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# Hybrid Rice Breeding in China

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**Abstract:** Hybrid rice technology in China was developed in three stages. From the 1950s onwards, hybrid rice researchers, as typified by Yuan Longping, sought out a feasible approach to utilizing rice heterosis, and developed the three-line *indica* hybrid rice. Led by the government, the hybrid rice technology R&D teams adopted the research mode of "large-scale cooperation" (大协作), and accomplished technical innovations in the three-line system, selective breeding, and production of hybrid seeds. In the ensuing decade, Yuan Longping and others discovered the photo-thermo sensitive genic male sterility (PTGMS) of rice and developed PTGMS lines, turning highly advantageous two-line rice breeding from scientific vision into reality. Over the next twenty-five years, China's super-rice breeding program integrated the conventional, three-line, and two-line breeding methods with modern molecular biotechnology methods. For nearly half a century, China made outstanding attainments in acquiring quality strains that yielded enormous economic and social benefits. Throughout this process, factors such as urgent social demand for increased grain production and scientific research cooperation provided significant impetus.
**Keywords:** hybrid rice, breeding technology, China, Yuan Longping

**摘　要**：中国杂交水稻技术的发展经历了三个主要的阶段：自 1950 年代，以袁隆平为代表的杂交水稻研究者探索出水稻杂种优势利用可行性路径，发明了籼型三系杂交水稻。在政府主导下，杂交水稻技术研发团队形成了"大协作"的科研模式，实现了三系配套关、良种选育关和制种关的技术创新。随后十年，袁隆平等发现水稻温光敏雄性不育现象并育成温光敏不育系，两系法育种从科学设想成为现实，具有明显的优越性。此后的 25 年，中国超级稻育种计划将常规选育、三系、两系选育方法和分子生物技术方法等现代技术统一起来。近半个世纪以来，中国的优良品种取得了突出成就，获得了巨大的经济效益和社会效益。在此过程中，社会对粮食增产的迫切需求、科研协作等因素起到了重要的推动作用。
**关键词**：杂交水稻，育种技术，中国，袁隆平

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## 1 Introduction

China accounts for over 21% of the world's entire population, yet has less than 10% of the global acreage of available arable land (Yu 2011, 5). Since 1964, research into rice hybridization, exemplified by the endeavors of the team led by Yuan Longping 袁隆平, has undergone the process "from three-line, to two-line, to super rice" (从三系、二系到超级稻), and augmented the average yield of rice by more than 20% (Zhu 2001). This achievement alleviated the long-standing food shortage in China, effectively mitigating the people-land contradiction, and contributing greatly to rice breeding worldwide.

Published in 1991, *The Development of Hybrid Rice in China* (*Zhongguo zajiao shuidao de fazhan* 中国杂交水稻的发展), compiled by the Chinese Academy of Agricultural Sciences (CAAS), systematically elucidated how China developed three-line hybrid rice breeding technology from 1964 to 1990, and evaluated the contributions of the institutions and individuals concerned. *The Development History of Hybrid Rice in Hunan: 1964–2000* (*Hunan zajiao shuidao fazhanshi: 1964–2000* 湖南杂交水稻发展史：1964～2000), compiled by the Hunan Provincial Department of Agriculture and published in 2001, recounted the research, promotion, and application of hybrid rice in Hunan during this period. Over twenty biographies of Yuan Longping (Xie 1990; Yao 2002), starting with the one published in 1990 by Xie Changjiang 谢长江, former first deputy director of the Hunan Hybrid Rice Research Center, have focused on Yuan's research into hybrid rice, bringing together the data collected by researchers through interviews with Yuan. These works thus provide many valuable clues to the history of the research into hybrid rice in China. In December 2010, the author of this article completed his doctoral thesis "A Study of the Advancement of Hybrid Rice Technology in China [1964–2010]" (Zhongguo zajiao shuidao jishu fazhan yanjiu [1964–2010] 中国杂交水稻技术发展研究［1964～2010］) (Li 2010). Research into hybrid rice in China has also been described in English in such publications as "Hybrid Rice in China" and "Strategy of Hybrid Rice Breeding" by Yuan Longping (1986; 1987), and "Forty Years' Development of Hybrid Rice: China's Experience" by Cheng Shihua 程式华 and others from the China National Rice Research Institute (2004). As regards works by scholars beyond China, *Hybrid Rice Technology: New Developments and Future Prospects* by S. S. Virmani (1994), and *Hybrid Rice-The Journey* by Robin Andrews (2017) have evaluated the history and international impact of China's hybrid rice programs.

At the very beginning, the academic community could not agree on whether or not rice exhibited heterosis.[2] In the 1950s, the classic textbook *Principles of Genetics* written

2 After two genetically different parents are crossed, $F_1$ hybrids outperform the parents in viability, growth vigor, resistance, adaptability, and high yield, which is referred to as heterosis.

by the American geneticists Edmund W. Sinnott and I. C. Dunn highlighted that self-pollinating crops such as rice did not exhibit heterosis (Sinnott and Dunn 1958). In contrast, as early as 1926, J. W. Jones, an American breeding expert, first discovered and proposed rice heterosis in breeding practice. Later, such scholars as B. S. Kadem from India, A. Alim from Pakistan, F. B. Broun from Malaysia, and Okada M. 冈田子宽 from Japan reported on the heterosis of rice (Yuan 2002, 1). In 1960, researchers from the Zhejiang Academy of Agricultural Sciences (ZAAS) and Zhejiang Agricultural University asserted that "crossbreeding is one of the significant ways to breed rice,"[3] and "as long as the correct parents for hybridization are selected and the hybrid progenies are directionally selected and cultivated, there is every likelihood that new varieties will be created to satisfy current production needs" (Seed Research Laboratory, Crop Breeding and Cultivation Institute, ZAAS 1960, 6, 9).[4]

## 2 Early research on rice hybridization in China

In the 1950s, many countries, such as the United States, Japan, India, the Soviet Union, and the Philippines, pursued research on rice crossbreeding. The research techniques carried out in China included asexual and sexual hybridization, the latter involving interbreeding, inter-subspecific hybridization, and distant hybridization.

As early as 1926, Ding Ying 丁颖 (1888–1964) from the College of Agricultural Sciences, Guangdong University (the present-day School of Agriculture, Sun Yat-sen University) had already employed common wild rice species in Guangdong and the locally cultivated "Zhuzhan" variety to breed "Zhongshan No. 1," the first novel late-season variety containing ordinary wild rice genes (Wu 2005). This pioneering attainment in China marked the world's first success in transferring the tolerance of wild rice to harsh environments into cultivated rice. Starting from 1953, Liu Chengguo 刘承国, Zhang Yiqun 张轶群, and others from the Hunan Agricultural College conducted systemic research at the Qiaowan Commune in Xiangxiang, Hunan Province, on the hybridization and breeding of *indica* and *japonica* rice varieties, including interbreeding, *indica*-and-*japonica* crossbreeding, and their distant hybridization (Liu, Zhang, and Wu 1959). For the selection of parents for hybridization, it was considered that for better results pairing should be made between complementary types that have a distant genetic relationship, distinctive ecological differences, the most desirable traits, and the least undesirable traits (Zhang, Ouyang, and Xie 1962, 16). In 1958, the Qiaowan Commune established an experimental farm for rice crossbreeding.

