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Hybrid Rice Technology Development

Ensuring China's Food Security

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2020 Vision Initiative

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A total of 20 case studies are included in this project, each one based on a synthesis of the peer-reviewed literature, along with other relevant knowledge, that documents an intervention's impact on hunger and malnutrition and the pathways to food security. All these studies were in turn peer reviewed by both the Millions Fed project and IFPRI's independent Publications Review Committee.

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ABSTRACT

China has used hybrid rice technology to help feed more than 20 percent of the world's population using just 10 percent of the world's total arable land. Hybrid rice allowed for a 14 percent reduction in total rice-growing acreage since 1978, while total rice production has increased 44.1 percent. Yield increases have helped China feed an extra 60 million people every year. Hybrid rice also has contributed to improved food security in China, which has limited the increase in global rice prices to the benefit of poor consumers in other countries.

China's rice breeders began hybrid development in 1964 using a three-line system. By 1976 China started large-scale commercial production of the three-line hybrid rice. In 1995, China successfully commercialized the two-line hybrid rice technology, and by 2002 the total area under two-line hybrid rice occupied 3.3 million ha, or 22 percent of the hybrid rice acreage. In 2000, the "super hybrid rice breeding" Phase I objective of 10.5 t/ha was attained, and the Phase II objective of 12 t/ha was accomplished in 2004. China's hybrid rice seed production yields rose from 450 kg/ha in the late 1970s to 3.75 t/ha in 2008. This has ensured the quantity of commercial seed and lowered costs.

The Chinese government provided critical support to the hybrid rice program through funding and policies. Government policies, standards, and investments in human resources and necessary infrastructure made hybrid rice attractive, profitable, and sustainable.

To ensure the continued success of the hybrid rice program, further advances in biotechnology will be crucial for overcoming the challenges from increasing biotic or abiotic pressure, including the ever-decreasing water supply and more severe drought from global warming.

Keywords: Millions Fed, Food Security, Hybrid Rice, China

ABBREVIATIONS AND ACRONYMS

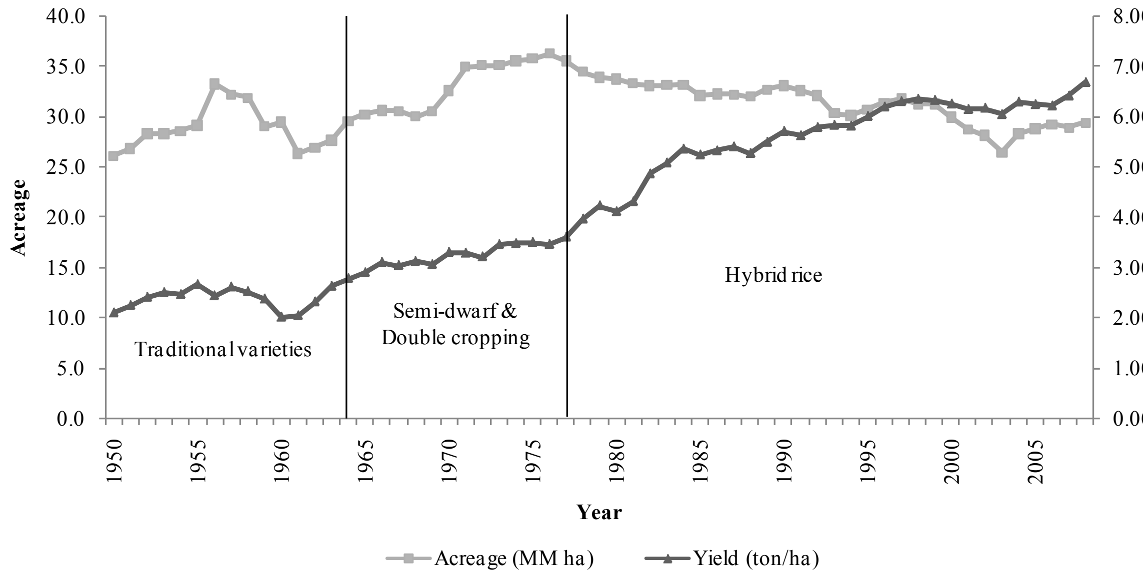
A	male sterile line
B	maintainer line
CAAS	Chinese Academy of Agricultural Sciences
CMS	cytoplasmic male sterility
CNHRRDC	China National Hybrid Rice Research and Development Center, Changsha
CNRRI	China Nation Rice Research Institute, Hangzhou
CST	critical sterility-inducing temperature (for an EGMS line)
DA	dwarf wild abortive male sterile cytoplasm
Di	Dissi-type male sterile cytoplasm
EGMS	environment-conditioned genic male sterile
GA	Gambiaca male sterile cytoplasm
GA3	gibberellic acid (to promote panicle exertion out of rice flag leaf sheath)
GCA	general combining ability
HAAS	Hunan Academy of Agricultural Sciences
HL	Hong Lian-type male sterile cytoplasm
HPGMR	Hubei photoperiod-sensitive genic male-sterile rice
IP	Indonesian Paddy-type male sterile cytoplasm
MAS	marker assisted selection
MOA	Ministry of Agriculture
MOAFF	Ministry of Agriculture, Forestry and Fishery
MOF	Ministry of Finance
MOST	Ministry of Science and Technology
NHRAC	National Hybrid Rice Advisory Committee (in China)
NPT	new plant type
PGMS	photoperiod-sensitive genic male sterile
PTGMS	photoperiod- and thermo-sensitive genic male sterile
PVP	plant variety protection
R	restorer line
TGMS	thermo-sensitive genic male sterile
Three-line	the hybrid rice system requiring A, B and R lines
Two-line	the hybrid rice system only requiring male sterile line and R line
WA	wild abortive male sterile cytoplasm
WC	wide compatibility
WCV	wide compatibility variety

1. INTRODUCTION

Overview

In the 1960s, China started to grow semi-dwarf rice varieties resulting in yields increasing from 2 tonnes per hectare (ha) to 3.5 tonnes/ha in 1975. By 1983, the successful commercialization of three-line hybrid rice in the late 1970s brought another revolution in rice production, and rice yields had risen to more than 5 tonnes/ha. By 1995, with further development of hybrid rice technology, nationwide rice yields averaged above 6 tonnes/ha (Figure 1).

Figure 1. Historical changes of rice yield per unit area (1950–2008)



Source: China MOA and IRRI rice statistics

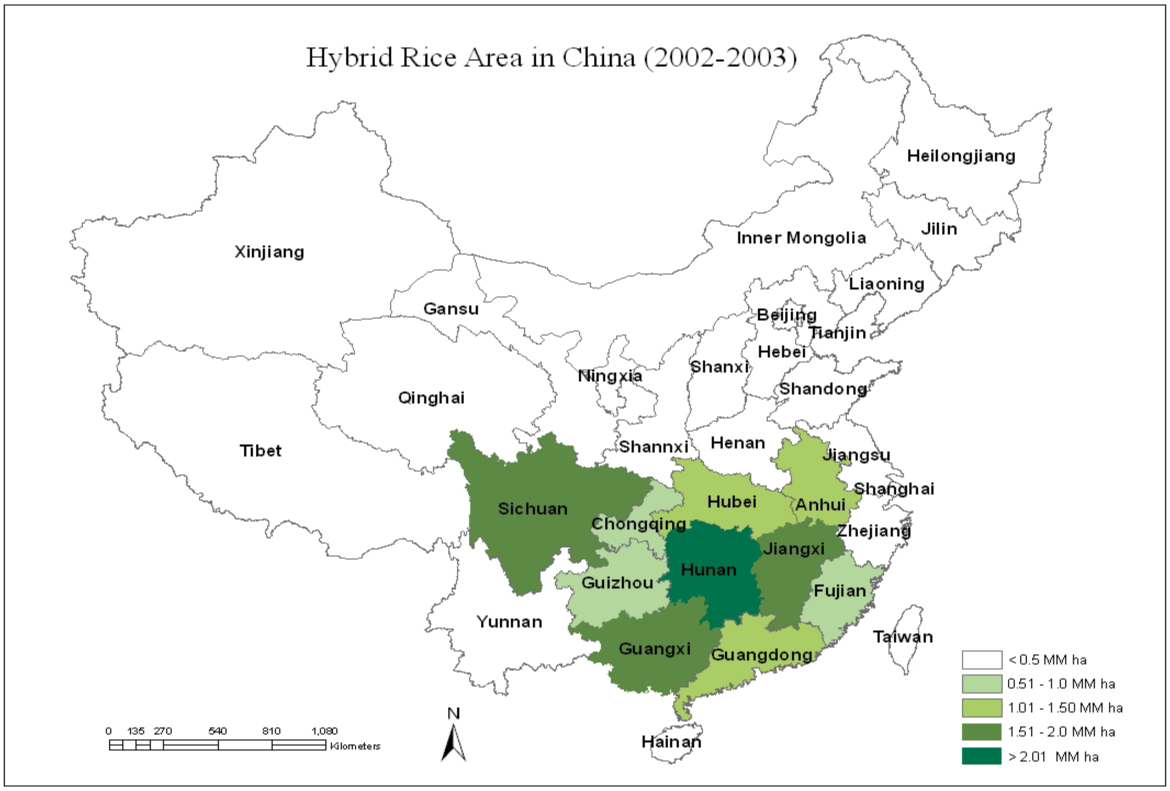
Geographical Distribution and Beneficiaries

In China, agriculture is a basic necessity for the general population and the foundation for economic prosperity, social stability and national independence. China is still facing population pressures and an unfavorable population-land ratio in spite of its family planning policy begun in the 1970s. The arable land per capita has decreased from 0.18 ha in 1950 to 0.1 ha today, while its population has doubled over the past 50 years to its current population of 1.3 billion (Riley 2004). Given this dynamic, agricultural production is one of the country's top priorities.

