3. Develop networks of laboratories using different mutagens, eg., T-DNA, transposons, or retrotransposons. Here the main task is to work out the process of pooling information from individual networks and to provide a unified channel for networking with laboratories using different approaches such as naturally occurring alleles, deletion mutants and gene silencing as mutant sources.

The workshop is a serious effort to bring together people, resources and expertise in the field of Rice Functional Genomics and will be a part of the “International Working Group of Rice Functional Genomics” (http://www.irri.org/genomics/index.htm).

The economic contribution of the Global Rice Gene Machine will become apparent when research groups and companies exploit useful genes and gene control sequences.

A Global Rice Gene Machine will develop a capacity in genomics that would otherwise be beyond the capabilities of individual laboratories. The economic contribution of the Global Rice Gene Machine will become apparent when research groups and companies exploit useful genes and gene control sequences either in transformation breeding or as molecular markers in classical breeding.

Due to the similarities in gene sequence, gene structure, gene order and gene function among all cereals and grasses, understanding rice genes will greatly facilitate understanding genes from other cereals.

Acknowledgments

Thanks to our other team members, Kerrie Ramm, Ramani Shivakumar, Shuting Pan, Kathryn Smith, Shamsul Hoque, Marcia Margis, Leakhla Henry, Xue-Rong Zhou for their valuable contribution and to Drs. T.J. Higgins and Michael Ayliffe for critical reading of the manuscript. We gratefully acknowledge support from RIRDC, NSW Agricultural Genomics Centre and GrainGene (a strategic alliance between AWB Limited, CSIRO, and the Grains Research and Development Corporation). Thanks to our collaborators from SPIC Science Foundation, Chennai, India.

The term “hybrid rice” refers to the first-generation (F₁) offspring of a cross of two genetically diverse parents that yields (performs) better than both parents due to manifestation of a biological phenomenon known as hybrid vigor or heterosis. Farmers can benefit from hybrids if the F₁ (hybrid) seeds are used for commercial cultivation; the grains produced on the commercial hybrid crop are unusable as seed for the next crop because, in the subsequent generations, the yield advantage expressed in the first generation offspring of a hybrid is significantly reduced due to inbreeding depression.

Besides, grains in the subsequent generations are not uniform due to genetic segregation and are therefore unacceptable to both farmers and consumers. The high-yielding rice varieties (HYVs) used widely by farmers around the world since the late nineteen sixties are true-breeding, fixed-inbred lines developed by rice breeders using the hybridization method of breeding. These are not hybrid varieties in the strict genetic sense.

Over the past three and a half decades, almost the entire irrigated rice land in tropical Asia has been covered by modern high-yielding inbred rice varieties, with the farm-level yield approaching the potential that can be obtained with optimum economic efficiency. In most of the countries with predominant irrigated ecosystem, the growth in rice yield has slowed down drastically in the 1990s. The situation is alarming since rice demand continues to increase because of increasing population and improving incomes of the poor. On the other hand, agricultural land area is shrinking, and irrigation water is being diverted to other uses. We have to produce more rice from less land with less water and less chemicals. To meet the challenge of increased rice production and alleviation of hidden hunger, we need rice varieties with higher yield potential. China was the first country in the world to have successfully developed rice hybrids. Commercialized since 1976, these hybrids have made substantial contribution to increasing rice production in the country through their 15-20 percent higher yield than inbred HYVs. Since 1979, the International Rice Research Institute (IRRI) has been actively engaged in research for
developing rice hybrids to increase rice yields beyond the level of inbred HYVs in the tropics. This paper describes our experiences in developing and using this technology in and outside China and discusses future outlook.

The Chinese experience

China initiated research in 1964 to explore the prospects of hybrid rice technology under the leadership of Prof. Yuan Long Ping, who is recognized internationally as the “Father of Hybrid Rice”. It took him until 1976 to release rice hybrids for commercialization in farmers’ fields. Thus, the country became a pioneer in this area of research and development.

Rice, being a self-pollinated crop (possessing female and male floral organs in the same floret or flower), requires a male sterility system in the female parent to facilitate bulk hybrid seed production. This breakthrough was achieved in 1970 when a male sterile plant (with abortive pollen grains) was found in a population of wild rice (*Oryza sativa* f. *spontanea*) growing in Hainan Island in China (Fig. 1). The male sterility of this plant was maintained by some elite rice cultivars, which, when crossed with it, resulted in male sterile hybrid progenies.