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3 "杂交育种是水稻育种的重要途径之一。"

4 "只要正确决定杂交亲本，在杂种后代进行定向选择和培育，创造出符合当前生产需要的新品种是完全可能的。"

**Figure 1:** Ding Ying (right) instructing Wu Zhuonian 吴灼年 how to experiment with rice under long photoperiod conditions in a large net house of the Laboratory of Rice Ecology, CAAS, in 1963 (Guo 2011).

From 1952 to 1959, Yang Minghan 杨明汉 from South China Agricultural College was committed to hybridizing rice and barnyard grass, and cultivating the "thousand-grain-ear" variety (千粒穗). He believed that "distant hybridization between different genera of gramineous rice can integrate the most valuable economic traits of different gramineous genera and species into a far superior and more promising variety (hybrid) than interbreeding" (Yang 1962, 24).[5]

A team led by Lu Peifan 卢培藩, from Guizhou Academy of Agricultural Sciences, and Chen Baowen 陈宝文 and Li Dingmin 李鼎民, from Guangxi Academy of Agricultural Sciences, explored the hereditary variation of interbred rice progenies and stated that "the selection of hybrid progenies and the selection and pairing of parents are primarily premised upon the hereditary variation of hybrid rice progenies' traits. Grasping the hereditary variation of hybrid rice progenies' traits can help avoid detours in crossbreeding and accelerate the cultivation of new varieties" (Chen and Li 1964, 5–12).[6] Still relying on I. V. Michurin's heredity theory to interpret the hereditary variation of hybrid progenies, although Chen and others recorded their test data in a quantitative manner, their analysis remained confined to the qualitative level and was unable to explain the hereditary variation of hybrid progenies.

In the mid-to-late 1950s, based on traditional breeding experience, breeders formed

5 "禾本科植物水稻异属间的远缘杂交，能将不同种属的禾本科植物品种中最有价值的经济性状结合在一个品种之内（杂种），它具有比品种间杂交更为巨大的优越性和无限广阔的前途。"
6 "水稻杂种后代性状的遗传变异规律，是正确的选择杂种后代和选配亲本的主要依据。掌握水稻杂种后代性状的遗传变异规律，可使杂交育种工作少走弯路，加速新品种的育成。"

their basic ideas on how to study the heterosis of hybrid progenies regarding such traits as the growth period, grain number, seed setting rate, plant height, and thousand-grain weight, and reached a consensus on test paradigms in terms of materials, methods, operation, data, and results analysis. "Heterosis, heading period, and thousand-grain weight are commonly deemed as the core of research on rice crossbreeding" (Mo 1962, 90),[7] and this laid a solid foundation for the later development of rice hybridization.

## 3 Yuan Longping and the development of three-line *indica* hybrid rice

Yuan Longping was born on September 7, 1930 in Beijing. He majored in genetics and breeding at the Department of Agronomy, Southwest Agricultural College, and after graduation in 1953 taught at Anjiang Agricultural School in Huaihua, Hunan. Based on his experience in teaching courses on genetics and breeding, Yuan conducted grafting experiments on sweet potatoes and other crops, though none of these yielded asexual hybrids with excellent economic traits. The period from the "Great Leap Forward" from 1958 to 1962 on to the 1970s witnessed unprecedented growth in demand for grain in China. The pressure of this social demand and the development of crossbreeding technologies of crops such as corn in other parts of the world quickly turned Yuan's attention from "asexual hybridization" to the exploration of high-yield rice breeding. In July 1961, during the selective breeding of seed rice, Yuan discovered a natural hybrid rice plant, a solid fact testifying to "self-pollinating rice having heterosis" (Yuan 1966, 185).[8] This discovery spurred Yuan to make use of heterosis. A hybrid strain can only be pollinated by exotic pollen when it is male sterile,[9] and this is the prerequisite for rice to complete self-hybridization. Hence, Yuan inferred that this natural hybrid rice plant stemmed from cross-pollination. Considering "uncracked anthers" (花药不开裂) to be a common feature of male infertility for many crops, Yuan, together with his wife and students, searched for male-sterile rice plants one by one at noon on clear days during the heading stage.

For two years, Yuan examined more than 14,000 ears and uncovered six male sterile plants among four different varieties. A further two years of research and observation revealed the genetic law of rice male sterility, and in 1966 Yuan published "Male Sterility of Rice" (Shuidao de xiongxing buyuxing 水稻的雄性不孕性) in *Chinese Science Bulletin* (*Kexue tongbao* 科学通报) (Yuan 1966, 185–188). The paper clearly propounded

7 "杂种优势问题、抽穗期问题、千粒重问题普遍被作为水稻杂交育种研究的中心问题。"
8 "自花授粉的水稻存在杂种优势。"
9 Rice, with monoecious flowers, is pollinated and fertilized by pollen from the same flower in order to reproduce. Male sterility means that the degenerated male organs are unable to form pollen or can only produce abortive pollen, thus rendering self-seeding impossible; however, the normal female organs can be fertilized and produce seeds with normal fertile pollen. A strain with such characteristics belongs to the male sterile line.

**Figure 2:** Yuan Longping and his assistant in the test field in Anjiang.[10]

the view that "rice has heterosis, the *indica-japonica* hybrids in particular."[11] Yuan was keenly aware that the difficulty of "artificial emasculation" (人工去雄) was the bottleneck for rice hybridization, and that to take advantage of rice heterosis it was necessary to first develop seed production technology to mass-produce hybrids—the utilization of male sterility was thus a vital solution based on research trends and the results of crop breeding using heterosis. In addition, drawing on the model of corn crossbreeding, he proposed the scientific concept of the three-line method for crossbreeding rice for the first time in China.

The "three-line" system, the basis for utilizing rice heterosis, includes the male sterile line, male sterile maintainer line, and male sterile restorer line, known in short as the sterile line (A), maintainer line (B), and restorer line (R). The "three-line" system involves the following three steps. First, cultivate a sterile line using a few "male sterile plants" (雄性不育植株) of rice. Then, through selective breeding, cultivate a maintainer line, a conventional type of rice that can 100% preserve the male sterility trait of the sterile line. Finally, find the restorer line, another conventional rice, and hybridize it with the sterile line. Thus, the hybrid progenies will fully restore male fertility and self-seeding ability, and the $F_1$ hybrid seeds, which have more advantages in yield increase, can be produced for farmers to apply to field production without having to resort to any other complicated technical measures. A schematic diagram can clearly outline the technicalities of the three-line hybrid system (Figure 3). In 1968, the Japanese scientist Shinjyo Chou 新城长友 first completed the three-line system of *japonica* hybrid rice, though this promising research was shelved due to unresolved technical issues of seed

10 http://news.cctv.com/20070518/101225.shtml.
11 "水稻具有杂种优势现象，尤以籼粳杂种更为突出。"

production and $F_1$ hybrid heterosis (Yuan 2002, 1).