China is the largest rice producing and consuming country in the world. China's rice accounts for 30 percent of total food crop acreage while producing 40 percent of crop yield. Annual rice acreage has been about 30 million ha which yields 180 million tonnes of rice grains. The surplus and deficit of rice production in China directly affects the food price within China and other countries (Qi et al. 2007).

Hybrid rice has been grown from Liaoning (43º N latitude, cold temperate region) to Hainan (18º N, tropical region), and from Shanghai (125º E longitude) to Yunnan Province (95º E) (Yuan and Virmani 1988). There have been dramatic geographical differences in the adoption rates of hybrid rice (Figure 2). In 2003 and 2004, Hunan was the largest hybrid rice growing province with 3 million ha (75 percent of total rice acreage) followed by Jiangxi with 2 million ha (73 percent of total rice acreage), and Sichuan Province with 1.9 million ha (91 percent of total rice acreage).

Figure 2. Distribution map for 2002-2003 hybrid rice acreage in China.



Source: CNHRRDC (2009)

Dramatic geographical and regional differences in hybrid rice acreage can be attributed to each area's emphasis on agricultural research, adaptive research investments, and the share of rice in total agricultural output (Lin 1990). Regions with more resources dedicated to rice research also have developed more rice hybrids along with increased rice acreage (Lin 1992).

Through hybrid rice technology, Chinese rice farmers obtain higher yields and incomes in commercial and hybrid seed production, seed production businesses profit from hybrid rice's popularity and increased yields, and consumers can buy rice at affordable prices. Researchers found a channel to contribute to society and maximize their value in their agricultural professional careers. Certainly, China saved foreign exchange by importing rice via very small international rice trade market.

Impact of Hybrid Rice on China's Food Security

In 2008, hybrid rice occupied about 63.2 percent of the total rice production area, or 18.6 out of 29.4 million ha. The yield advantage of hybrid rice over inbred rice ranged from 17.0 percent to 53.2 percent from 1976 to 2008 in China, which equates to a 30.8 percent higher average yield (unpublished data from MOA 2009). Hybrid rice has helped China to save rice land for agricultural diversification while reducing rural poverty and feeding an increasing number of people.

To summarize, hybrid rice technology in China has contributed significantly to hunger eradication, poverty alleviation, food security, and economic development in the country (Box 1).

Box 1. Economic impact of hybrid rice in China

- Current hybrid rice acreage is 18.6 million ha, 63 percent of the total rice area (2008)
- Hybrid rice yields an average of 7.2 tons/ha compared with 5.9 tons/ha for conventional rice (2008)
- Average yield of hybrid rice is 30.8 percent higher than inbred rice (1976-2008)
- Accumulated planting acreage is 401 million ha under hybrid rice (1976-2008)
- Accumulated yield increase is 608 million tons due to hybrid rice technology (1976-2008)
- The yield increase from hybrid rice has helped China feed an extra 60 million people every year
- Hybrid rice technology has helped China save 5 million ha of rice land from 1978 to 2008, while increasing total rice production by 44.1 percent
- Hybrid rice technology has created more than 0.1 million direct job positions and 10 million indirect job positions

Experience and Lessons Learned

The success of hybrid rice technology depends on adequate numbers of scientists, together with the infrastructure and government support for hybrid rice research and development. Multidisciplinary research teams are needed to support and advance this technology. Hybrid rice seed production should also be increased to reduce production costs and make this technology economically feasible.

In the past 40 years of technological development, other countries have replicated China's successful experiences vis-à-vis institutional and policy functions, and technological generation and uptake, as detailed in Section 5 of this paper.

2. INNOVATIVE DEVELOPMENT OF HYBRID RICE TECHNOLOGY IN CHINA

China's hybrid rice seed production can be classified into four stages: (1) early low-yielding seed production stage (1973–1980): the average hybrid seed yield only reached 450 kg/ha; (2) exploration stage (1981–1985): seed yield increased significantly to 1.5 t/ha and the price of hybrid seed dropped 30 to 40 percent (Xu and Li 1988); (3) improvement stage (1986–1990): the hybrid seed yield increased up to 2.25t/ha; and (4) high-yielding stage (1991–2009): yield of large-scale hybrid seed production reached 3.75 t/ha and even up to 7.4 t/ha for a small plot (see Box 2 for a chronology of hybrid rice development in China). In China's first 30 years of hybrid rice development, the field area ratio of A line multiplication, F1 seed production, and F1 commercial production had increased from 1:30:1,000 in the late 1970s to 1:50:6,000 in the mid-1990s (Yuan 1998a).

Box 2. History of hybrid rice technological development in China

1964 -	Research on three-line hybrid rice initiated
1970 -	Wild abortive (WA) rice identified on Hainan Island in China
1973 -	PTGMS material identified
1974 -	First sets of three lines (A, B and R lines) developed for three-line system hybrid rice
1976 -	Hybrid rice commercialization started
1977 -	Systematic hybrid rice seed production technique developed
1983 -	Hybrid rice seed yield more than 1.2 ton/ha
1987 -	Hybrid rice seed yield more than 2 ton/ha
	Hybrid rice acreage more than 10 million ha
	National Two-line System Hybrid Rice Program established
1990 -	Hybrid rice acreage more than 15 million ha
1995 -	Two-line hybrid rice system developed
1996 -	"Super Rice Breeding" national program initiated
1998 -	Hybrid rice seed yield more than 2.5 ton/ha
2000 -	Super hybrid rice Phase I objective (10.5 ton/ha) achieved
2004 -	Super hybrid rice Phase II objective (12.0 ton/ha) achieved
2006 -	Super hybrid rice Phase III objective (13.5 ton/ha) initiated

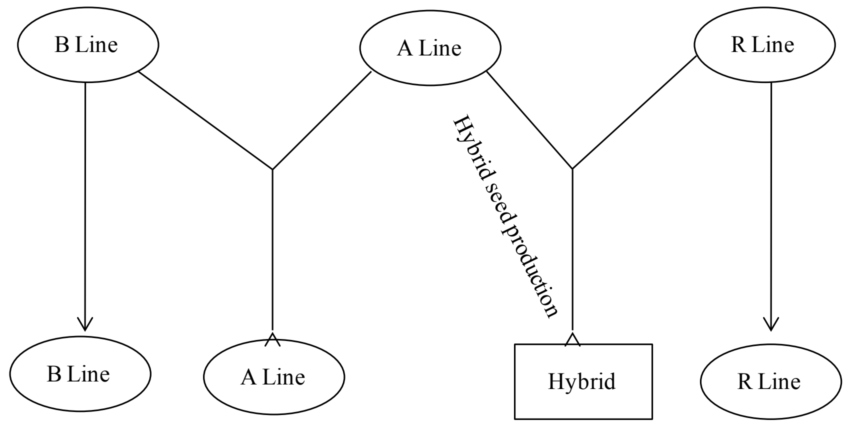
Initiation and Early Stages (1964--1976)

Rice is a self-pollinated crop. The tiny florets with male and female organs in the same floret, along with short flowering duration, are the major obstacles for production of rice hybrids. Heterosis, or hybrid vigor, is a phenomenon where offspring are superior to their parents in one or more traits. To stimulate rice heterosis in a controlled environment, a male sterile line is required. China's hybrid rice initially used a cytoplasmic male sterility (CMS, or three-line) system. This system requires the following three lines: (1) a cytoplasmic male sterile or A line; (2) a maintainer or B line to produce offspring with male sterility, but with normal fertility itself and (3) a restorer or R line to produce F1 seeds and to undergo the F1 heterosis (Box 3).

Box 3. China's three-line (CMS) system

The three-line hybrid rice system includes the following lines:

- Male sterile line (A line): The cytoplasmic male sterility trait is controlled both cytoplasm and nucleus; this line is used as female in hybrid seed production.
- Maintainer line (B line): This line is used as a pollinator to maintain the male sterility. The maintainer line has viable pollen grains and sets normal seed.
- Restorer line (R line): Any rice cultivar that restores fertility in the F1 when it is crossed to a CMS line.



China initiated research on rice male sterility in 1964 (Yuan 1966). In this early stage, breeders observed strong heterosis in rice as an occasional natural occurrence in the field. Between 1964 and 1970, Chinese rice breeders attempted to develop nuclear male sterile lines but were unable to develop maintainer lines by screening with wide test-crossing (Lin and Yuan 1980). Therefore, breeders led by Longping Yuan, a rice scientist, started to search for male sterile materials using wide crossing. In 1970, a rice researcher in Longping Yuan's team identified the critical rice germplasm for the three-line hybrid rice—wild abortive (WA) male sterile rice—on China's Hainan Island, providing a new opportunity for the successful exploitation of rice heterosis (Li 1977).