Plant breeders call such cultivars “maintainers”; these are used to multiply CMS lines and develop new male sterile lines in their genetic background by following the backcross breeding procedure. Several other elite rice cultivars, especially those introduced from IRRI, resulted in fertile hybrid progenies. Such cultivars are called fertility restorers and are used as male parent to develop commercial hybrids. Plant breeders call this male sterility system as cytoplasmic male sterility (CMS) system.

Chinese scientists called this system as “three-line” hybrid breeding system because it involved the use of male sterile (A), maintainer (B), and restorer (R) lines. Over the years, Chinese hybrid rice scientists have bred numerous A, B, and R lines to develop commercial hybrids, which yield 1-2 t ha⁻¹ higher yield than the popular inbred HYVs, which yield 5-8 t ha⁻¹ under farmers’ field conditions. Concurrently, hybrid rice scientists also developed seed production technology for rice hybrids in two steps (Fig. 2) using A, B, and R lines. Seed yields in 1975 were very low (274.5 kg ‘ha⁻¹) and uneconomical.

However, a concerted effort of rice agronomists, seed production experts, and seed growers resulted in a seed production technology that now helps to give seed yields ranging from 1.5 to 6 t ha⁻¹ (mean of 2.75 t ha⁻¹).

Between 1976 and 1991, hybrid rice area in China increased to 17.6 million ha, which constituted 54 percent of the total rice area. During the past decade, total rice area in China has decreased by 2-3 million ha because farmers have adopted other cropping and/or farming systems due to the economic liberalization policies of the government. This has also affected the extent of hybrid rice cultivation. In 2001, about 15.5 million ha were planted to hybrid rice varieties, which produced 107 million t of paddy (average yield, 6.9 t ha⁻¹) compared with inbred HYVs planted to a similar area and producing 84 million t (average yield, 5.4 t ha⁻¹). The extra paddy production (23 million t) through hybrid rice can feed 60 million people (Ma and Yuan, 2002).

Besides, high-yielding hybrid rice also gives higher per-day productivity than inbred HYV since the former have identical or sometime even shorter growth duration. The increased rice production due to large-scale cultivation of hybrid rice in China has not only contributed to the country’s food security but has also helped in environment protection. This is because, otherwise, China would be required to cover about 6 million ha of additional marginal land for rice cultivation to feed its population.

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Since hybrid rice technology requires farmers to use fresh hybrid seeds every crop season, China has developed an extensive seed industry to produce and market the estimated 310,000 t of hybrid rice seeds every year. Since hybrid seed production is more labor-intensive than inbred rice seed production, this technology has generated additional rural employment opportunities in the country. The country also exports about 6000 t of hybrid rice seeds annually to Vietnam and is exploring other such possibilities in other countries around the world.

**Outside China**

The Chinese rice hybrids and parental lines were tested in IRRI trials in 1979-1980 and compared with popular inbred HYVs in the tropics. These hybrids did not outyield the inbred checks because of their susceptibility to major tropical diseases and insects and therefore could not be used as such. Besides, the Chinese government had imposed restrictions in the sharing of hybrid rice breeding materials to other countries as well as IRRI.

Consequently, IRRI had to start from scratch to develop tropical rice hybrids. Experimental evidence was collected during 1980-81, which indicated that certain hybrids derived from elite rice cultivars in the tropics yielded 19-34 percent higher than the popular inbred check rice varieties (Virmani et al., 1982). Since then, a large number of parental lines and hybrids adapted to the tropics have been developed at IRRI and freely shared with public and private research institutions around the world which have developed close collaboration with IRRI. These collaborative research efforts have proven beyond doubt that even in countries outside China (Bangladesh, India, Indonesia, Philippines, Sri Lanka, Vietnam, Myanmar, Korea, Egypt, Mexico, Brazil, Colombia, etc.), rice hybrids can outyield the inbred HYVs by a margin of 1-1.7 t ha⁻¹ under farmers’ field conditions in irrigated rice ecosystem (Table 1). The other advantages of hybrids are their increased per-day productivity (Table 2) and increased fertilizer use efficiency over inbred HYVs (Fig. 3).

Recently, we have also gathered evidence (George et al., 2002) to indicate that certain hybrids can outyield inbreds in an aerobic rice ecosystem, in which rice is
cultivated under fully fertilized and irrigated upland (aerobic soil irrigated to maintain soil water at about field capacity), thus, showing their increased water use efficiency. Strong and well-developed root systems of hybrids (Fig. 4) should also make them more water-use efficient than inbreds under an irrigated ecosystem. Evidence from IRRI and Egypt (Fig. 5) shows stronger heterosis in rice hybrids under saline soil conditions than under normal soil conditions. IRRI is collaborating with rice scientists from India and the Philippines to explore the prospects of hybrid rice under certain rainfed lowland transplanted conditions. If hybrid rice spreads to half of the irrigated riceland in the humid tropics, global rice production can increase by at least 50 million t valued at US$6.25 billion.