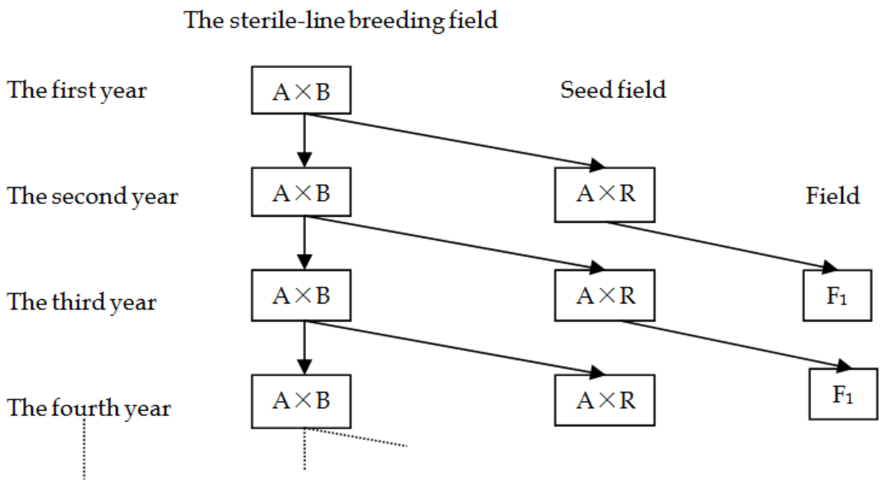


**Figure 3:** The relationship of the three lines' application in production.

Breeding of the sterility line was the key to breakthroughs in three-line technology. From 1964, when the first sterile rice plant was found, to 1970, Yuan, together with Li Bihu 李必湖, performed over 3000 experiments of test crossing and backcrossing using more than 1000 varieties of conventional rice and the first sterile rice plant and its progenies. Unfortunately, though, they were unable to produce a rice strain that could maintain 100% sterility. The "Nanguangzhan" sterile material (C-system sterile material), first discovered by Yuan, displays nuclear sterility,[12] which is generally controlled by a pair of recessive nuclear genes, while the fertile varieties belong to its restorer line, but no maintainer line was found. Thus, sterility could not be ensured, preventing the material from being directly put into use. Yuan was not discouraged by the failure of his six-year-long endeavors, however. His analysis had revealed that the genetic relationship between the Nanguangzhan strain and the variety used for test crossing was too close, and the genetic difference slight, so distant hybridization should be the solution by means of ferreting parent materials with distant genetic relationships. Thereupon, Yuan prioritized "seeking wild rice seeds and utilizing distant wild rice" (寻找野生稻种子，利用远缘野生稻) as the primary focus for the research group, and instructed researchers such as Li Bihu to hunt for new sterile materials with genotype S (*rr*) to replace the C-system sterile materials with genotype S (*rr*). In November 1970, guided by the technician Feng Keshan 冯克珊 from the

12 The hereditary male sterility of rice that can be applied to genetic breeding includes cytoplasmic male sterility, nuclear male sterility, and cytoplasmic-nuclear male sterility. Nuclear male sterility refers to sterility controlled only by nuclear genes and is unrelated to cytoplasm, a common phenomenon in nature.

Nanfan Base Nanhong Farm, Li Bihu carried out a search for wild rice and eventually found the "wild abortive" cytoplasm (Hunan Provincial Department of Agriculture 2001, 20–22), which was the key to the three-line system. Cytoplasmic-nuclear male sterility was found in the "wild abortive" sterile materials, only occurring when there was the concurrent existence of sterility genes in both cytoplasm and nucleus. This type of sterility has both the maintainer line, with cytoplasmic fertility genes and nuclear sterility genes, to maintain sterility, and the restorer line, with cytoplasmic fertility or sterility genes and nuclear fertility genes, to restore the fertility of the first-generation hybrid, thus realizing the three-line system. Hence, sterile plants could be obtained through distant hybridization (including interspecific hybridization and *indica-japonica* inter-subspecific hybridization), hybridization between varieties of geographically distant and different ecological types, natural mutation, and artificial mutation. Then, based on the principle of nucleus substitution, a sterile line could be produced using multi-generation backcrossing. In this process, the already cultivated sterile line undergoes multi-generation test crossing, selective backcrossing, or simultaneous stable transformation, thus breeding the new sterile line for cultivation purposes.

Yuan Longping and others bred the sterile line of Erjiunan No. 1 and the homologous maintainer line. Subsequently, multiple institutions in China cultivated ten major types of sterile lines that were grown over large areas (Zhu et al. 2006, 9). Researchers summarized six qualities required to make an excellent sterile line, which served thereafter as the technical standard for breeding sterile lines.

In 1972, the focus of three-line breeding research turned to the maintainer line, the bridge enabling the inheritance of rice male sterility and the central link of the three-line system. Several conditions were emphasized for selecting the parents of the maintainer line: distant genetic relationship with the restorer line, excellent combining ability, superior resistance, high rice quality, outstanding outcrossing traits, and one of the parents being a strong maintainer. Breeding was conducted first through the crossbreeding of an available maintainer line and one or several high-quality parents, from the progenies of which a new maintainer line was selected. Single crossing and composite crossing were employed as the hybridization methods. Single crossing was to hybridize two maintainer lines with their own characteristics, from the offspring of which suitable single plants were selected for test crossing and backcrossing. This simple crossing pattern could help accelerate breeding and improve a few traits for some sterile lines. The Xinxiang B maintainer line produced through single crossing exhibited high quality and excellent maintainer traits. In a few cases, although the parents or restorer lines with some desirable trait that possessed minor fertility restorer genes could not act directly as backcrossing parents, they served as hybrid parents to cross with the maintainer line, and from them individual plants with this desirable trait could be selected for test crossing (Lei, You, and Zheng 1986, 16–21). Though time-consuming and difficult to conduct, this composite crossing could potentially breed a new sterile line with comprehensive desirable traits. For instance, Longtefu A displayed great combining ability and had a high outcrossing rate, though it was unstable in fertility. Fujian Agriculture University undertook composite crossing using Zhenshan 97B, Digu B, and Longtefu B, and after multi-generation backcrossing, yielded the T55A sterile line, which retained the above-mentioned merits of Longtefu A and maintained stable fertility (Pan 2000, 3–4).