In the same year, Yuan's team distributed this WA material to 18 institutes in 13 provinces to screen and breed restoration lines and new CMS lines (Yuan 1973; Yuan 2001). In 1971, China's Ministry of Agriculture (MOA) selected three-line hybrid rice technology as one of 22 key research projects. This facilitated the development of a series of male sterile lines and corresponding maintainer lines from the WA germplasm in 1972. These male sterile lines became the mainstream breeding lines in large-scale commercial production from the mid-1970s to late 1980s. The year after the establishment of the China National Cooperative Hybrid Rice Research Group in 1972, researchers from different provinces identified several restorer lines. While working at HAAS, Yuan developed the first *indica* rice hybrid, Nan-You 2, which initially demonstrated strong hybrid vigor in 1974. From 1972-1975, the Hunan Academy of Agricultural Sciences (HAAS) tested 87 hybrids with the best inbreds as control. The best hybrids showed a 20 to 30 percent yield increase over the inbreds in large-scale testing (Lin and Yuan 1980).

In 1975, China planted 373 ha of hybrid rice which showed remarkable yield advantage over the rice inbreds. In the winter of 1975, the largest group of hybrid rice researchers and technicians in China's agricultural history went to Hainan to produce hybrid rice seeds in more than 4,000 ha of land. This massive seed production campaign enabled China to produce enough hybrid seeds for large-scale commercial production in 1976. The MOA formally approved large-scale dissemination of hybrid rice at their 1976 Guangzhou meeting with participants from 13 southern provinces. In this early stage, Shan-

You and Wei-You hybrids occupied the largest acreage under *indica* hybrid rice in China's southern rice growing region, while Li-You 57 and Zhong-Za 1 were the largest *japonica* rice hybrids in China's northern rice growing region (CAAS/HAAS 1991).

Technological Improvements and Large-Scale Commercialization of Three-line Hybrid Rice (1977–1985)

In the early 1980s, China's hybrid rice still faced a number of problems, such as poor disease resistance, a single WA male sterile cytoplasm, uniform growth duration (single- and late-cropping), and low seed production yield, that discouraged its more widespread adoption. However, hybrid rice breeders developed and released new rice hybrids to replace the first-generation, single-cropping *indica* hybrids. Wei-You 64, in particular, showed high yield potential and resistance to five major rice diseases and insect pests (Yuan and Virmani 1988). Breeders also developed early-cropping hybrids in 1987. The commercialization of these new hybrids increased hybrid rice acreage to 6.7 million ha in 1983 and 8.4 million ha in 1985. The release of the new rice hybrids and the substantial increase of the seed production significantly contributed to the rapid expansion of hybrid rice acreage.

In addition to developing improved rice hybrids, hybrid rice breeders developed male sterile lines with diversified male sterile cytoplasms in the 1980s (Yuan and Virmani 1986; Cheng, Cao and Zhan 2005). During this stage, breeders developed more than 600 male sterile lines, which represented 60 types of male sterile cytoplasm (Li and Zhu 1988). The diversification of male sterile cytoplasm resulted in rice hybrids that were more resistant to disease and pests. After the successful development of diverse parental lines, more and more top-performing rice hybrids were released and commercialized.

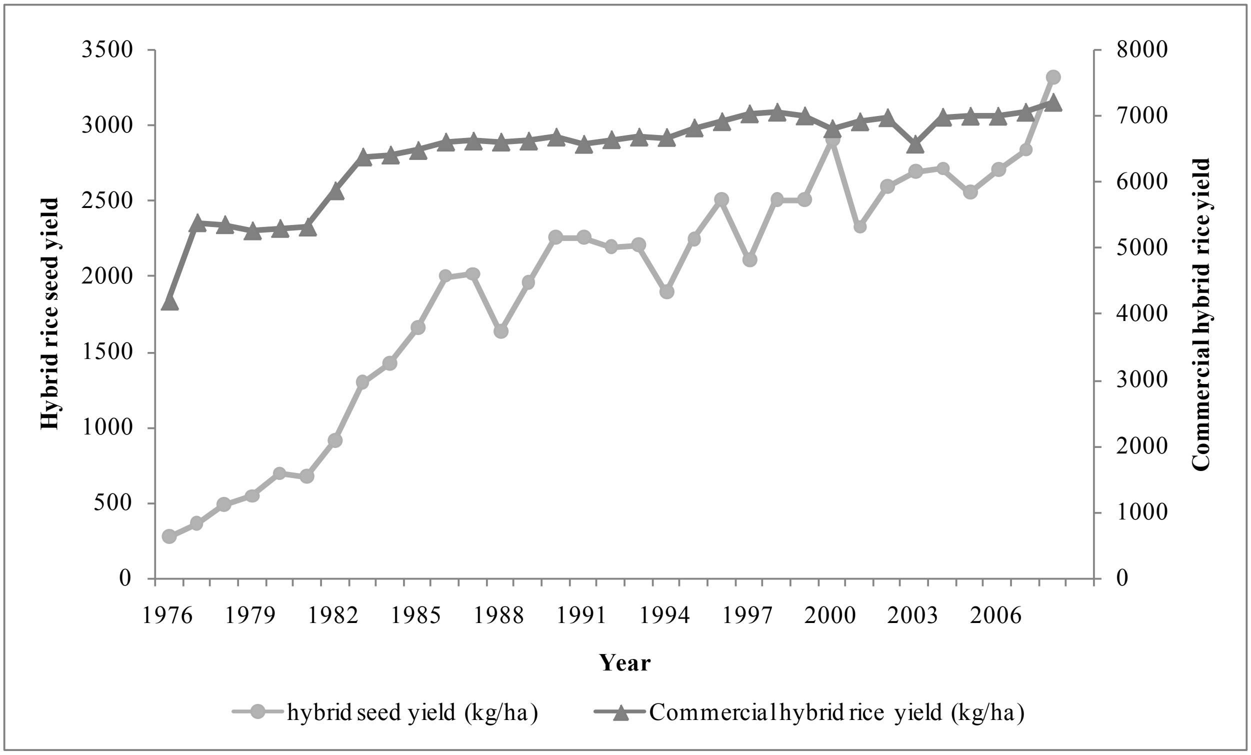
After the mid-1980s, Chinese scientists had developed many male sterile lines with fine grain quality and high outcrossing rates. Using these A lines, researchers developed rice hybrids with good grain quality, resulting in significant improvements in head rice recovery, chalkiness, and amylose content. New male sterile lines with high outcrossing potential provided a solid foundation for high-yielding and cost-effective hybrid rice seed production. Their outcrossing rates were generally 30 to 50 percent higher than those of the previous leading CMS lines.

In the early stage of the hybrid rice breeding program, breeders identified restorer lines by testcross screening from rice germplasm pools, and inbred rice varieties from Southeast Asia became the major R line source. With a better understanding of the genetic mechanism for male fertility, breeders could develop more effective methods for R line breeding, in addition to testcross screening, such as cross breeding, backcross breeding, mutation breeding, molecular breeding, and space induced breeding. San Ming Agricultural Research Institute of Fujian Province developed MH63 from the cross of Gui 630 X IR30. Rice hybrids with MH63 as the male became popular in China for many years because of its good general combining ability (GCA). Other restorer lines with different maturity dates were commercialized and contributed to the increasing acreage of hybrid rice in China.

Apart from breeding, more effective seed production technology and hybrid rice seed businesses made up the core for further propagation of hybrid rice in China in this stage. In the early 1970s, the yield of hybrid rice seed production was low and sometimes reached only 83 kg/ha in the experimental seed production field (Li and Xin 2000). Hybrid rice seed yield significantly increased after two years of extensive study on the outcrossing mechanism with regard to genetics, environmental conditions, and water/ fertilizer management. Chinese breeders developed a systematic packaging of hybrid rice seed production techniques by 1975. Improved production techniques included flowering synchronization and stage adjustment using leaf number method, optimum and safe heading stage, optimum row ratio, supplemental pollination, and timing and dosage for GA3 (gibberellic acid) application (Yuan 1977). These seed production techniques were further improved by Chinese rice agronomists after the late 1970s.

The yield increase of hybrid seed production (Figure 3) ensured sufficient quantity for commercial hybrid rice production, lowered costs for seed businesses and farmers (Zhou and Peng 2005), and promoted the fast and steady expansion of hybrid rice production in China. After years of demonstrated yield advantage of hybrid rice and a commercially viable hybrid seed production system, the Chinese government established many large and effective hybrid rice seed businesses in the late 1970s at all levels from county to state. This was the first time in Chinese history for crop seed businesses to be financially sound.

Figure 3. Commercial hybrid rice yield and hybrid rice seed yield in China (1976-2008)



Source: CNHRRDC (2009)

With every percentage point of genetic impurity in F1 seeds, yield went down by about 100 kg/ha (Yuan 1985). Therefore the purity of parental lines became a priority when entering the expansion phase with large-scale hybrid rice seed production, and seed companies at provincial levels accordingly focused on purification of parental lines.