To express their yield potential, hybrid rice needs to be managed somewhat differently than inbred HYVs, especially with regard to seedbed management, seedling number per hill, and spacing during transplanting (to economize on seed rate because seed is more expensive than inbred seed).

Even the nitrogen and potash management strategy in hybrid rice is somewhat different than inbred rice (Peng et al., 2002). Under favorable growing conditions, the higher yield of hybrid rice is attributed to greater biomass (total dry matter) production, whereas under sub optimal conditions (such as low radiation), a higher harvest index (ratio of dry matter in the grain to total dry matter) contributes to higher yield (Peng et al., 2002). Inadequate agronomic management of hybrid rice contributes toward their unstable performance under farmers’ field conditions.

Table 1. Yield of selected hybrids and inbred checks in trials conducted in different countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Hybrid Yield (g)</th>
<th>Inbred Yield (g)</th>
<th>Gain (g)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>3.48</td>
<td>2.64</td>
<td>0.84</td>
<td>32.4%</td>
</tr>
<tr>
<td>India</td>
<td>3.79</td>
<td>3.12</td>
<td>0.67</td>
<td>21.2%</td>
</tr>
<tr>
<td>Philippines</td>
<td>6.33</td>
<td>5.91</td>
<td>0.42</td>
<td>7.1%</td>
</tr>
<tr>
<td>Vietnam</td>
<td>5.85</td>
<td>5.07</td>
<td>0.78</td>
<td>15.3%</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>6.07</td>
<td>5.07</td>
<td>1.00</td>
<td>19.7%</td>
</tr>
</tbody>
</table>

Some of the first-generation rice hybrids, released prematurely in the national programs, gave higher yield than popular inbred HYVs, but these did not possess comparable grain quality. Consequently, farmers received a lower market price for their hybrid rice produce than inbred rice and therefore did not attain the anticipated profit. In contrast, some other first-generation rice hybrids (Mestizo in the Philippines and BRRI Dhan Hybrid 1 in Bangladesh) possessed grain quality comparable/superior to the inbred check variety and farmers had higher profitability by growing such hybrids.

There is no evidence to indicate that hybridity impairs grain quality, the latter depends on the quality of parental line used to make the hybrids (Khush et al., 1988). With conscious efforts and appropriate choice of parents, hybrid rice breeders are developing hybrids with any desired grain quality. Recently, a Basmati grain-type rice hybrid (Pusa RH 10) has been developed and released in India.

Adopting the major seed production guidelines developed in China, hybrid rice technology for the tropics was developed at IRRI in collaboration with national programs. This has been packaged in the form of a manual, a video and a CD and is available electronically at IRRI website (http://www.irri.org/hybrid). Its use in different countries has given seed yields ranging from 0.5 to 2.5 t ha⁻¹ (mean, 1.2 t ha⁻¹) in commercial seed production plots. Being somewhat
labor-intensive, it requires extra labor of 50-100-person days ha⁻¹ and provides opportunities for rural employment generation in Asia, especially for women. National programs are at various stages of development and use of this technology. The RiceTec Company in the US is involved in developing hybrid rice technology for the US and South America and has successfully mechanized hybrid rice seed production under labor-scarce US situation, obtaining seed yields of 1.5-2.5 t ha⁻¹.

Commercial hybrid rice seed production requires the active participation of the seed industry in national programs. Different countries are at different stages of seed industry development, which can operate under public, private, and/or NGO auspices. While public seed industries play a predominant role in handling hybrid rice technology in Vietnam, the private sector is very active in India, and all three sectors are seeking their participation in this enterprise in Bangladesh. It appears that private and NGO-based seed industries, including farmers’ cooperatives, would play a major role in hybrid rice seed production and marketing in free-market countries. During the past decade, more than 58 public, private, and NGO-based seed companies have started investing in hybrid rice research and/or seed production and marketing.