The final goal of heterosis utilization can be realized by the restorer line, the heterosis of which embodied all the research aims. The breeding methods included test-cross screening, hybridization, irradiation-induced mutation, and others, the former two being the most commonly used ones. From 1976, China started to collaborate with the International Rice Research Institute (IRRI). With the development of international exchanges and cooperation, large quantities of hybrid rice seeds and parent materials were introduced from China to many countries for research and the production of hybrid rice. At the same time, some rice germplasm resources of great value were introduced from abroad, such as IR24, IR26, IR661, IR30, Gu 154, Taiyin No. 1, Indonesian paddy rice, Miyang 46, Shuiyuan 287, and IR9761-19-1 (Chinese Academy of Agricultural Sciences and Hunan Academy of Agricultural Sciences 1991, 195), which were employed by Chinese researchers as restorer lines to cultivate a number of ideal hybrid rice combinations. In the early 1970s to the early 1980s, typical examples include such combinations as Nanyou No. 2 and Weiyou No. 6, their restorer lines having been imported from the IRRI and some Southeast Asian countries after large amounts of test-cross screening, and which belong to middle-season rice and late-maturing late rice. Shanyou 63 and Shanyougui 33 were the typical cross combinations from the early 1980s, with crossbred restorer lines and well-developed traits of resistance, rice quality, and adaptability. In the mid-1980s, Weiyou 35 and Weiyou 49 emerged as pioneering combinations, while in the 1990s, success in cultivating hybrid early rice, exemplified by Weiyou 402 and Jinyou 402 with their early-maturing restorer lines, overcame the dilemma of breeding technology "being early-ripening but low-quality, or high-quality but late-ripening" (早而不优、优而不早). The development of hybrid rice reveals that the development of the three-line hybrid rice and the replacement and change of combinations were linked to the improvement and development of restorer lines. Hence, the breeding of restorer lines was instrumental in developing three-line hybrid rice.

In July 1973, Zhang Xiancheng 张先程 from Guangxi Agricultural College and others were the first to discover a restorer line with high heterosis, IR24. At this point, a decade of research on rice male sterility in China finally realized the *indica*-type three-line system thanks to the discovery and transformation of the "wild abortive" cytoplasm.

Despite the success of the three-line system, only high-heterosis combinations could truly realize the value of large-scale application. According to the goals of breeding at that time, only those combinations the hybrid offspring of which showed yield heterosis could be selected. In 1974 and 1975, the repeated experiments and collective efforts of multiple provincial cooperative research groups helped to identify the basic laws of high-heterosis hybrid combination. Yuan Longping first bred the high-heterosis combination Nanyou No. 2, followed by the selective breeding of Shanyou No. 2 by the Pingxiang Institute of Agricultural Sciences, Jiangxi, Nanyou No. 6 by the Hunan Cooperative Research Group, and Weiyou No. 6 by Zhou Kunlu 周坤炉.

Low seed production became the next problem that breeders had to address, as large-scale cultivation would not be possible without doing so. As mentioned above, although Japan had completed the three-line system of *japonica* hybrid rice in 1968, it could not be widely cultivated primarily due to low seed production (Chinese Academy of Agricultural Sciences and Hunan Academy of Agricultural Sciences 1991, 288). In the early stage of the three-line system, seed production could only yield about 90 kg/hm$^2$. In-depth research was thus conducted on such key technologies as the overall planning of "the safe flowering stage, sowing-time interval, and florescence regulation" (安全扬花期、播差期、调节花期), the improvement of the outcrossing rate, purification, and quality control. As a result, seed production output increased alongside the continuously upgraded high-yield supporting technologies, and by 1983 exceeded 1500 kg/hm$^2$. In 1986, with improved super-high-yield hybrid rice seed production technology, the outcrossing rate increased from 30% to about 50%, and that in high-yield areas reached 85.2%. As a result, seed production yield reached 4500 kg/hm$^2$, the highest being 7386 kg/hm$^2$ (Hunan Provincial Department of Agriculture 2001, 71–73), removing the obstacles to the large-scale cultivation of hybrid rice (Table 1).

Among the above hybrid rice varieties, Shanyou 63, Shanyou 64, Shanyou No. 6, Weiyou 64, Gangyou 22, and II You 838 were the most widely cultivated, reaching a maximum of over ten provinces. In particular, for fifteen years from 1986 to 2001, almost all the rice producing areas of southern China cultivated Shanyou 63, with an annual planting area of over 760,000 hectares, eventually reaching an annual maximum area of 6.813 million hectares, and a cumulative area of 60.617 million hectares, thus overtaking the main hybrid rice varieties (Yang, Cheng, and Shen 2005, 6–7).

With quality varieties of hybrid rice having been obtained, the cultivation of hybrid rice became the last step for heterosis utilization. The cultivation technologies required for hybrid rice in China can be summarized as follows: (1) select the appropriate

**Table 1: Largest areas of the cultivation of hybrid rice post 1983**[13]

| No. | Name | Variety | Breeding institution | Leader | Earliest appraisal time | Average yield (kg/hm$^2$) | Cumulative cultivation area ($10^3$hm$^2$) |
|---|---|---|---|---|---|---|---|
| 1 | Shanyou 63 | *Indica* three-line | Sanming Academy of Agricultural Sciences, Fujian | Xie Hua'an | 1984 | 7500 | 62,642 |
| 2 | Shanyou 64 | *Indica* three-line | Zhejiang Seed Company; Wuyi County Agriculture Bureau; Hangzhou Seed Company | Chen Kunrong 陈昆荣 | 1986 | 6750 | 12,913 |
| 3 | Weiyou 64 | *Indica* three-line | Anjiang Agricultural School, Hunan; | Yuan Longping | 1985 | 14,250 | 11,864 |
| 4 | Gangyou 22 | *Indica* three-line | Crops Research Institute of Sichuan Academy of Agricultural Sciences; Rice Research Institute of Sichuan Agricultural University | | 1995 | 9075 | 9297 |
| 5 | Shanyou No. 2 | *Indica* three-line | Pingxiang Institute of Agricultural Sciences, Jiangxi | Yan Long'an | 1978 | 5250 | 8442 |
| 6 | Shanyou No. 6 | *Indica* three-line | Pingxiang Institute of Agricultural Sciences, Jiangxi | | 1983 | 6750 | 7949 |
| 7 | II You 838 | *Indica* three-line | Sichuan Institute of Nuclear Technology Application | | 1995 | 9000 | 6781 |
| 8 | Weiyou No. 6 | *Indica* three-line | Hejiashan Seed Stock Station, Hunan | Zhou Kunlu | 1978 | 5625 | 6467 |
| 9 | D You 63 | *Indica* three-line | Sichuan Agricultural University | | 1987 | 7500 | 6401 |
| 10 | Shanyou 10 | *Indica* three-line | China National Rice Research Institute; Taizhou Academy of Agricultural Sciences, Zhejiang | Ye Fuchu 叶复初 et al. | 1989 | 6000 | 6163 |

combinations based on local conditions, such as different ecoregions; (2) upgrade seedling-raising techniques to cultivate tillers and strong seedlings; (3) develop the technique of spreading soft-tray seedlings; (4) promote ridging cultivation of hybrid rice in low- and middle-yield fields; (5) cultivate ratooning rice after the harvest of hybrid middle-season rice; and (6) increase the application of organic fertilizers and

13 *Source:* Data from Database for Chinese Rice Varieties and Their Genealogy, National Rice Data Center, available at http://www.ricedata.cn/variety/.

increase the ratio of phosphorus-potassium fertilizer (Chinese Academy of Agricultural Sciences and Hunan Academy of Agricultural Sciences 1991, 60–83). From 1984, such techniques as formula fertilization by soil testing and foliage dressing were promoted for the cultivation of hybrid rice, greatly boosting fertilizer utilization (Hunan Provincial Department of Agriculture 2001, 131–150).

