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Integrating mechanization with agronomy and breeding to ensure food security in China

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ABSTRACT

Productivity of intensive rice cropping systems plays a pivotal role in national food security in China. By 2030, a 20% increase in rice yield will be required to meet the growing demand for food that will result from population growth. The success of China's super hybrid rice was expected to provide an opportunity to cope with the increased demand for rice. However, in China the planting area of super hybrid rice is less than 8% of the national total rice planting area and the planting area of hybrid rice has continued to decline since 1996. The decreased planting area of hybrid rice is related to the shift in rice establishment methods from manual transplanting to direct seeding and mechanical transplanting. These shifts can result in increased seeding rates and reduced morphological advantages of heterosis (e.g. reduced panicle size), both of which can influence cultivar choice by rice farmers, who will tend to favor cheaper inbred cultivars. The shifts in rice establishment methods can also eliminate or reduce the seedling nursey period and subsequently shorten the growth duration and negatively affect the yield. We anticipate that the above problems will be resolved by integrating mechanization (e.g. designing high-precision seed sowing machines) with agronomy (e.g. improving management practices for increasing seed vigor) and breeding (e.g. developing high-yielding cultivars with short growth durations). This strategy also has implications for production of other crops in intensive farming systems in China and for other developing countries with rice-based intensive cropping systems.

1. Challenges to rice production for ensuring food security in China

China has 22% of the world's population but only 7% of the world's arable land (Piao et al., 2010). In order to produce enough food, intensive cropping systems have been extensively developed in China. Considerable progress has been made by developing high-yielding crop cultivars and improving crop management practices. As a result, there has been remarkable growth in both crop production and national food security in China (Fan et al., 2012).

Rice is a staple food for more than 65% of the population in China. Double-season rice systems and single-season rice in rotation with other crops such as wheat and oilseed rape are the major intensive rice-based cropping systems in China. Over the last 60 years, the production of rice has more than tripled in China mainly due to increased grain yield rather than increased planting area (Fig. 1).

However, the population of China continues to grow, and thus domestic production of rice must increase in the next 13 years. It is projected that China needs to produce 41 million t (Mt) more rice by 2030, compared to the 207 Mt produced in 2017 (Fig. 1). Because the area of cropland will decrease with urban expansion (Bren d'Amour et al., 2017), future increases in rice production must come from greater yields. Though the rice planting area will be the same in 2030 as in 2017, an increase in rice yield of 1.36 t ha^{-1}, or 20%, is required in the next 13 years (Fig. 1). This increase is more than double that (0.60 t ha^{-1}) achieved in the last 13 years, presenting a challenge for national food security in China.

2. Constraints in increasing rice production in China

To meet the challenges of rice production in China, it is essential to breed rice cultivars with higher yield potential (Peng et al., 2008). The development of hybrid rice is a primary method for increasing the yield potential of rice (Yuan et al., 1994). Hybrid rice cultivars have a yield advantage of more than 10% over inbred cultivars (Cheng et al., 2007).

In 1998, Prof. Longping Yuan, known as the "father of hybrid rice", proposed a strategy for developing super hybrid rice using heterosis combined with the ideotype approach in order to further increase the yield potential of hybrid rice (Yuan, 2001). Over the past 20 years, significant progress has been made in breeding super hybrid rice

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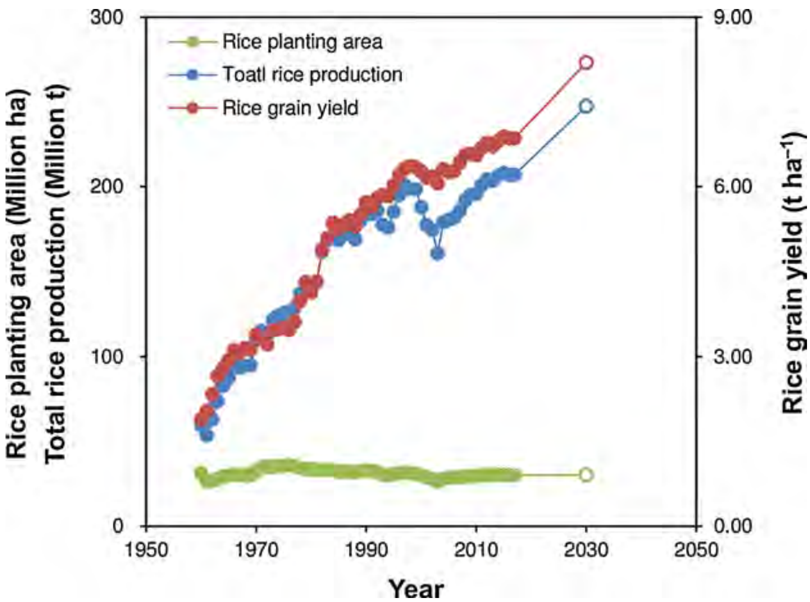