Economic assessment

Socioeconomic studies based on data collected from farmers who adopted hybrid rice in Bangladesh, Vietnam, the Philippines, and several states in India show that hybrid rice varieties do have 1-1.5 t ha⁻¹ yield advantage compared with the popular inbred varieties in farmers’ fields. However, this yield advantage does not necessarily translate into increased profitability if the grain quality of the hybrid were inferior to the popular inbred HYV. In some parts of India (e.g., Andhra Pradesh), the profitability difference between the hybrids and inbred HYVs was only marginal. Therefore, the commercial farmers would not be interested in adopting such hybrids. Subsistence and below-subsistence farmers who buy rice from the markets to meet the deficit (the gap between household needs and family production) were interested in adopting hybrids, even if these had some grain quality limitations. In the Philippines, where the grain quality of the first set of released hybrids was acceptable, the hybrid rice farmers earned US$235 ha⁻¹ more than the inbred rice farmers (Table 3). Studies also noted that with a seed yield of 1-1.5 t ha⁻¹ and a procurement price of US$0.6-1.00 kg⁻¹, hybrid rice seed production was more profitable than cultivating inbred rice varieties (Table 4).

Outside China, an important factor behind the high price of hybrid seeds at the farm level is the prevailing price in the market. With the faster adoption of hybrids and expansion of the seed market, the unit cost of processing and transport would go down, contributing to a reduction in the price of hybrid seed. The increase in seed yield with development and adoption of improved seed production technology will also help reduce seed price (Table 5).

The relatively faster pace of adoption of hybrid rice technology in Vietnam compared with other countries can be attributed to the role played by agricultural cooperatives. They supply hybrid seeds to farmers as loan in kind and recover the loan after harvest when farmers market their produce through the cooperative.

Thus, shortage of working capital to procure the costly hybrid seed did not constrain the adoption of hybrid rice technology in Vietnam.

Likewise, the Philippines government is providing 50 percent subsidy on high-cost hybrid rice seed to
facilitate adoption of the technology initially. This subsidy would be phased out in three years' time, when the price of seed is projected to be reduced due to the establishment of more efficient and productive mechanisms of hybrid seed production, processing, and marketing in the country. The government of India is currently providing support by allowing free sharing of parental lines of publicly bred rice hybrids with private seed companies and creating awareness of and demand for both public and private hybrids by conducting large-scale, front-line demonstrations on farmers’ fields. More direct support to the promotion of the technology is being visualized in the 10th Five-Year Plan of the country. Thus, different countries are facilitating the adoption of hybrid rice technology through policy support provided in different ways.

International network on hybrid rice

To expedite the development and use of hybrid rice technology in Bangladesh, India, Indonesia, Philippines, Sri Lanka, and Vietnam, IRRI has established an international network on hybrid rice in collaboration with the Food and Agriculture Organization of the United Nations (FAO), the Asia Pacific Seed Association (APSA), and China, with financial grant from the Asian Development Bank (ADB) since 1998. The network has helped these countries in i) establishing an effective regional collaboration; ii) organizing coordinated international hybrid rice trials (CIHRT) to share elite hybrids and parents; iii) strengthening national capacity for research, seed production, and technology transfer for hybrid rice; iv) generating technology locally; v) strengthening national seed industry and forging their links with IRRI through a Special Interest Group on Hybrid Rice formed by APSA; vi) conducting economic analyses of the technology and identifying policy options for support by the national governments; and vii) providing extensive technical assistance through consultancy missions. Myanmar, Korea, and Thailand have also joined this network in 2002 and several other countries inside and outside Asia (Egypt, Mexico, Brazil, Iran, Pakistan) have also expressed desire to join and expand this international network.

Extent of adoption of the technology

In China, the pace of adoption of hybrid rice technology was so fast that during 1976-91, it covered an average additional one million ha of rice area per year. In 1991, China grew 17.6 million ha (54 percent of its total rice area). Since then, the area of hybrid rice has stabilized at about 15.5 million ha (50 percent of total rice area). Outside China, the pace of adoption of this technology has been rather slow, since 1994, when certain hybrids were released in India, Vietnam, Philippines, and Bangladesh, the total area coverage has been a modest 700 000 ha.

The reasons for slow adoption are i) poor grain quality of some earlier released hybrids, ii) high price of hybrid seed, iii) inadequate supply and variable quality of hybrid seed, and iv) inadequate policy support of the national governments to promote the technology. Considering the fact that most of the rice-growing countries are self-sufficient in rice, their governments total rice area). Outside China, the pace of adoption of this technology has been rather slow, since 1994, when certain hybrids were released in India, Vietnam, Philippines, and Bangladesh, the total area coverage has been a modest 700 000 ha.

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are not paying much emphasis to higher yielding technologies; rather they are looking for better quality rice.