**Table 2: Hybrid rice planting area and per unit yield in China (1976–1997)**[14]

| Year | Total rice acreage ($10^6hm^2$) | Hybrid rice | | | Conventional rice | | | The yield increase rate of hybrid rice compared with conventional rice (%) |
|---|---|---|---|---|---|---|---|---|
| | | Area ($10^6hm^2$) | Percentage of total rice acreage (%) | Per unit area yield (kg/hm$^2$) | Area ($10^6hm^2$) | Percentage of total rice acreage (%) | Per unit area yield (kg/hm$^2$) | |
| 1976 | 36.20 | 0.14 | 0.38 | 4200.0 | 36.04 | 99.62 | 3469.5 | 21.2 |
| 1977 | 35.53 | 2.07 | 5.82 | 5383.5 | 33.46 | 94.18 | 3514.5 | 53.2 |
| 1978 | 34.40 | 4.27 | 12.40 | 5353.5 | 30.13 | 87.60 | 3780.0 | 41.6 |
| 1979 | 33.87 | 5.00 | 14.76 | 5260.5 | 28.87 | 85.24 | 4069.5 | 29.3 |
| 1980 | 33.87 | 4.81 | 14.21 | 5296.0 | 29.06 | 85.79 | 3940.5 | 34.4 |
| 1981 | 29.93 | 5.13 | 17.15 | 5317.5 | 24.80 | 82.85 | 4113.0 | 29.3 |
| 1982 | 33.07 | 5.60 | 16.93 | 5865.0 | 28.07 | 84.07 | 4447.5 | 31.9 |
| 1984 | 33.13 | 6.73 | 20.32 | 6375.0 | 26.40 | 29.68 | 4774.5 | 33.5 |
| 1986 | 32.27 | 8.93 | 27.68 | 6600.0 | 23.34 | 72.32 | 4539.0 | 45.4 |
| 1988 | 32.00 | 12.67 | 39.58 | 6600.0 | 19.33 | 61.42 | 4539.0 | 45.4 |
| 1990 | 33.07 | 15.93 | 48.18 | 6675.0 | 17.14 | 51.82 | 5314.5 | 25.6 |
| 1992 | 31.73 | 15.47 | 50.86 | 6636.0 | 16.26 | 49.14 | 4986.0 | 33.0 |
| 1994 | 30.67 | 15.73 | 51.29 | 6670.0 | 14.94 | 48.71 | 5149.0 | 30.6 |
| 1996 | 30.61 | 15.53 | 50.74 | 6740.0 | 15.08 | 49.26 | 5326.0 | 26.5 |
| 1997 | 30.86 | 15.68 | 50.81 | 6765.0 | 15.18 | 49.19 | 5408.0 | 25.1 |

## 4 The two-line method and super rice

Yuan Longping came to the realization that "the three-line method for rice hybridization is classic, with the merit of having stable sterility and the demerit of fertility being restricted by the restorer-maintainer line relationship, with few restorer lines and fewer maintainer lines. Thus, the probability of yielding excellent combinations is low" (Yuan 2016, 3404).[15] Only through novel breeding materials and innovative technologies and methods could new breakthroughs be made in the yield

14 *Source:* Data from the China National Hybrid Rice R&D Center.

15 "三系法杂交水稻是经典的方法，优点是不育性稳定，不足之处是其育性受恢保关系制约，恢复系很少，保持系更少。因此，选到优良组合的机率较低。"

and quality of hybrid rice. In 1973, Shi Mingsong 石明松, an agricultural technician at the Shahu Seed Stock Station in Mianyang, Hubei, discovered the first photosensitive genic male-sterile rice. After years of hard work, in October 1985, the photosensitive genic male-sterile line cultivated by the Hubei Provincial Cooperative Group passed appraisal. At this point, Yuan held that this line could effectively solve the technical problems of heterosis utilization for inter-subspecific hybridization and lead to the "two-line system," and in 1987 published an important article "Strategy of Hybrid Rice Breeding" (Yuan 1987, 1–3). In this paper, he mapped out hybrid rice breeding into three stages, progressing from the first stage of heterosis utilization for interbreeding based on the three-line method, to the second stage of using heterosis utilization for *indica-japonica* inter-subspecific hybridization based on the two-line method, and finally to the third stage of distant heterosis utilization based on the one-line method. These three stages were chronologically interconnected, and complementary to each other, the theory developing progressively, while the method became gradually simplified. This idea established the "pattern or model" (模式或模型) for hybrid rice research, and was designated the "Yuan Longping Idea" (袁隆平思路)[16] among the hybrid rice scientific community. It offered a theoretical grounding for the road map for developing two-line hybrid rice technology, inferring that the two-line method "is expected to gradually replace the three-line method in the near future" (Yuan 1987, 1),[17] a guiding role that was not limited to hybrid rice research alone. Two-line hybrid sorghum, two-line hybrid rape, two-line hybrid cotton, and two-line hybrid wheat were all successfully cultivated under the inspiration of the theory of two-line hybrid rice.

As scientists obtained batches of new genic male sterile resources with fertility conversion, practice proved that there were promising prospects for this type of sterility to be applied in cultivating two-line hybrid rice, with steady increases in hybrid rice yield and improvement of rice quality. Thus, not only could procedures of seed production be streamlined, but also labor and costs be reduced. Additionally, these materials enriched the cytoplasmic types of two-line sterile materials, greatly boosting the confidence of researchers working to produce two-line hybrid rice. On this basis, they explored further and bred a series of new photo-thermo sensitive genic male sterile (PTGMS) lines (Table 3).

Compared with the three-line method, which always used the cytoplasmic-nuclear male sterile line, the two-line method utilized PTGMS lines to multiply and produce hybrids rather than using maintainer lines. Under different weather conditions, the sterility of PTGMS lines could be transformed into fertility, omitting the step of hybridizing the maintainer and sterile lines to produce the sterile-line offspring.

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16 The "Yuan Longping Idea" was first put forward by Yin Huaqi 尹华奇 (1994), as has been widely referred to in academic circles.

