF	-3.07	1.86	16.83	-6.07	-3.41	4.55	3.44	3.44
2017-LSR-COF	-1.55	0.08	11.68	-7.73	-6.96	5.25	5.85	5.79
2018-LSR-COF	-6.58	2.62	2.31	0.38	-5	7.21	9.24	9.23
2018-LSR-CUF	-4.94	-0.29	6.28	0.63	-4.92	7.42	15.45	15.37

ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization,

PH: plant height, EPN: effective panicle number per hill, GNP: grain number per panicle, SSR: seed set rate, KGW: 1000-grain weight, HI: harvest index,

PFP_N: grain yield with N application.

Figures

Figure 1 Biomass accumulation of early-season and late-season rice under different fertilization conditions. ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization.

Figure 2

The standard heterosis (HCK) for biomass accumulation of early-season and late-season hybrid rice under different fertilization conditions. BPH: biomass accumulation per hill, ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization.

Figure 3

Performance of traits of different early-season and late-season rice varieties under different fertilization conditions. ESR: early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization.

Figure 4

The standard heterosis (HCK) for main traits of early-season and late-season rice under different fertilization conditions. PH: plant height, EPN: effective panicle number per hill, GNP: grain number per panicle, SSR: seed set rate, KGW: 1000-grain weight, HI: harvest

index, PFPN : N partial factor productivity, ESR:early-season rice, LSR: late-season rice, CUF: customary fertilization, COF: combined fertilization.

Figure 5

Standard heterosis (HCK) for early-season and late-season hybrid rice under different fertilization conditions. PH—Plant height , EPN—effective panicle number , GNP—grain number per panicle (GNP), SSR—seed set rate (SSR), KGW—1000 grain weight (KGW), HI—harvest index (HI), PFPN: N partial factor productivity, ESHR: early-season hybrid rice, LSHR:late-season hybrid rice, CUF: customary fertilization, COF: combined fertilization.

Supplementary Files

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