Hybrid rice technology revolutionized rice farming practice because unlike inbred rice, hybrid rice requires different degrees of agronomic management depending on its stage of growth. Therefore, it was important to develop optimum field management practices to manipulate yield components such as plant population and canopy structure to realize the maximum economic yield of hybrid rice. Chinese hybrid rice agronomists accomplished this by developing systematic methods for high-yielding field management, such as "Tonnes-Rice-Grain-Production," "wide spacing and few seedlings," Standardized Cultivation, Structural Fertilization, dry seeding, seedling broadcasting, sparse sowing for hybrid rice nurseries, and integrated pest management (Yan 1988; Xu and Shen 2003). With these agronomic management packages that used special practices (Box 4), farmers were able to maximize hybrid rice yield (Lou and Mao 1994). These improved cultivation techniques played an important role in the rapid growth of hybrid rice (CAAS/HAAS 1991).

Box 4. High-yielding field management practices for hybrid rice in China

- Raising effective tiller seedlings
- Rationally close planting to established a suitable plant population
- "Ideal" application of fertilizers, both as basal and top dressing
- Efficient water management
- Effective disease and pest control

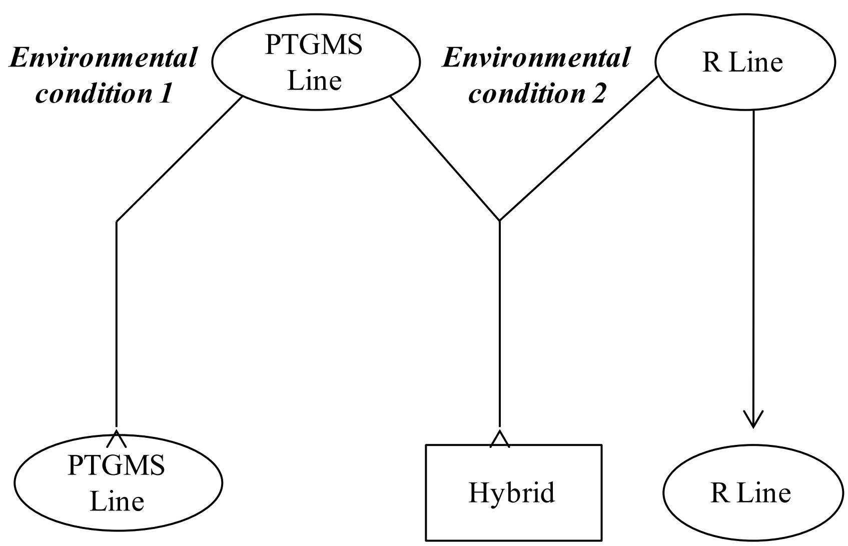
Progression from the Three-line to the Two-line Hybrid Rice System (1986–1995)

Researchers identified environment-conditioned genic male sterility (EGMS) in tomatoes as early as 1948 (Rick 1948). In 1973, Shi Mingsong discovered the source material Nong-ken 58s for the two-line system male sterile line in rice in Hubei, China. He spent eight years studying how photoperiod and temperature conditions affected the male sterility of this material (Shi 1981). From 1982 to 1986, many rice researchers studied the plant physiology, biochemistry, and genetics of Nong-Ken 58s, previously dubbed "Natural dual-purpose male sterile lines" and later known as HPGMR (Hubei Photoperiod-sensitive Genic Male-sterile Rice). In 1987, Yuan proposed a strategy for the two-line system hybrid rice breeding using the EGMS materials, including Nong-Ken 58s (Yuan 1987; see Box 5).

Box 5. Two-line system hybrid rice

Two-line system hybrid rice included the following two lines:

- Male sterile line: nuclear gene(s) and environmental conditions such as photoperiod and/or temperature control male sterility. Male sterile lines can be EGMS (environmental-conditioned genic male sterile), PGMS (photoperiod-sensitive genic male sterile), TGMS Thermo-sensitive genic male sterile) or PTGMS (photoperiod- and thermo-sensitive genic male sterile) lines.
- Restorer line (R line): any rice cultivar that restores fertility in the F1 when it is crossed to the male sterile line



Pros and Cons of the Two-line System

Two-line system hybrid rice has a number of advantages over the three-line system: (1) It is simple and effective due to the removal of the maintainer line from three-line system; (2) The removal of the restrictions of male sterile cytoplasm increases the probability of developing a commercially sustainable hybrid—studies show that more than 95 percent of varieties can restore the male fertility from the EGMS line in the same subspecies (Yuan 1998); (3) EGMS genes are more easily transferred into almost any rice lines; (4) The field acreage ratio of EGMS line multiplication, seed production, and commercial production can be increased to 1:100:12,000-15,000 and reduce hybrid rice seed cost; and (5) There are no negative effects on the agronomic performance of the EGMS line itself and its resulting hybrids from male sterile cytoplasm.

However, the dependency of male sterility on temperature and day length requires more attention from breeders and seed producers. Temporal and geographical limitations also existed for hybrid seed production and EGMS multiplication (Li and Yuan 2000).

In-Depth Research on the EGMS to Minimize Risk in Hybrid Seed Production

Chinese rice scientists found that both photoperiod and temperature regulate the fertility alteration of initially-dubbed PGMS (Lu 1994). The relatively high CST (Critical Sterility-inducing Temperature, such as 26º C) of any EGMS line would induce pollen fertility, even in hot seasons, and, therefore, hybrid rice seed production would not be reliable (Yuan 1998). To minimize the risk to the two-line hybrid rice seed production, scientists determined the stable period of a specific EGMS line at certain locations through sequential sowing experiments. China initially had difficulty in EGMS line multiplication because a stable and practically safe EGMS line should have a relatively low CST depending on the historical meteorological data of the target seed-producing region. For example, the CST for an EGMS line was limited to 23.5º C in central China (Yuan 1998b). The difference between CST and the temperature of chilling injury was small, which could result in low yield for EGMS multiplication. Xiaohe Luo, a hybrid rice breeder at CNHRRD, and his team invented a “cold water continual irrigation” method and solved the problem of low yielding multiplication of EGMS lines Pei-Ai 64s with low CST.

One risk was that the seed purity was not assured because of the short stable sterility-inducing time in seed production. As for two-line hybrid seed production, the sterility-inducing period should be longer than 40 days: that is, from late July to late September with the flowering time in mid-to-late August in central China including Hunan, Hubei, Anhui and Jiangxi (Mou et al. 2003). Therefore, seed production locations were carefully selected based on the local multi-year meteorological data and the CSTs of the specific PTGMS lines.

Another risk was that the CST of an EGMS would be raised and become unusable after several generations of multiplication without intentional purification procedure due to genetic drift. To address this risk, Yuan (1994b) proposed the EGMS core seed and nucleus seed production procedure, which, in maintaining a stable CST over time, proved to be successful in the two-line hybrid rice production practice.

Large-Scale Commercialization of Two-Line Hybrid Rice

EGMS lines have more freedom to produce hybrids with normal fertility, good rice grain quality, high yield potential, and improved disease resistance. The developed hybrids with EGMS lines like Pei-Ai 64s showed remarkably strong heterosis. In 1995, the two-line hybrid rice technology was successfully commercialized in China (Li and Yuan 2000; Yuan 2004). In China’s southern regional trials from 1998 to 2003, 11 out of 39 two-line hybrids showed remarkable yield increases over the three-line hybrid checks (Yang et al. 2004). Prior to 2001, hybrid rice breeders in China used 11 out of more than 100 EGMS lines to develop large-scale commercial rice hybrids, 32 two-line rice hybrids were certified and released into commercial production, and another six two-line *japonica* hybrids were approved and commercialized for the late-season rice crop in nine provinces. In the same region, breeders released four *indica* two-line hybrids for the early-season crop and six *indica* two-line hybrids for the late-season crop. In southern rice-growing regions, breeders released 11 two-line rice hybrids for double cropping. These two-line hybrids demonstrated 5 to 8 percent more yield than the three-line rice hybrid checks (Mou et al. 2003).

The acreage grown under two-line hybrid rice increased significantly at the turn of the new millennium. In 2002, the total area under two-line hybrid rice occupied about 2.8 million ha, 18 percent of the total hybrid rice acreage (Yuan 2004; Cheng et al. 2005). In 2008, the commercial two-line hybrids occupied 3.3 million ha in China, about 11 percent of the total rice acreage and 22 percent of China's hybrid rice acreage. In terms of the regional distribution, PGMS lines were mainly distributed in the Yangzte River basin and the more northern region that had varied day length across different seasons. TGMS lines were mainly used in South China where day length differences were smaller (Lu, Virmani and Yang 1998).