17 "预计在不久的将来便可逐步取代三系法。"

**Table 3: Main PTGMS lines**[18]

| No. | Name of PTGMS lines | Type | Breeding institution |
|---|---|---|---|
| 1 | 3111S | *Japonica* | Huazhong Agricultural University |
| 2 | 8902S | *Indica* | Wuhan University |
| 3 | WD-1S | *Japonica* | Wuhan University |
| 4 | 7001S | *Japonica* | Anhui Academy of Agricultural Sciences |
| 5 | C407S | *Japonica* | Institute of Crop Breeding & Cultivation, Chinese Academy of Agricultural Sciences |
| 6 | 1541S | *Japonica* | Yichang Institute of Agricultural Sciences, Hubei |
| 7 | AB0195 | *Japonica* | Institute of Agricultural Sciences, Dongxihu District, Wuhan, Hubei |
| 8 | 6334S | *Japonica* | Central China Normal University |
| 9 | W741S | *Indica* | Hubei Academy of Agricultural Sciences |
| 10 | N5047S | *Japonica* | Hubei Academy of Agricultural Sciences |
| 11 | W6154S | *Indica* | Hubei Academy of Agricultural Sciences |
| 12 | 8801S | *Indica* | Institute of Agricultural Sciences, Xiantao, Hubei |
| 13 | K7S | *Indica* | Guangxi Academy of Agricultural Sciences |
| 14 | K9S | *Indica* | Guangxi Academy of Agricultural Sciences |
| 15 | K14S | *Indica* | Guangxi Academy of Agricultural Sciences |
| 16 | 2177S | *Indica* | Institute of Agricultural Sciences, Guangde County, Anhui |
| 17 | Pei'ai 64S | *Indica* | Hunan Hybrid Rice Research Center |
| 18 | M901S | *Indica* | Sanming Institute of Agricultural Sciences, Fujian |
| 19 | Hunong 5S | *Indica* | Hunan Agricultural College |
| 20 | 1647S | *Japonica* | Crop Research Institute, Beijing Academy of Agriculture and Forestry Sciences |
| 21 | Lunhui 422S | *Japonica* | Hunan Hybrid Rice Research Center |
| 22 | 165S | *Indica* | Pingxiang Institute of Agricultural Sciences, Jiangxi |
| 23 | 1286S | *Indica* | Jiangxi Academy of Agricultural Sciences |
| 24 | F131S | *Indica* | Institute of Agricultural Sciences, Ganzhou, Jiangxi |

18 *Source:* Data from Yan (1999, 16).

Two-line hybrid rice was an important avenue for heterosis utilization due to its advantages of simple procedures, free combinations, and no negative effects of sterile cytoplasm. Consequently, the cultivation area of two-line hybrid rice increased rapidly, expanding from 180,500 hectares in 1996 to 5,440,400 hectares in 2013. During this period, the percentage of two-line hybrid rice in total hybrid rice cultivation rose from 0.92% to 33.59% (Hu, Tian, and Xu 2016, 1), making it an indispensable component of hybrid rice production.

Three major technical problems remained to be solved for crossbreeding methods of *indica-japonica* rice: the difficulty in controlling segregation of the character of hybrid offspring, the low hybrid seed setting rate, and the difficulty in stabilizing the heterosis of hybrid offspring (Yuan 1999, 29). In 1981, Japan launched their program of super-high-yield rice breeding, planning to augment the per unit yield by 50% within fifteen years. In 1989, the International Rice Research Institute[19] also initiated a breeding program of new plant type rice aimed at increasing the per unit yield by over 20% (referred to as the super rice breeding program). These targets were not met, however, due to the great difficulties posed by these technical problems (Fei et al. 2014, 5634).

Fortunately, super hybrid rice breeding researchers in China completely overcame the technical bottleneck caused by these issues, making *indica-japonica* hybridization a conventional method for rice breeding, and providing a major breakthrough in hybrid rice breeding technology (Chen et al. 2008, 13). In the mid-1980s, Yang Shouren 杨守仁 and Chen Wenfu 陈温福 from Shenyang Agricultural University took the lead in proposing the concept of breeding new varieties of super-high-yield rice with hybridization technology (Zheng 2003, 590). In 1996, the Ministry of Agriculture commenced the two-phase "China Super Rice Breeding" project. Using the middle-season rice in the Yangtze River Basin as a test case, the first and second phases were to breed rice varieties with yields of $10.5\times10^3$ kg/hm$^2$ and $12\times10^3$ kg/hm$^2$ by 2000 and 2005, respectively.[20]

In 1997, Yuan Longping designed a super-high-yield plant type, characterized by high canopy, dwarf spike layer, and medium and large panicles, and proposed a technical method for the cultivation of super hybrid rice. In 2000, he put forward the idea that the two-line method could breed a new super-high-yield combination with a yield 20% higher than three-line hybrids of the time. However, in practice, the direct inter-subspecific hybridization generated a strong "negative heterosis," degrading the

19 Located in the Philippines, the International Rice Research Institute (IRRI) is an autonomous non-profit organization for rice research and education, affiliated to the Consultative Group on International Agricultural Research (CGIAR).

20 The National 863 Program inaugurated the third phase of the super hybrid rice research program in 2005: 2006–2015, $13.5\times10^3$ kg/hm$^2$; the Ministry of Agriculture launched the fourth phase of the super hybrid rice program in 2013: 2016–2020, $15\times10^3$ kg/hm$^2$.

ideal plant type during the technical process, greatly undermining the yield-increasing effect. Faced with this scenario, Yuan developed the selective breeding principle of "seeking the close genetic relationship among the distant ones and seeking the short plants among the high ones" (远中求近，高中求矮) (Chen et al. 1999, 23). In 2003, he proposed in detail the technical method for improving both morphology and heterosis. The plant type designed as "high canopy, dwarf spike layer, and medium and large panicles" was better able to give full play to the canopy photosynthesis of the flag leaf at the canopy in the late growth stage, thereby increasing daily output and achieving the highest efficiency of dry matter production. He also noted that there were abundant sources of inter-subspecific hybrid rice, and the potential to increase yields by 30% compared with the inter-specific hybrid rice (Yuan 2003, 3). Other breeders of the same period from Fujian Province, such as Xie Hua'an 谢华安, proposed to adopt the technical method of improving both morphophysiology and heterosis to cultivate three-line super hybrid rice.

Through over two decades of joint efforts, breeders represented by Yuan Longping were committed to making innovations on the basic theoretical research of super rice breeding, and made many fruitful explorations into breeding practice, creating new plant types and excellent super rice germplasm. At the beginning of the twenty-first century, such varieties of first-phase super rice as "Liangyoupeijiu" were cultivated up to a maximum annual area of around 1,000,000 $hm^2$, with an average yield of $8.3\times10^3$ $kg/hm^2$. In all, five phases of super hybrid rice breeding were launched in succession, achieving a yield index of $16\times10^3$ $kg/hm^2$ (Yuan 2018, 71–73). As of 2019, as confirmed by the Ministry of Agriculture and Rural Affairs, multiple research teams have bred ninety high-caliber super hybrid rice varieties that have been named, including forty-seven *indica* three-line hybrid rice varieties, one *japonica* three-line hybrid rice variety, and fifty-two *indica* two-line hybrid rice varieties.