Fig. 1. Rice planting area, total rice production and rice grain yield in China. The data from 1960 to 2017 were collected from the World Rice Statistics Database (IRRI, 2018). The total rice production in 2030 was projected by Cheng et al. (2007). The rice grain yield in 2030 was calculated by keeping planting area the same as in 2017.

(Cheng et al., 2007; Peng et al., 2008; Wu, 2009; Yuan, 2017). Currently, 94 cultivars have been approved as super hybrid rice by the Ministry of Agriculture of China (China Rice Data Center, 2018). Super hybrid rice cultivars have increased rice yield potential by more than 10% compared with ordinary hybrid cultivars (Zhang et al., 2009; Huang et al., 2011a), and this increase is likely to grow with the development of new super hybrid rice cultivars (Huang et al., 2017a).

The success of super hybrid rice was predicted to allow China to deal with the challenge of increased rice demand. However, during the last 20 years, super hybrid rice cultivars were grown on a total area of only about 45 million ha (Mha), which is less than 8% of the total national rice planting area (Fig. 2A). Additionally, the planting area of hybrid rice has continued to decline since 1996 (Fig. 2B), and this decline has had an enormously negative effect on the hybrid rice seed industry. According to data released by the National Agricultural Technology Extension and Service Center of China, the amounts of unsold hybrid rice seeds reached as high as 80–120 million kg per year in the last 5 years, which accounts for 33–46% of the yearly total produced (Fig. 2C).

The declining area of hybrid rice planting in China is closely related to shifts in rice establishment methods induced by changes in socio-economic environments. Manual transplanting is the traditional rice establishment method in China. However, this method requires a large amount of man-power (about 400 man-hours ha^{-1}) and the operation is very laborious, involving working in a stooping posture and moving through a muddy field (Thomas, 2002). In recent years, urban expansion has led to a labor shortage and an increase in wages for agricultural production in China (Peng et al., 2009). As a consequence, direct seeding (manually broadcasting pre-germinated seeds onto saturated soil), a labor-saving technology, was quickly developed for rice production in China in the mid-1990s (Zhang and Zhu, 1996). It is estimated that the total area of direct-seeded rice in China in 2017 was about 4 Mha, corresponding to approximately 13% of the total rice planting area nationwide.

On the other hand, farmland rental has increased in China in recent years, and a new class of farmers who obtain farmland on lease for large-scale farming has emerged (Kung, 2002). The development of large-scale farming has promoted the adoption of mechanical transplanting techniques for rice production in China. A few farmers established rice with mechanical transplanting in the early 2000s, but the percentage of machine-transplanted rice planting area compared to the national total rice planting area reached about 10% in 2008 (Zhu and Chen, 2009), and increased to more than 20% in 2012 with a total of 436,000 rice transplanters (Zhang et al., 2012). Currently, the total number of rice transplanters has increased to over 680,000 units in China. It is estimated that the current percentage of machine-transplanted rice planting area in China exceeds 30%.

The shifts from manual transplanting to direct seeding and mechanical transplanting have led to large increases in rice seeding rates, namely increasing from 45–60 to 60–90 kg ha^{-1} for inbred cultivars and from less than 22.5 to 30–45 kg ha^{-1} for hybrid cultivars. The increased seeding rates have little negative impact on inbred rice production, because the inbred rice seeds can be reproduced by rice farmers themselves at low cost. However, hybrid rice production can be severely negatively affected by increased seeding rates, since the hybrid rice seeds are expensive. The highest seed price of hybrid rice in China exceeds 25 USD kg^{-1} (1 USD = 6.5 CNY) (Chen et al., 2015), which is about 1.2 times and 55% higher than that in the USA and international markets, respectively (Peng, 2016). To cut down on production costs, rice farmers choose inbred cultivars.