Enhancement of Hybrid Rice Heterosis (1996-present)

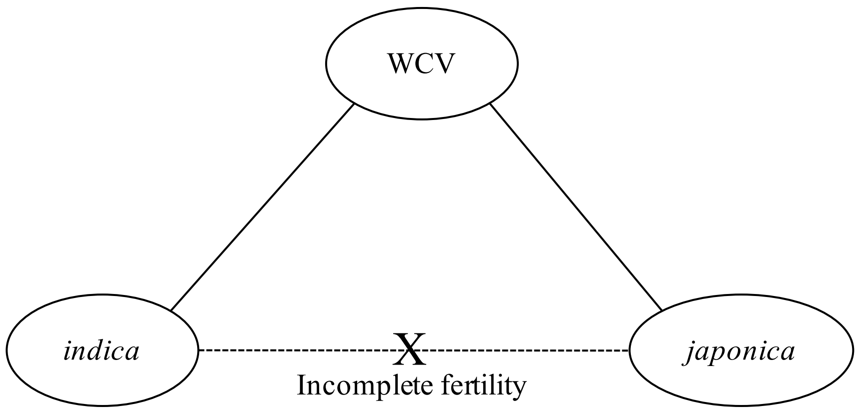
Development and Use of Intersubspecific Hybrid Rice

Rice has three subspecies: *indica*, *japonica,* and *javanica*. Rice scientists have observed superior heterosis between *indica* and *japonica* in China and elsewhere. Theoretically, the intersubspecific heterosis in *indica*/*japonica* hybrids is 30-50 percent higher than intervarietal heterosis. Unfortunately, these F1 hybrids are generally too tall with long growth duration, poor seed set and grain filling, asynchrony in flowering time, and segregation of grain quality traits. Poor seed set (10-30 percent) in particular made it difficult to use the *indica*/*japonica* hybrid (Zhu and Liao 1990). However, the discovery of WCG (wide compatibility gene) by Japanese scientists presented a new opportunity for the utilization of *indica*-*japonica* intersubspecific heterosis (Ikehashi and Araki 1986, Box 6). In China's hybrid rice breeding practice, the seed setting rate between *indica* and *japonica* increased to close to normal levels by using the WC genes (Yuan 1994a).

Currently, the most efficient approach for intersubspecific hybrid breeding is to use *javanica* rice germplasm or intermediate type (that is, with mixed pedigree between typical *indica* and *japonica*) to develop hybrid rice with typical *indica* or *japonica* as one parent. Using this approach, several top-performing parental lines were successfully commercialized, such as Pei-Ai 64S (Xiao et al. 2006). Some certified top-performing super rice hybrids in China are intersubspecific hybrids using *javanica* or the intermediate type as one parental line such as Liang-You-Pei-Jiu (Pei-Ai64S – *javanica*, 9311 – *indica*) and Xie-You 9308 (Xieqingzao A – *indica*, Zhonghui 9308 – intermediate-type) (Zhong et al. 2005).

Box 6. Use of rice intersubspecific heterosis

- Heterosis: hybrid vigor, a phenomenon in which the resulting offspring are superior to their parents in one or more traits.
- Generally, rice is classified as two subspecies: *indica* and *japonica*. Rice geneticists and breeders sometimes define tropical *japonica* as *javanica* subspecies.
- It has been known that F1 hybrids between typical *indica* and typical *japonica* produce incomplete fertility.
- Some rice varieties (mainly in *javanica*) with the wide compatibility (WC) gene(s) can produce complete fertility by crossing with either *indica* or *japonica*.



"Super Hybrid Rice" Program in China

Rice is estimated to have 21.6 t/ha yield potential under natural conditions (Cao and Wu 1984). Having seen Japan's government-sponsored "Super high-yielding rice breeding" program in 1981 and the International Rice Research Institute's (IRRI) "super rice" or "New Plant Type (NPT)" plan in 1989, China's MOA endorsed the Chinese "super rice" program that Chinese rice scientists proposed in 1996 (Chen et al. 2007). In 1996, China's MOA established yield targets for this program (Table 1) (Yuan 2003; Yuan 2008).

Table 1. Yield standards (t/ha) set for China's "super hybrid rice" program

Phase	Hybrid Rice			Yield increase percent
	Early season	Late season	Single season	
1996	7.50	7.50	8.25	0
Phase I (1996–2000)	9.75	9.75	10.50	>25
Phase II (2001–2005)	11.25	11.25	12.00	>45
Phase III (2006–2015)	NA	NA	13.50	>60

Notes: It is required that grain yield be up to standards in two consecutive years and at two locations, each location with more than 6.67 ha

Source: Yuan 2008

In 1997, the MOA proposed a three-phase "super hybrid rice breeding" strategy as part of the program (1996–2000, 2001–2005, and 2006–2015), the key components of which were integration of an ideal plant type and intersubspecific heterosis (Yuan 1997). Yuan proposed an ideal rice plant type with the following traits: long, erect, narrow, V-shaped uppermost three leaves; and large, uniform, and droopy panicles below a taller erect-leaved canopy (Yuan 1998b).

Through the work of Chinese rice scientists, the Phase I objective (10.5 t/ha) was achieved in 2000 and the Phase II objective (12 t/ha) was achieved in 2004, with yield increases of 25 percent and 45 percent, respectively, over the best hybrid checks before 1996. For example, the first two-line super rice hybrid, Liang-You-Pei-Jiu, had high commercial yield across multiple years and locations in large-scale rice production because of the good plant type and the remarkable level of interspecific heterosis. This two-line hybrid was the first to reach the Phase I yield level goals, and the Chinese Rice Genome Sequence Initiative sequenced the genome of its parental lines (Quan 2005; Yu et al. 2002). The Phase II three-line hybrid Ming-You 8 (Fujian province) and two-line hybrid P88s/0293 yielded more than 12 t/ha in Fujian province and Hunan province, respectively, surpassing the Phase II yield target (Yuan, Deng, and Liao 2004). By 2006, the MOA certified 34 rice hybrids as "super rice," including Xie-You 9308 (Qi et al. 2007). Chinese rice breeders are currently working on Phase III super hybrid rice, with large-scale yield objectives of 13.5t/ha.

Future Japonica Hybrid Rice in China: The yield advantage of three-line *japonica* hybrid rice over conventional *japonica* varieties was negligible, and therefore the dissemination was limited. Its underperformance was primarily due to the unstable male sterility of the BT-type CMS lines and the marginal heterosis level, which resulted from narrow genetic diversity and the difficulty in developing *japonica* restorer lines. However, using the two-line hybrid rice system instead of the three-line system allowed for the elimination of the male sterile cytoplasm, enabling hybrid rice breeders to more easily develop *japonica* restorer lines.

Prospects of Future Hybrid Rice in China

The planted acreage of *japonica* hybrid rice had been limited to about 0.1 million ha prior to the mid-1990s (Yuan 1998a). After liberalization of the rice retail market, *japonica* rice-growing acreages rapidly expanded, not only in the northern China, but also along the Yangtze River Basin. Several provinces in the lower Yangtze River Basin became major *japonica* rice producers, such as Jiangsu, Zhejiang, Shanghai and Anhui. These changes raised the share of the *japonica* rice area from 11 percent in 1980 to 16 percent in 1990 and 27 percent in 2000 (Huang, Rozelle and Li 2002).

The current acreage under *japonica* hybrid rice in China is 0.33 million ha, about 4 percent of total *japonica* rice acreage (8 million ha). *Japonica* rice hybrids have demonstrated strong heterosis. For example, Chang-You 1, a *japonica* rice hybrid, yields an average of 12.1 t/ha. The two-line system provides the opportunity to further increase the heterosis level of *japonica* hybrid rice and China's total rice production. In addition, there is still potential to develop superior three-line system *japonica* hybrid rice. For example, three-line *japonica* rice hybrids, such as Liao-You 5218 and Liao-You 1052, demonstrate high yield potential (Qi 2007). Challenges for further expanding the use of *japonica* hybrid rice in China include its poor grain quality and limited disease resistance, seed production yield, and adaptability.

*Molecular Breeding***:** Molecular marker assisted selection (MAS) has been shown to be an effective breeding methodology in hybrid rice. The China National Hybrid Rice Research and Development Center (CNHRRDC) developed an elite restorer line, Yuan-Hui 611, through selection of the high yielding alleles from wild rice (*O. rufipogon*) at *yld 1.1* and *yld 2.1* loci using flanking SSR markers. The hybrids crossed with this restorer line showed more than 20 percent yield increase over the best hybrid check (Deng et al. 2004). Another example using MAS is MH63 (*xa21*), developed through integration of the resistant allele of *Xa21* locus into MH63. It is well known that wild rice harbors favorable alleles for important traits like resistance to disease pests, new source of cytoplasmic male sterility, and yield-enhancing loci (Xiao et al. 1996). MAS has become a promising breeding method to shorten the hybrid rice breeding cycle and to increase breeding efficiency in well-characterized traits. With current low-cost genotyping technology, it will not be long before Chinese hybrid rice breeders routinely use MAS to improve parental lines and hybrids for biotic/abiotic resistance, grain quality, and other traits.

The super hybrid rice genome sequence project (SRGP) has entered the second phase. The Beijing Genomics Institute will sequence PA64s (maternal parent of Liang-You-Pei-Jiu) after the draft assembly of the 9311 (paternal parent of Liang-You-Pei-Jiu) sequence. This project will promote the understanding of rice heterosis at the genomics level and thus molecular breeding applications in hybrid rice breeding (Yu et al. 2003).