## 5 Large-scale scientific research cooperation and national investment

On January 14, 1956, the Central Committee of the Communist Party of China held a national conference on intellectuals in Beijing. Premier Zhou Enlai delivered "A Report on the Issues of Intellectuals" (Guanyu zhishifenzi wenti de baogao 关于知识分子问题的报告), in which the task of keeping up with world-level advanced science and technology was proposed, and the important status of intellectuals was affirmed (Zhou 1956). In December of that year, the "Long-term Outline for Science and Technology Development (1956–1967)" (1956–1967 nian kexue jishu fazhan yuanjing guihua gangyao 1956～1967 年科学技术发展远景规划纲要) was approved by the central government for implementation, proposing the development goals for the scientific and technological community at the national level. This offered favorable policy conditions for later nationwide large-scale scientific research cooperation on hybrid rice. Through the direct intervention of the government, various agricultural research institutions were founded, and a vast quantity of human, material, and financial resources were pooled to undertake nationwide research on hybrid rice in the form of a "mass movement" of "large-scale scientific research cooperation." As a result, theoretical research, technical testing, and results appraisal and promotion concerning hybrid rice were able to form a relatively coherent system in a short period of time. In this way, the research, development and implementation patterns of "three-line" hybrid rice was established under a highly planned economic system, contributing significantly to the development of hybrid rice technology that was still in the early stage of research and development.

The earliest hybrid rice research institution was the "Research Group for Male Sterility of Rice", composed of Yuan Longping and his two students Yin Huaqi and Li Bihu, which was set up after Yuan's publication of "Male Sterility of Rice" in *Chinese Science Bulletin* (Yuan 1966). Zhao Shiying 赵石英, Director of the Ninth Bureau of the State Scientific and Technological Commission, recognized from that paper the significance of research on rice male sterility to national food production. In the name of the commission, an official document was issued by him to the Hunan Provincial Scientific and Technological Commission and Anjiang Agricultural School instructing them to support Yuan's scientific research. Accordingly, the Hunan Commission dispatched personnel to Anjiang Agricultural School for more details. In April 1967, Yuan drafted "The Anjiang Agricultural School Plan for Breeding Rice Male Sterile Lines" (Anjiang nongxiao shuidao xiongxing buyunxi xuanyu jihua 安江农校水稻雄性不孕系选育计划), which was submitted to the Qianyang Scientific and Technological Commission and the Hunan Commission. The Hunan Commission granted him financial support, providing a research fund of 600 *yuan* in the first year. The Hunan Provincial Department of Agriculture also approved his request to keep Yin and Li as his assistants at Anjiang Agricultural School. In June 1967, with Yuan in charge and the assistance of Yin and Li, the "Research Group for Male Sterility of Rice" was formally established. Yuan was spared criticism during the "Cultural Revolution," thanks to Director Zhao's official document supporting Yuan's research, thus enabling the group to carry on hybrid rice research.

In 1969, the Hunan Provincial Scientific and Technological Commission and the Department of Agriculture decided to place the "Male Sterility of Rice" research project under the supervision of the Hunan Academy of Agricultural Sciences, increasing the number of participating institutions to three and the number of researchers to nine. In 1970, Hua Guofeng 华国锋, first secretary of the Hunan Provincial Party Committee, issued an instruction that Yuan's research group should "entrust the research on rice

**Figure 4:** Yuan Longping (second from right) Yin Huaqi (first from right) from Hunan, Yan Long'an (second from left) from Jiangxi, and Zhang Xiancheng (first from left) from Guangxi working in a hybrid rice test field in 1976 (Sun 2015).

male sterility to the masses" (Li 1977, 8),[21] and the professionals-and-farmers mass movement of "three-line" rice breeding immediately sprang up in Hunan Province. At the end of 1970 the well-known rice breeder Zhou Kunlu joined the cooperative research group as a member of the first batch of research collaborators who went to Hainan Island with Yuan's team to engage in cooperative research.

In April 1972, the State Scientific and Technological Commission upgraded hybrid rice technology research to a national key research subject. To realize the technical conception of the "three-line system" as soon as possible, multiple cooperative research groups were founded by agricultural research departments and some colleges and universities from nineteen provinces, municipalities, and autonomous regions under the leadership of the Chinese Academy of Agriculture and Forestry Sciences and Hunan Academy of Agricultural Sciences. In October 1972, the first conference on national cooperative research on hybrid rice was held, symbolizing the establishment of the national large-scale cooperative research group. During the eleven years from 1972 to 1982, nine such conferences were convened, involving over a thousand participants from all over the country (Chinese Academy of Agricultural Sciences and Hunan Academy of Agricultural Sciences 1991, 202–262). Those attending were all key personnel in the field of hybrid rice research, and the conferences provided them with the opportunity to share their research experiences and progress, and exchange different germplasm materials for scientific experiments. In addition, these meetings enabled the demonstration and promotion of technologies and achievements to be standardized, theoretical and technical problems in research practices to be collectively discussed, and the next steps in research to be identified. Such large-scale scientific research cooperation brought together theoretical viewpoints of all kinds, enriched researchers' vision, and efficiently brought uniformity to technical standards. Through this large-scale cooperation, the hybrid rice technology paradigm swiftly took shape, along with the production and dissemination of knowledge, technology, and concepts. This large-

21 "把水稻雄性不育的研究交给群众去搞。"

scale research cooperation in Hunan and nationwide not only accelerated the progress of the "three-line" system, but also hugely increased the probability of screening excellent "three-line" and hybrid combinations, raising public understanding of hybrid rice on a national scale. In 1973, the "three-line system" of hybrid rice was successfully completed. The cooperative research team utilized the "wild abortive cytoplasmic sterile materials" provided by Yuan's team to successfully breed many desirable sterile lines, resulting in a series of *indica* hybrid rice combinations, such as "Nanyou," "Weiyou," and "Shanyou," which enabled the rapid application of hybrid rice technology to field production.

In 1970, the mass movement of "three-line" hybrid rice breeding was expanded from Hunan Province to the whole country. In the spring of 1971, "three-line" hybrid rice cooperative research groups were established in Jiangxi, Guangxi, Guangdong, Xinjiang, and Fujian, bringing in "wild abortive" cytoplasmic materials from Hunan, thus initiating truly nationwide research. In February 1971, many provinces sent researchers to Hunan and the Nanfan base in Hainan to acquire experience in such cooperative research. Xie Hua'an from Fujian and Yan Long'an from Jiangxi were the first to be sent to the cooperative research group during this period of national large-scale cooperation. Other examples include Wu Renshan 伍仁山 from Jiangxi, Huang Ming'an 黄明安 from Xinjiang, Li Dingmin 李丁民 from Guangxi, Yang Jubao 杨聚宝 from Fujian, Yang Xianlin 杨显林 from Hubei, and the thirty-two researchers sent by agricultural sciences institutions from Anhui, Zhejiang, Shanxi, and Shanghai to the Nanfan base (Chinese Academy of Agricultural Sciences and Hunan Academy of Agricultural Sciences 1991, 202–208). In addition to offering free "wild abortive" materials to their counterparts, Yuan's team held training classes to equip newcomers with the theories and technologies of "three-line" breeding.