The increased seeding rates caused by the shifts in rice establishment methods can also result in changes in rice plant morphology. Under manual transplanting, hybrid rice cultivars generally have large panicle size and/or high tillering capacity due to the expression of heterosis (Peng et al., 1998; Peng et al., 2008; Yan, 1988). However, the morphological advantages of hybrid rice are always reduced or even eliminated under direct-seeded and machine-transplanted conditions. As compared with manual-transplanted hybrid rice, panicle number per hill and panicle size (spikelet number per panicle) are generally reduced in direct-seeded hybrid rice (Fig. 3A and B), while a reduction in panicle size is often observed in machine-transplanted hybrid rice. Thus, the heterosis of hybrid rice seems to be reduced with the shifts from manual transplanting to direct seeding and mechanical transplanting. This also influences the decision of rice farmers to favor cheaper inbred cultivars.

The shifts in rice establishment methods can also shorten the rice growth duration under intensive cropping conditions. For manual transplanting, subsequent crop seeds are always sown in reserved

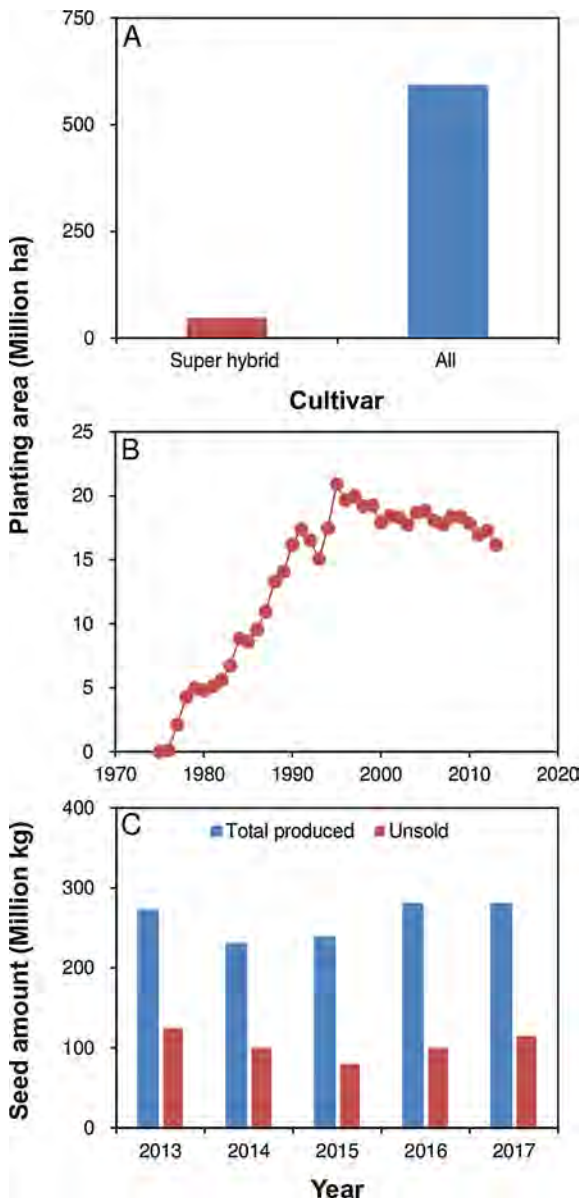

Fig. 2. Planting area of super hybrid rice cultivars and total rice planting area in China from 1998 to 2017 (A); planting area of hybrid rice in China from 1975 to 2013 (B); and amounts of total produced and unsold hybrid seeds in China from 2013 to 2017 (C). In (A), data of planting area of super hybrid rice cultivars and total rice planting area were collected from the China Rice Data Center (2018) and the World Rice Statistics Database (IRRI, 2018), respectively. In (B), data were collected from Hu et al. (2016). In (C), data were collected from meeting minutes released by the National Agricultural Technology Extension and Service Center of China.

seedling fields before harvesting the pre-crop to allow longer crop growth durations and hence higher yields in the intensive cropping systems (Fig. 4). The period from sowing to transplanting – the seedling nursery period or seedling age – is generally 25–35 d for manually-transplanted rice. However, the seedling nursery period is not available for direct-seeded rice and is 10–15 d shorter for the machine-transplanted rice compared to manually-transplanted rice. The shortened seedling age for machine-transplanted rice is related to the small space available for seedling growth caused by the high seeding rate, which is used to avoid the potential yield loss from missing plants due to lack of germination or poor establishment.