Biotechnology Applications: Chinese rice scientists have developed and tested transgenic hybrid rice—with herbicide resistance and Bt for resistance to rice stem borers—for environmental evaluations. In 1999, the MOA announced the first sets of transgenic rice lines, which have the following traits: insect resistance using Bt or GNA gene, disease resistance using *Xa21*, and low amylase content using antisense-Waxy gene (Yuan 2002b). Rice scientists have transformed some other genes into rice such as the Bar gene for herbicide-sensitive restorer lines, and genes with C4 plant photosynthesis potential. As with hybrid rice, Chinese rice scientists developed parental lines using a transgenic approach. These transgenic parental lines conferred herbicide resistance in restorer lines, bacterial blight resistance, and stem borer resistance using Bt. Other genes may be transferred into hybrid rice in the near future such as genes for drought tolerance, nitrogen use efficiency, and disease resistance.

3. IMPROVED FOOD SECURITY AND OTHER SOCIAL BENEFITS

Food Security

China has been facing the dual pressures of increasing population and decreasing arable land. Over the past 20 years, China's arable land has been decreasing by 0.2 million ha on average per year. From 2004 to 2006, 0.87 million ha of arable land acreage was cut down because of the shifts in agricultural production and the return of crop land to forestry (Xue 2007). At the same time, China's population increased from 1.1 billion in 1987 to 1.32 billion in 2007. Further, China cannot depend on the relatively small world rice trade market (about 25 million tonnes from 2002 to 2003) if faced with a significant rice production deficit. Therefore, food security has been the most important and challenging issue for the Chinese government.

The higher yield of hybrid rice over conventional inbred rice has enabled China to decrease its rice growing acreage by 14.5 percent, from about 34.4 million ha in 1978 to 29.4 million ha in 2008. At the same time, the total rice production increased 44.1 percent, from 136.7 million tonnes to 197 million tonnes, and the national average yield increased from 3.4 t/ha to 6.7 t/ha (67.5 percent yield increase per area unit), mostly as a result of the hybrid rice program. The increase of total rice production per year due to the adoption of hybrid rice in China is close to the total annual rice production from a single high-production province.

Impact of Hybrid Rice on Use of Heterosis in Other Crops

The success of two-line hybrid rice breeding in China encouraged agricultural scientists to explore the two-line breeding system in other crops. By 1997, they identified environment-conditioned genetic male sterility in rice, sorghum, soybean, millet, rape, and barley in China, and in maize, flax, and pigeon pea outside China (Yuan 1997b). The CNHRRDC organized an international symposium on crop breeding using the two-line system in 1997 and shared their experiences using two-line hybrid rice technology with scientists working on other crops. Breeding efforts using the two-line approach are underway in these crops (Tang et al. 1997; Tang et al. 2007).

Economic Benefits

The intensive labor input in hybrid rice seed production has increased both rural employment opportunities and famers' incomes. Hybrid rice technology has generated more than 100,000 jobs related to hybrid rice research, extension, and seed production, and indirectly has generated 10 million jobs in rural areas (Yuan, Deng and Liao 2004).

4. SUSTAINABILITY OF HYBRID RICE TECHNOLOGY

Prior to the 1980s, China sought to generate more food by increasing the quantity of rice production. This explains why the early-stage hybrid rice generally showed high yield but poor grain quality. After China's growth and reforms in the early 1980s, the rural economy entered a new stage, with the central goal of raising farmers' incomes. As the national economy developed and people's living conditions improved, attention shifted to improving the quality of rice products without sacrificing yield. After the Chinese government liberalized the retail rice market in 1993, hybrid rice breeders then needed to develop hybrids with fine grain quality in addition to high yield and multiple resistances to biotic and abiotic stress. As a result of this breeding effort for superior quality hybrid rice, China developed and released some top-quality male sterile lines and hybrids as previously described.

Financial Sustainability

Public Subsidies in Early Stages: After realizing the great potential of hybrid rice from multi-location yield trials, the Chinese government decided to invest 8 million RMB for 4,000 ha of hybrid rice seed production on Hainan Island in the winter of 1975. This investment resulted in the largest seed production campaign in China's rice farming history and made the rapid expansion of hybrid rice in 1976 possible. The government also granted tax concessions to seed companies and provided subsidies when seed yield was low during the late 1970s (Yuan 2002a).

Economic Return on Investment: Hybrid rice became an important approach in improving the economic efficiency of China's agriculture. Lin and Pingali (1994) report that hybrid rice had about 15 percent yield advantage over conventional inbreds. According to another study of 209 farms in Jiangsu Province, hybrid rice showed a 37 percent increase for net returns per hectare, a 26 percent increase for labor return, a 12 percent increase for non-labor returns, and a 30 percent increase for the rate of net returns to total cost compared to conventional inbred rice.[1]

Importantly, He and Flinn (1989) confirmed that the higher yields of hybrid rice were largely due to technical innovation instead of differences in management. They found that *Indica* rice hybrids in Jiangsu Province were more profitable than conventional rice varieties due to higher returns to both labor and non-labor inputs. In another small-scale (333 ha) single-cropping rice growing area in Hubei Province, experimental results showed that the hybrid Shan-You 2 yielded 2.4 t/ha (15 percent) more than the popular inbred check 691, corresponding to an increase of 382 RMB per hectare. The same study found that inbred rice required more water use and labor input. The total input (including labor and non-labor input) was 1,290.3 RMB/ha for hybrid rice and 1,317.8 RMB/ha for inbred rice. The net investment return to farmers of hybrid rice was 21.9 RMB/ha, compared to 16.2 RMB/ha for inbred rice, a difference of 35 percent (Tao 1987).

Despite these high rates of return, at least one study contends that the rapid diffusion of hybrid rice in China resulted from technological promotion under pressure from the Chinese government rather than its economic superiority. Lin (1991) studied 952 observations in 101 counties of Hunan Province from 1976 to 1986. In this early extensive study, the adoption rate of hybrid rice technology was tested against county-level, time-series data. A major conclusion from the study is that in the early stage of the collective system, the Chinese government pressured farmers to adopt hybrid rice without consideration of its profitability. The government's pressure was the main reason for the rapid expansion of hybrid rice technology initially, along with the effective research and extension network.

In line with these findings, Lin (1991) also reported some degree of rejection of hybrid rice in the 1980s, with farmers returning to conventional rice varieties. One possible explanation is that the

[1] At the same time, hybrid rice produced as seed (as opposed to grain) provided farmers with even greater returns—3.8 times higher for net returns per hectare, and 2.1 times for labor returns (He et al. 1988).

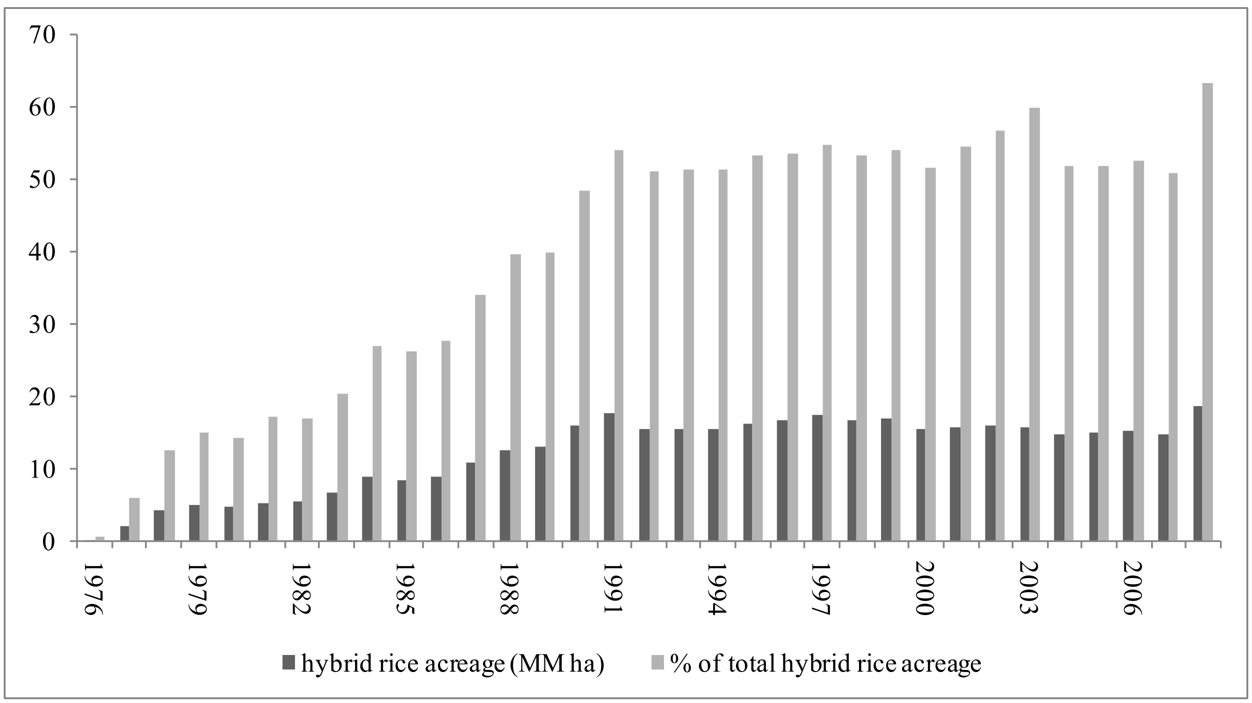
phenomenon was regional in nature, and may only have been experienced in Hunan Province where the study was conducted. Another reason may have been the limited availability of hybrid varieties, especially for the early-season rice hybrids and the hybrids with strong biotic and abiotic resistance traits.