The breeding of sterile lines was central to hybrid rice development at that stage and yielded substantial results. In 1972, using the "wild abortive" materials, researchers in Jiangxi, Hunan, and other provinces bred the first batch of male sterile and maintainer lines of *indica* rice, such as Erjiu'ai, Zhenshan 97, Erjiunan No. 1, and 71-72. In 1974, Zhou Kaida 周开达 and others from Sichuan Agricultural University, and Zhu Yingguo 朱英国 from Wuhan University bred a stable Gang-type sterile line and a Honglian-type sterile line, respectively. Practice proved that it was easier to acquire cytoplasmic male sterile materials by taking common wild rice as the female parent, and common cultivated rice as the male parent. However, it was much harder to gain cytoplasmic male sterile materials through reciprocal crossing—even when individual male sterile plants had been obtained, it remained difficult to breed sterile lines with stable fertility (Zhu 2000, 359). Through the joint endeavors of multiple provincial cooperative research groups and repeated experiments during 1974 and 1975, a feasible method was developed for realizing high-heterosis hybrid combinations through heterosis utilization.

In 1971, the hybrid rice project was listed as a national cooperative project, and the "wild abortive" materials were distributed to rice research institutions nationwide. In October 1973, at the rice research conference held in Suzhou, Yuan presented a paper entitled "Progress of Breeding 'Three-Line' Rice Using 'Wild Abortive'" (Liyong "yebai" xuanyu "sanxi" jinzhan 利用"野败"选育"三系"进展) (Yuan 1973), signifying the success of the three-line system of Chinese *indica* hybrid rice (sterile line, maintainer line, and restorer line). In the meantime, Yan Long'an bred the sterile line Zhenshan 97A using "wild abortive."

In April 1971, the first training course on rice male sterile lines was organized in Hunan Province, where Yuan and other researchers from the research groups pioneered the dissemination of hybrid rice science and technology. It was during this training that the Hunan Provincial Rice Male Sterility Cooperative Research Group was formally established, with five institutions enrolled: Hunan Academy of Agricultural Sciences, Hunan Agricultural College, Department of Biology of Hunan Normal University, Anjiang Agricultural School, and Hejiashan Seed Stock Station. The division of labor was also made clear. Anjiang Agricultural School, Hunan Academy of Agricultural Sciences, and Hejiashan Seed Stock Station, the first three members of the group, continued to breed the male sterile and maintainer lines of "Nanguangzhan" and "wild abortive" materials. Hunan Agricultural College conducted physiological and biochemical research into rice male sterility, and the Department of Biology of Hunan Normal University was responsible for the morphological and anatomical research of rice male sterility. The number of researchers in the group then increased to fifteen. In June, the Hunan Provincial Bureau of Agriculture and Forestry held a second phase of training classes, making a total of 141 trainees in the two phases. In Hunan, over 150 institutions were involved in the research in 1971, with a total of over 800 participants (Hunan Provincial Department of Agriculture 2001, 12–13).

Researchers exploring first-generation hybrid rice technology would often exchange information, updating all the research teams on the latest progress. Hunan Academy of Agricultural Sciences, the first to initiate research on hybrid rice technology, provided preliminary training for researchers in agricultural science and technology nationwide, and offered 13,000 kg of sterile rice seeds for free to twelve provinces and regions for experimental purposes. The guarantee of manpower in such large-scale national research cooperation testified to the beneficial role of the planning system. During the thirty-four years of research from 1966 to 2000, the government mobilized over 170,000 personnel, among whom were around 500 scientific personnel directly developing hybrid rice technology, 350 testing workers, 11,000 scientific personnel promoting the technology, and 162,000 farmer technicians. It would have been impossible to organize research teams of this magnitude to complete such complex scientific undertakings over such a long period without the planning system as a foundation.

Further emphasis was given to the funding, status, and organizational management of scientific research. From 1971 to 1990, the Ministry of Agriculture and Forestry listed the hybrid rice technology research project among the national major scientific projects every single year, and invested a total of over twenty million yuan, mainly for the "Nanfan" breeding research. According to available statistics, during the thirty-four years from 1966 to 2000, China directly invested about twenty million yuan into research and development of hybrid rice technology, with about a further twenty million yuan in indirect funding; nearly 600 million yuan was invested in the promotion of hybrid rice technology, as well as such resources as 600 million kilograms of fertilizer, 15.55 million kilograms of fuel, and 115,000 kilograms of gibberellin[22] (Hunan Provincial Department of Agriculture 2001, 185–186). National leaders inspected the Hunan Hybrid Rice Research Center many times, and made three grants totaling forty million yuan from the Prime Minister's Fund. The Hunan Provincial Government also provided supporting funds over the same period. Considering the dearth of financial and material resources available, these investments served as a powerful material guarantee for the rapid development of hybrid rice.

Despite increases in the absolute amount of funding, however, under the planned economy system, China's agricultural research funding, which was only funded by the government, was generally on a downward trend once inflation is taken into account. Researchers' morale also was undermined as their remuneration was inconsistent with their endeavors, leading to a serious brain drain (Hu et al. 1996, 168–170). In addition, during the period of "mass movement"-style research cooperation, the duplication of labor at the same level led to waste of resources, and the practice of planting by blindly following trends resulted in widespread poor harvests. The progress of cooperative research was also hindered by other factors, such as the ownership of research results, distribution of remuneration, use of materials, and credit for publications.

## 6 Conclusion

Although China was a relative latecomer when compared to some foreign countries in the development and understanding of hybrid rice, by the new millennium, foreign scholars could note that "the country [China] has not only embraced hybrid rice but also become the world leader in its research and development. . . . China was the first country to seriously investigate the technology's potential" (Barclay 2007, 22). This change was inseparable from the powerful driving force of society's needs, as China

22 Gibberellins (GAs) are plant hormones that facilitate the growth, germination, flowering, and fruiting of such crops as potato, tomato, rice, wheat, cotton, soybean, tobacco, and fruit trees, thus significantly increasing production.

was faced with the threat of hunger over several decades. Famine in the late 1950s once again claimed the lives of tens of thousands of Chinese people, highlighting the direct threat of food security to the country's stability and development. Hybrid rice technology, which was aimed at breeding improved varieties and increase yields, was developed in response to this situation.

Chinese experts benefited from developments in hybrid rice technology internationally, and fully exploited such advantages as local natural resources and research cooperation to give full play to the technological research and development advantages of the system of "large-scale teams" (大团队). Yuan Longping dedicated himself for over five decades to hybrid rice research, contributing enormously to the breeding and promotion of three-line and two-line hybrid rice, and research into super rice. His findings transcended the traditional concept of "self-pollinating crops [such as rice] lacking heterosis," leading to the proposition of a new theory of hybrid rice breeding, enriching the theory and technology of crop genetics and breeding.

The development and widespread cultivation of hybrid rice ushered in a new avenue for substantial increases in rice production, bringing huge economic and social benefits. In November 1987, when Amadou-Mahtar M'Bow, Director-General of UNESCO, awarded Yuan Longping the 1987 Science Prize in Paris, he extolled the attainments of hybrid rice as the "second green revolution," following the example of semi-dwarf rice cultivated in the early 1960s. Yuan replied that: "This scientific achievement belongs not only to China, but also to the world, which will hopefully make a greater contribution to addressing hunger that still confronts mankind" (Chinese Academy of Agricultural Sciences 1991, 201).[23]

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23 "这一科研成果不仅属于中国，也属于世界。希望这项成果为解决人类仍然面临的饥饿问题作出更大的贡献。"

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