The rice growth duration can be further shortened under large-scale farming conditions, because increases in time of farming operations (pre-crop harvesting, land preparation, planting) often occur under such conditions. The length of the further shortened growth duration induced by large-scale farming is equal to that of the increased time of farming operations, and largely depends on the area of farming land. The shortened growth duration has become a critical constraint for increasing rice yields in Chinese intensive cropping systems.

3. Strategies for improving rice production in China

To overcome the above constraints on rice production in China, it is necessary to develop new technologies. One strategy to reduce seed costs in direct-seeded and machine-transplanted hybrid rice production is to reduce seed prices, which can be achieved by reducing the cost of seed production through developing mechanized seed production technologies (Peng, 2016). Another strategy is to reduce seeding rates. Improving seed sowing accuracy is the first step to reducing seeding rates for both direct-seeded and machine-transplanted rice, and designing high-precision seed sowing machines is the most effective way to achieve this step. In recent years, remarkable advances have been made in improving rice seed-sowing machines in China. For example, the South China Agricultural University has invented a precision hill-drop drilling machine for direct-seeded rice production (Luo et al., 2008), and the Hunan Agricultural University has developed a mechanical single-seed sowing system for single-seedling machine-transplanted rice (Fig. 5). It is reported that 30–75% of rice seeds can be saved by adopting these machines, and seedling age can be prolonged by 7–10 days for machine-transplanted rice due to increased room for seedling growth.

However, there are still some constraints affecting the widespread use of these machines for rice production in China. In particular, the seed germination rates are not high enough for most rice cultivars. The national standard of seed germination rate for rice in China is only 80%. This means that the missing plant rate can be as high as 20% or even higher under the single-seed sowing conditions. These problems highlight the fact that technical solutions through agronomy and breeding are required to increase the seed germination rate of rice. Special attention should be paid to developing high-vigor seed production and screening technologies, seed coating and priming techniques, and cultivars with high seed germination rates. In 2013, China established a large-scale project on the research and demonstration of key technologies for high-vigor seed production of major crops, with the China Agricultural University as the lead institution.

The most effective strategy for coping with shortened crop growth duration is to breed high-yielding and short-duration cultivars. Rice yield can be increased by increasing biomass production and/or harvest index, but it is obvious that further improvement in rice yield mainly depends on increasing biomass production (Evans and Fischer, 1999; Peng et al., 1999; Zhang et al., 2009). Biomass production is the product of intercepted solar radiation by the canopy and radiation use efficiency (RUE, i.e. biomass produced per unit of radiation intercepted), and the former is determined by incident solar radiation and intercepted percent (i.e. fraction of incident radiation intercepted by the canopy). It is apparent that the incident solar radiation cannot be increased under shortened growth duration conditions. It is also difficult to increase the intercepted percent, because it depends on canopy architecture, which is close to the optimum in current high-yielding rice cultivars (Peng, 2000; Phyo and Chung, 2013). Increasing RUE may be