Importantly, with the institutional transition from the collective or commune production system before 1979 to the "household responsibility" system after 1981, it is also possible that farming decisions became less driven by government pressure. Under the household responsibility system, the decision to cultivate hybrid rice or inbred rice shifted from production teams to individual farmers, possibly providing farmers with more opportunity for independent decisionmaking.

As Lin (1991) points out, adoption might not be driven entirely by the return rates because government pressure might have also been a factor. But given the limitations to Lin's study, and given the continued diffusion of hybrid rice under the household responsibility system, where individuals can make decisions autonomously, it is feasible to assume that the economic return to hybrid rice was a more powerful factor in its adoption than government pressure.

Indeed, statistical data from 1976 to 2008 (Figure 4) show a constant increase of hybrid rice acreage from 1982 to 1987 after the full adoption of the household responsibility system. The increased acreage in hybrid rice from 1976 to 2008 suggests that the large scale expansion of hybrid rice was a success not only because of the Chinese government intervention, but more importantly due to hybrid rice's proven high-yielding performance (Figures 3 and 4).

Figure 4. Hybrid rice acreage in China (1976–2008)



Source: CNHRRDC (2009)

Environmental Sustainability

Reduced Land Use for Rice Farming: With pressure to divert an increasing amount of land for non-agriculture use, the threat of food insecurity is becoming more severe in China. China also faces many ecological challenges for agricultural production including shortage of water resources, soil erosion, land desertification, and environmental pollution. These challenges have irreversibly damaged rice acreage in China.

The high-yield potential of hybrid rice enables China to produce more rice on less land and provides opportunities for crop diversification. In addition, the seeding rate per hectare of hybrid rice is much lower than that of conventional inbred rice. Transplanting density is 40-50 percent less than for inbred rice. This has saved rice seed production area (He et al. 1988).

Recently, with the rapid extension of super hybrid rice in the past 10 years, the yield per unit land has been greatly enhanced in China. For example, the average yield of super hybrid rice reached 9.9 t/ha in 67 ha of rice fields in Jin Hua City of Zhejiang Province, 10.5 t/ha in 800 ha of rice fields in Xu Pu County of Hunan Province, and 9 t/ha in rice fields of Guizhou Province under adverse natural conditions. Yuan proposed to the Hunan provincial government and then to the central government the "Planting Three Producing Four" program, which aimed to produce enough rice from current four unit acreages with three unit actual production acreages (Yuan 2007). This further enabled China to produce enough food with less land usage, to the tremendous benefit of Hunan, Sichuan, and several other provinces. So far, hybrid rice technology has helped China to save more than 6 million ha of land each year for agricultural diversification and non-agricultural use.

Better Adaptability to Stress Environments: Hybrid rice has a vigorous root system, strong culm, thick leaves, and high photosynthetic efficiency, and thus, significant yield advantage over conventional inbred rice (CAAS/HAAS 1991). Further, hybrid rice is more adaptable to various climatic (tropical, subtropical and temperate), topographical (plain, coastal area and hilly regions), and ecological (irrigated, drought-prone, and upland) conditions. Hybrid rice has been grown in single-cropping and double-cropping regions. It was reported that hybrid rice was grown with 50 percent less water in irrigated fields but with no significant yield loss (Yuan, Virmani and Mao 1989), a clear advantage over inbred rice within drought prone regions. In Liaoning Province, hybrid rice showed soil alkalinity tolerance and so was grown in the coastal areas (Yuan, Virmani and Mao 1989). Selected rice hybrids demonstrated stronger tolerance over inbred rice to wind and flooding in Guangdong province in the south, which frequently is subject to typhoons and heavy rains (Lin 1989).

Reduced Vulnerability to Rice Disease and Pests: In the early stage of hybrid rice technological development, WA was the only source of male sterile cytoplasm. This presented potential vulnerabilities from disease or insect epidemics such as the southern corn leaf blight caused by the unitary "T cytoplasm" in the United States in 1969−1970 that resulted in significant maize losses. To address this vulnerability, hybrid rice breeders identified different male sterile cytoplasms in addition to WA. The diversification of CMS lines and hybrids helped reduce the risk of epidemic.

Other Environmental Benefits: Due to the biological heterosis, hybrid rice generally produces more rice straw, which has been used as manure to improve the soil texture and fertility. Also, the decrease of total rice acreage minimizes the emission of greenhouse gases such as methane and nitrous oxide (Tran and Nguyen 1998).

Social and Political Sustainability

Full Government Support and Commitment: During the development and refinement of hybrid rice technology (described earlier), the Chinese government provided critical support through funding and policy (Box 7). In China, the MOA and Ministry of Science and Technology (MOST) established the national hybrid rice research programs in 1971 and 1972, respectively. The successful development of the first rice hybrid in 1974, Nan-You 2, demonstrated to Chinese rice farmers and policymakers the dramatically improved phenotype and yield benefits from hybrid rice. When the cross-country demonstration of hybrid rice succeeded in 1975, the then central governmental leader, Hua Guofeng, provided timely and strong support with prioritized and special funding, more labor, and more resource materials for hybrid rice seed production. With this central government commitment, more than 30,000 people from rice-growing provinces converged on Hainan Island to produce hybrid rice seeds in the winter of 1975. This massive agricultural campaign led to an increase in the planting of hybrid rice, from 373 ha in 1975 to 0.14 million ha in 1976. In the mid-1970s, the Chinese government commenced an effective information campaign to encourage the acceptance of hybrid rice technology. From the central to local governments, at least one high-ranking official was assigned to monitor the progress of hybrid rice extension and commercialization.

Box 7. Chinese central governmental support for hybrid rice technology

1971 (MOAFF)	Hybrid rice research listed as 1 of 22 key research programs. A national collaborative research group established, comprising 14 provinces, municipalities, and autonomous regions, and led by CAAS and HAAS.
1972 (MOST)	Hybrid rice research listed as a key national project. A national collaborative hybrid rice program established with 19 provinces participating.
1975 (MOAFF)	8 million RMB invested for 4,000 ha of hybrid rice seed production in Hainan Island
1977–87 (MOAFF/MOA)	The second to sixth national hybrid rice project meetings
1982 (MOA)	National Hybrid Rice Advisory Committee established
1984 (MOF)	Hunan Hybrid Rice Research Center (HHRRC) established
1987 (MOST)	Two-line hybrid rice research listed in the National Hi-Tech or “863” Plan, and renewed in 1991, 1996, and 2001
1994 (MOST/Premier Fund)	China National Hybrid Rice R & D Center (CNHRRDC) established
1998 (Premier Fund)	10 million RMB funded for super hybrid rice research
1998 (MOST)	Super hybrid rice breeding program established
2003 (Premier Fund)	10 million RMB special fund for super hybrid rice research
2006 (Premier Fund)	20 million RMB for hybrid rice research
2008 (MOST)	Super hybrid rice research listed as National Research Aid plan

Source: CNHRRDC (2009)

In a further show of government commitment, the MOA convened a national meeting in Guangzhou that addressed problems in hybrid rice seed production and initiated the long-term agricultural shift to hybrid rice breeding, seed production, and extension. Between 1977 and 1987, the MOA held an additional five national hybrid rice project meetings to discuss challenges and coordinate research efforts at different developmental phases (CAAS/HAAS 1991).

In 1982, the MOA established the National Hybrid Rice Advisory Committee (NHRAC), composed of more than 10 hybrid rice experts. After touring hybrid rice growing regions two to three times annually, these experts provided strategic suggestions to the MOA about the development and use of hybrid rice technology (CAAS/HAAS 1991).

For two-line hybrid rice technology, China’s Ministry of Science and Technology (MOST) initiated the “National Two-line Hybrid Rice Research Program” in 1987. This program established a network comprising 16 research institutes and universities. The national two-line hybrid rice research program was renewed in 1991, 1996, and 2001 with substantial funding support.

Close to the turn of the new century, the Chinese government committed considerable support to the commercialization of super hybrid rice. Between 1996 and 1997, the MOA and the Chinese

Agricultural Science and Education Foundation co-sponsored the project, "Research on super rice breeding and cultivation system in China," with detailed objectives and yield targets to be achieved in two phases (Yuan 2008).

In 1998, Premier Zhu Rongji provided 10 million RMB for the project, "Super hybrid rice breeding." The same year, the then Vice Premier Wen Jiabao urged the MOA to enhance research on super rice. As a result, the project "Super rice breeding and production technique integration" was funded in 1999 with another 10 million RMB. At the same time, super hybrid rice breeding was included in China's 863 Hi-Tech Plan, a long-term plan for the advance of science and technology. From 1998 to 2003, the MOST established several programs to support the extension and commercialization of the new super hybrid rice, Liang-You-Pei-Jiu. In addition to the central government, the provincial governments also supported commercialization of Liang-You-Pei-Jiu with funding and special programs (Quan 2005). In 2005, the Chinese central government included "The extension of super rice" into the China's Central Document No. 1, thus further promoting the proliferation of super hybrid rice.