This is a shortsighted approach. As mentioned earlier, the higher yielding technologies are not only relevant to meet the future demand for rice; these are also important to save on land, water, and chemical inputs and to reduce unit cost of production of rice to enable it to compete in the world market during this era of globalization.

A sustained and adequate supply of hybrid rice seeds with acceptable quality requires an effective seed industry and easy access to seed production technology. In China, the government has developed a vast hybrid rice seed industry in the public sector during the past 25 years, which is closely linked to research institutions, which are developing the economically viable hybrid rice seed production technology. Outside China, the seed industry is still developing in different sectors (public, private, NGO and farmer cooperatives) and its strength varies from country to country.

The status of development of economically viable hybrid rice seed production technology is also variable. While India and Vietnam have developed such a technology, the Philippines, Bangladesh, and other countries interested to promote the technology are still developing it. The links between public-sector hybrid rice research institutions and the seed industry are not yet strong enough to support rapid expansion of the technology outside China. Besides, in free-market economies, market forces determine the pace of adoption of any technology.

**Future opportunities**

Researchers at IRRI and the national programs are working together to overcome the constraints experienced in the promotion of the technology. Parental lines possessing the desired grain quality and adequate level of disease/insect resistance are being developed.

There are indications that hybrid rice with enhanced yield levels can be developed using currently available *indica* rice parental lines and the newly developed new plant type (super rice) lines developed at IRRI from tropical *japonica* x *indica* crosses. Seed parents possessing higher outcrossing rate are being developed to enhance seed yields and reduce seed production costs.

An environment-sensitive genic male sterility (EGMS) system is now available to substitute for the CMS system to make hybrid seed production more efficient. This system involves the use of thermo- (TGMS) and/or photoperiod-sensitive genic male sterile (PGMS) lines in which expression of sterility is determined by specific temperature and/or daylength regimes, respectively.

TGMS/PGMS lines can become sterile or fertile, depending on the temperature and daylength conditions. They do not require maintainer lines to multiply them; rather, their seed multiplication is done by self-fertilization in a specific temperature and/or daylength regime. Rice hybrids developed by using TGMS/PGMS lines are also called two-line “Two-Line Hybrids”.

China has already started using this system in some commercial rice hybrids grown in about 1.5 million ha. IRRI has also developed some experimental rice hybrids for the tropics, which are in the initial yield evaluation trials; these should be ready for sharing with NARS during the next three years.

The efficiency of hybrid rice breeding and seed production can be further increased by using biotechnological tools Æ anther culture, marker-aided selection, transformation, and genomics. Biotechnology can also help develop novel approaches to breed true-breeding rice hybrids through the phenomenon of apomixis (seed formed on hybrids without sexual fertilization).

This research is being pursued at IRRI. If successful, this would put hybrid rice technology within the reach of even resource-poor farmers because buying fresh seeds of the apomictic hybrids every season will not be necessary. Certain countries outside China (India, Vietnam, Philippines, Bangladesh, Indonesia, Sri Lanka, and Myanmar) plan to expand hybrid rice area to about 2-2.5 million ha during the next five years.

The increased production through this greater area coverage can help reduce land and water use for rice production. The opportunities for growing hybrid rice to increase yields in aerobic and certain rainfed lowland subecosystems are also real. This should further contribute toward food security and environment protection by saving rice lands.

All these developments should enhance the participation of the seed industry in the production, processing, and marketing of hybrid rice seed. This would increase rural employment opportunities, especially for women. The regional collaboration established through the international network on hybrid rice would accelerate the pace of adoption of the technology in national programs in cooperation with FAO, APSA, and China.
Conclusion

Hybrid rice technology has made tremendous impact on rice production in China during the past 25 years. Experience outside China in the development and use of this technology is also encouraging. While the technology helps individual farmers to increase their production and income, it can also contribute significantly to the national economy by contributing toward food security, environment protection, development of seed industry, and increased rural employment opportunities. Therefore, this high-yielding technology is certainly a future, even though it is not the future.

Hybrid rice technology contribute significantly toward food security, environment protection, development of seed industry, and increased rural employment opportunities.

References


Antifreeze proteins enable organisms to avoid freezing under extreme conditions. The greatest diversity of known antifreeze proteins is in teleost fish and much work has gone into the understanding of these proteins and their applications.

Antifreeze proteins are an exciting model system for the study of protein–surface(ice) interaction. They have served as unique model structures in protein science and they are also useful tools in the study of fish physiology and behavior. Their emergence in some fish species has even provided a rare glimpse of de novo protein evolution in action.

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