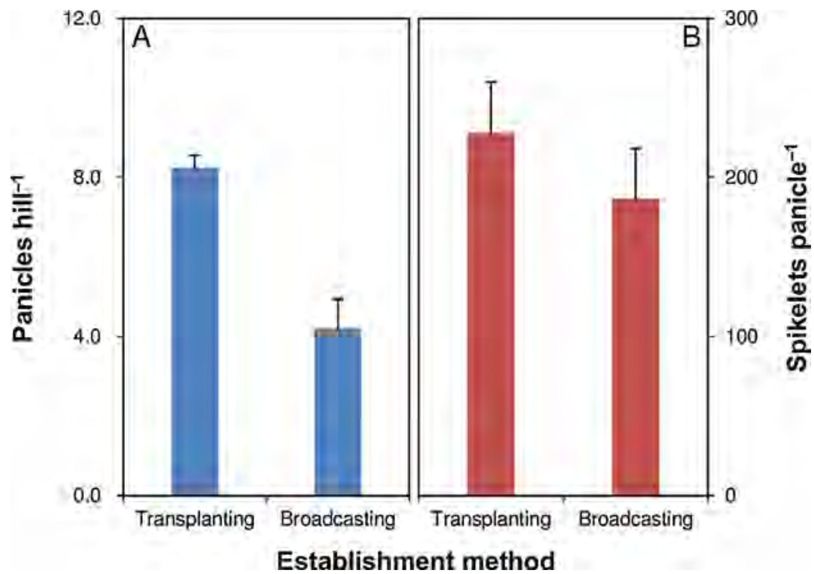

Fig. 3. Panicles hill^{-1} (A) and spikelets panicle^{-1} (B) in the super hybrid rice cultivar Liangyoupeijiu grown under manual transplanting and broadcasting. Data were collected from Huang et al. (2011b). Vertical bars represent standard deviations of the means across six years.

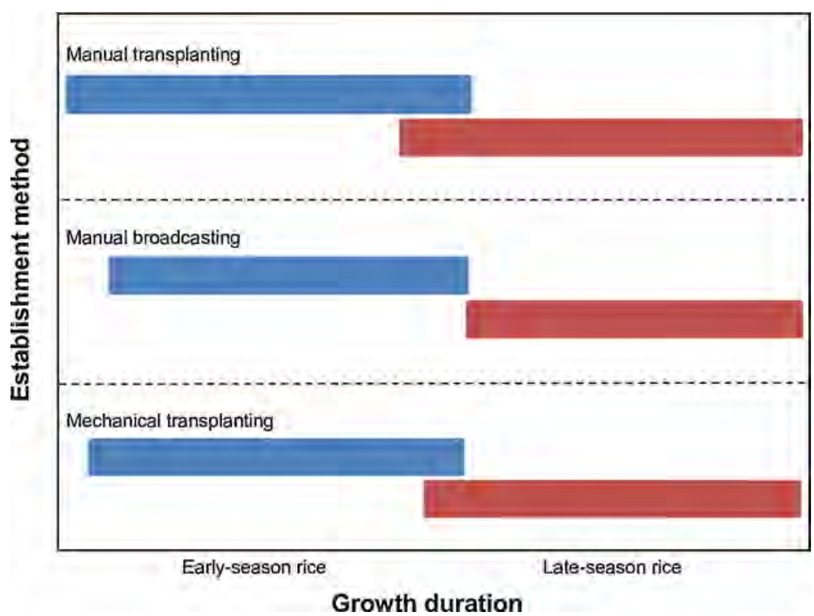

Fig. 4. A schematic diagram of the difference in growth duration of double-season rice among three establishment methods in the middle and lower reaches of the Yangtze River basin in China.

the only way to achieve a substantial increase in rice yield in short-duration cultivars. In this regard, findings from China's super hybrid rice and the international C_4 rice projects that are focused on improving photosynthesis can provide some guidance (Huang et al., 2016; Peng et al., 2008; von Caemmerer et al., 2012).

Another commonly used strategy to cope with shortened growth duration in crop production is increasing planting density. This solution is also beneficial to compensate for the potential of missing plants from ungerminated seeds in single-seedling machine-transplanted rice production and to reduce nitrogen inputs and related environmental problems (Huang et al., 2013; Huang et al., 2018; Zhu et al., 2016). Paradoxically and inevitably, increasing planting density can increase seeding rates. However, planting density is increased under the conditions of improved seed sowing accuracy (e.g. single-seed sowing) that can result in largely reduced seeding rates. The increases in seeding rates caused by increasing plant density can be masked under such conditions.

Taken together, we anticipate that integrating mechanization with agronomy and breeding will help to reverse the declining trend of hybrid rice planting area and provide the greatest possible rice yield, and consequently ensure a stable increase in rice production and national food security in China. This report also has implications for production of other crops in intensive farming systems in China and for other developing countries with rice-based intensive cropping systems.