Coordination and Collaboration for Technology Generation and Uptake: In 1970, Chinese rice breeders, led by Longping Yuan, freely distributed the critical WA material to 18 institutes in 13 provinces for collaborative research. Hunan province established a collaborative hybrid rice breeding program in 1971 followed by the national collaborative hybrid rice project led by the Chinese Academy of Agricultural Sciences (CAAS) and Hunan Academy of Agricultural Sciences (HAAS) in 1972. This collaborative group comprised 14 provinces, municipalities, and autonomous regions. The joint effort of these research organizations resulted in the development of the first set of WA-type male sterile lines and a series of restorer lines by 1973 (Lin and Yuan 1980; Shen 1980).

China's sophisticated three-tier seed system and four-level research extension network also contributed to the success of hybrid rice development. The three-tier seed system included provincial seed companies that specialized in parental line purification; prefectural seed companies for A line multiplication; and county-level seed companies for F1 hybrid seed production. This system ensured the quantity and quality of hybrid rice seed supply for commercial production. The four-level extension network comprised county, commune, brigade, and production teams. This network proved to be efficient for rapid evaluation, selection, and adoption of hybrid rice, as well as information diffusion (Lin and Pingali 1994). The government has established stations specializing in seed, agricultural technology, soil and fertilizer, and plant protection to encourage the dissemination of hybrid rice technology at the national, provincial, prefectural, and county levels. Every commune had one or more agricultural technicians to instruct farmers on hybrid rice technologies or new hybrids. This extension network played an important role in the rapid and large-scale commercialization of hybrid rice technology (Xu and Shen 2003).

The successful commercialization in 1995 of two-line hybrid rice also was the result of concerted nationwide collaboration, with hundreds of rice scientists from 23 research institutes and universities working together for nine years using the EGMS gene(s) and WC (wide compatibility) gene(s).

Established Hybrid Rice Seed Business: Along with the development and upgrade of hybrid rice technology, the market for hybrid rice seed increased 111 fold from 0.14 million ha in 1976 to 15.4 million ha in 2000. Hybrid rice would not have been successful in China without an efficient hybrid rice seed industry.

Evolution of China's hybrid rice seed industry can be divided into the following three phases based on the planning economy or market economy.

1. Planning economy phase (1978–1995): Shortly after the successful development of three-line hybrid rice, the China Seed Corporation was established under the Ministry of Agriculture and Forestry. The total number of hybrid rice seed companies reached 1,500 in 1995, among which 600 county-level seed companies had distributed seed supplies to more than 50,000 seed stations at the township level. Annual hybrid rice seed sales reached 0.6 million tonnes through this seed distribution system.

2. Early market economy phase (1996–2000): After the 1995 Tianjin national seed conference, China's seed business made following changes: from traditional production to centralized large-scale production; from regional to cross-regional seed distribution; and from separate research and seed business to an incorporation of research, production, extension, and sales into a single seed business.
3. Current consolidation phase (2001–present): The implementation of China's Plant Variety Protection (PVP) in 1997 and the publication of China's Seed Law in 2000 further promoted China's hybrid rice seed business with regard to seed market segmentation and business consolidation. Quite a few large hybrid rice seed businesses were established through consolidation in this phase, such as Longping Hi-Tech and Hefei Fengle Seed Co (Yuan, Deng and Liao 2004).

5. LESSONS LEARNED AND ISSUES GOING FORWARD

Chinese Experiences in the Development of Hybrid Rice Technology

The following lessons learned throughout China's more than 40 years of technological development and improvement in its hybrid rice programs will provide a valuable model for other rice growing countries to develop their own hybrid rice programs.

Institutional and Policy Functions

The Chinese government's support and commitment was a key factor in the success of its hybrid rice program. Well-defined policies have led to financial support for research, seed production, and extension agencies; guidelines or regulations for hybrid rice seed production; and seed certification standards and distribution. Government policies and standards also made hybrid rice cultivation and seed production attractive, profitable, and sustainable. In addition, the Chinese government subsidized commercial hybrid rice seed production in the early years to ensure sufficient supply of affordable, high quality hybrid rice seed to farmers. Farmers also had access to government- subsidized fertilizers and pesticides, which helped ensure use of appropriate farming inputs in hybrid rice production (Lou and Mao 1994).

A high-ranking scientist with the requisite knowledge, capability and authority was designated as the national coordinator of China's hybrid rice program. The coordinator worked with the technological steering committee, and coordinated and regularly monitored the progress of the research, seed production and other technology-related programs in the nation. In addition, full-time researchers and extension workers were devoted to the generation and uptake of hybrid rice technology. Hybrid rice breeders played a leading role in the development of China's hybrid rice technology, developing more than 1,000 parental lines and more than 300 large-scale commercialized rice hybrids in the last 40 years. Among them there were 10 three-line rice hybrids occupying more than 667,000 ha since 1990 (Qing and Ai 2007).

The China state government and Hunan provincial government established the CNHRRDC (previously Hunan Hybrid Rice Research Center), a research institute with expertise in multiple disciplines related to hybrid rice, facilities and equipment.

Close collaboration and strong links among public research institutes, seed production businesses, and extension agencies created an effective network with clearly defined roles and responsibilities. China has established an efficient and coordinated infrastructure for breeding, seed production, certification, and distribution.

Several agencies affiliated with the government, research organizations, and academia organized extensive comprehensive training programs for breeders, seed producers, extension workers, and commercial production farmers. Demonstration of hybrid rice yield improvement has been essential for the successful extension of hybrid rice technology. Once convinced by the performance of hybrid rice, farmers were then trained in seed production and high yielding cultivation. More than one-fourth of farmers were trained for hybrid rice technology in China's southern rice growing regions in addition to more than 400,000 farmer technicians (CAAS/HAAS 1991). In addition to working with industry specialists, the government successfully raised awareness about hybrid rice among the general population through workshops, technical briefings, frontline demonstrations, field tours, and mass media campaigns.

The government at the state, province, prefecture, and county level established a reward and recognition mechanism for hybrid rice researchers, seed producers, and extension personnel (Yuan 1993). For example, in 1981 China awarded the "*Indica* Three-line System Hybrid Rice Technology" program with its first Extraordinary-class National Invention Prize (Li and Xin 2000). Others who have made significant contributions to hybrid rice technology since the 1980s also have been rewarded at state and provincial levels.

Technological Generation and Uptake

Adequate and effective seed production infrastructure has been the foundation for China's success in hybrid rice technology. China's MOA established minimum seed quality standards in 1985. This has ensured the long-term maintenance of genetic purity of parental lines and F1 seeds in addition to the quantity of hybrid seed supply.

Chinese rice scientists identified ecological regions for adaptability and grain quality preferences. Based on China's experience, different ecological rice-growing regions or markets need rice hybrids with different quality and biotic/abiotic resistance. Rice hybrids that perform well in one region may not be useful in another rice growing region. Therefore, regional research and extension infrastructures were established for hybrid rice breeding and commercialization. Before commercial release, a new hybrid must pass a multi-location and regional trial for two seasons, and a production demonstration in the farmer's field.

Pilot regions were identified for each eco-geographic region to demonstrate the new hybrid rice technology. These pilot regions were identified after taking into account the availability of well-trained and capable personnel, weather parameters, the extent of irrigation area, present yield levels, and prevailing management practices. Extensive on-farm demonstrations, large-scale public awareness campaigns, concerted multi-disciplinary approaches, and national and/or regional funding support were organized. For example, demonstration plots comparing hybrid rice with inbred rice varieties were set up in target areas to introduce the concept of hybrid rice to traditional farmers in the mid-1970s in China.

Key Issues for Future Hybrid Rice Production

In spite of the success of hybrid rice in the past decades, this technology faces a number of challenges. Increasing urbanization has brought significant change in rural social structures as the majority of the educated young and middle-aged labor force has been moving to the metropolitan area for jobs with more financial opportunities. Moreover, the biggest rural labor flow into urban regions came out of the largest rice producing provinces in China. The diminished quality and quantity of the remaining rural labor force has made extension and production of hybrid rice a more difficult endeavor. For example, seed producers must have a certain level of education and a good understanding of seed production techniques. With agricultural reforms and social structural changes, China needs to establish a new system for agricultural innovations, technical extension, and social services to accelerate the new research innovations and to promote China's hybrid rice technology to a higher level (Xu and Shen 2003).

Another challenge pertains to environmental stresses. The foundation of rural field facilities, including the irrigation water reservoir system, have become more fragile; soil erosion resulting from long-term chemical fertilizer applications is another threat to rice farming in China. Also, with changes in races or biotypes, hybrid rice has gradually lost resistance to disease and insects. Therefore, Chinese hybrid rice breeders are continuously working to develop hybrids with multiple disease and insect resistance (Yuan, Virmani and Mao 1989; Zhou, Deng and Li 2008). With the advance of biotechnology, the development of new traits in hybrid rice breeding should be an immediate task for overcoming the challenges from increasing biotic or abiotic pressure, the increasing fertilizer application, the ever decreasing water supply, and more severe drought from global warming. This will enhance the sustainability of hybrid rice technology and reduce environmental pollution from fertilizers and pesticides.

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