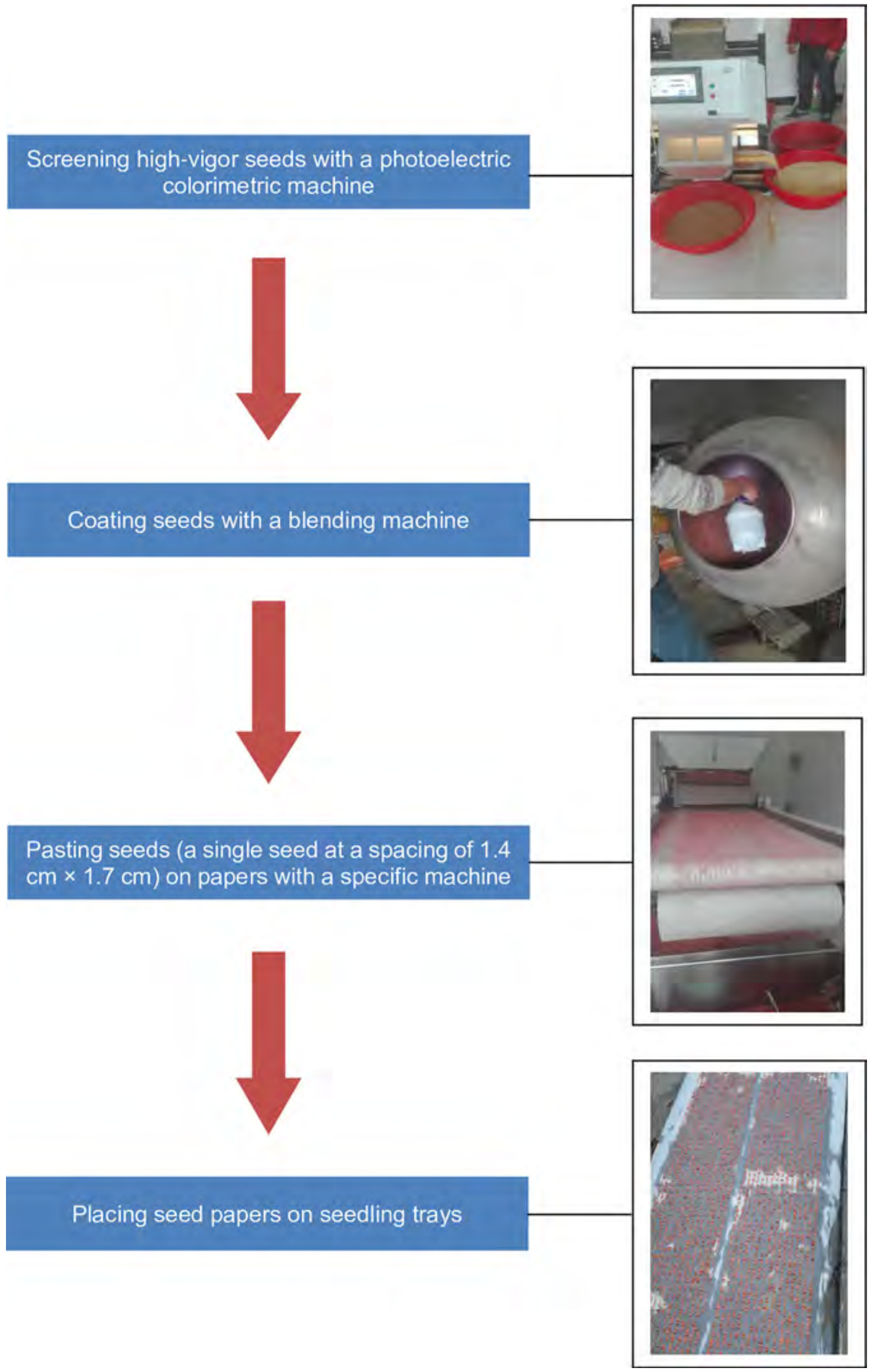

Fig. 5. A single-seed sowing system for machine-transplanted rice (from Huang et al., 2017b).

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