Rice Breeding

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Abstract This chapter deals with breeding aspects of one of the most important crops for food security in the world. Initially it shows how diverse rice is with 22 species, different levels of ploidy and six diversity groups. The choice of parents for crossing, when having such wide genetic diversity available, requires careful characterization and evaluation of the germplasm as well as good knowledge and breeding skills to make the right decisions. Rice breeders have been very successful in improving the crop. Some milestones are: the contribution to the green revolution with the semi-dwarf varieties, the new rice plant type, hybrid rice, and the NERICA rice. Even though there was a series of breakthroughs the main breeding goals in most national programs remain similar since a long time ago: increasing grain yield potential, resistance to blast disease, grain quality, and drought tolerance. The main breeding method used to improve rice is the pedigree, but development of hybrids and population improvement were added to the breeder's portfolio. Breeders have been taking advantage of biotechnology tools to enhance their breeding capacity; however, many national programs are still struggling on how to integrate them into the breeding programs and how to balance the allocation of resources between conventional and modern tools. The chapter closes with information on the rice breeding capacity around the world, showing that rice breeders are widely distributed across all regions and the existing capacity, using the above mentioned information, will still be able to cope with the challenge of making genetic progress for one of the most important food security crops.

1 Introduction

Rice is the world's most important food crop with a total production around 600 million ton occupying 11% of the world's total arable land; it supplies 2,808 calories/person/day, which represents 21% of the total calorie supply. It is source

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of income for more than 100 million householders around the world (IRRI, 2002). It is one of the crops responsible for the so-called green revolution that happened in the 1960s and 1970s. In addition of having strong breeding programs in all different regions around the world, this crop has three Consultative Groups on International Agricultural Research (CGIAR) centers with the mandate to work with rice: the International Rice Research Institute (IRRI), with global mandate; the West Africa Rice Development Association (WARDA), with mandate to work in West Africa; and the International Centre for Tropical Agriculture (CIAT), with the regional mandate for Latin America.

International centers made a tremendous effort to educate and train rice breeders at the time of the green revolution. Today, 25–35 years later most of the rice breeders working in national programs around the world represent that period. The international germplasm evaluation nurseries [International Rice Testing Program (IRTP) and International Network for the Genetic Evaluation of Rice (INGER)] were excellent tools to provide new breeders with improved breeding lines as well as additional opportunities for training, including hands-on exercises on breeding techniques.

This chapter aims at proving general information on the following matters: the sources of genetic diversity available to breeders; criteria to be considered when selecting parental material to generate genetic variability for variety development; the most relevant breeding achievements; rice breeding methods used around the world, how biotechnology has been integrated into breeding programs, genetic seed production strategy; and elements related to the world's capacity to carry out rice breeding programs.

2 Genetic Diversity

The success of the breeding strategies relies heavily on the genetic diversity of the crop. Rice gene banks around the world exhibit a very large amount of genetic diversity present in farmers' cultivars, landraces, as well as in the genetic make up of the 22 *Oryza* species. At the IRRI, in Manila, Philippines, there are more than 108,000 accessions conserved (Jackson and Lettington, 2003); in addition, there are hundreds of rice accessions held in trust in other CGIAR centers; WARDA; CIAT; and International Institute for Tropical Agriculture (IITA). Almost as many accessions are preserved in genebanks in other Asian countries such as China, India, Indonesia, Philippines, and Thailand (Jackson et al., 1997). Furthermore, considering that the International Rice Genome Sequencing Project has identified more than 80,000 genes in the rice genome and that each gene has an unknown number of alleles, the conclusion is that breeders will continue to have useful genetic diversity to draw on for many generations to come as long as there is a good choice germplasm.

Rice belongs to the genus *Oryza* and the various attempts to classify it no agreement was obtained regarding the number and the names of the species belonging to this genus. In 1994, Vaughan (1994) published a handbook indicating

that the genus has 22 species. However, only *O. sativa* and *O. glaberrima* are cultivated. The number of chromosomes of the cultivated rice and its related species varies from 24 to 48, with the "*n*" number equal to 12. According to Morishima (1984), based on the chromosome paring in the meiosis, rice has the following genomes: AA, BB, CC, EE, and FF for the diploid species and BBCC and CCDD for the tetraploid species.

The two cultivated species, which are diploid ($2n = 24$), were domesticated under different environmental conditions. *O. sativa* was domesticated in South and Southeast Asia and has the species *O. rufipogon* and *O. nivara* as its direct ancestors. *O. glaberrima* comes from tropical West Africa and has *O. barthii* as progenitor. The former is cultivated throughout all the rice growing environments around the world. However, cultivation of the African species is confined to its region of origin.

Morishima and Oka (1981) divided the cultivated species in two groups called *indica* and *japonica* based on principal component analyses of 11 variety characteristics. Their study indicated that there was no specific characteristic that clearly distinguished the two groups; however, the existence of the two groups can be proved by combining two or more characteristics. Khush et al. (1984), using trisomics, observed a complete correspondence between *japonica* and *indica* linkage blocks; meaning, there was not a single case where genes located in one *japonica* chromosome were found in a different *indica* chromosome. Harushima et al. (2002) believe that the domestication process caused the differences between the two groups including their reproductive barriers. The evolutionary process gave these two groups their distinct characteristics such as tolerance to low temperatures and drought stress, responsiveness to fertilizers, ability to compete with neighboring plants, and photosynthetic capacity, among other things.

Based on geographical distribution, Morinaga (1954) described three morphological groups called *japonica*, *javanica,* and *indica*. Oka (1958) indicated that *japonica* and *javanica* groups can be considered as tropical and temperate *japonicas*, respectively. The former has tall varieties with heavy panicles (Glaszmann and Arraudeau, 1986). The ideal plant type designed by Khush (1994), which can help boost the rice yields by up to 30%, capitalizes on the genetic variability of this group.

A breakthrough related to rice genetic diversity groups was made by Glaszmann (1987) who analyzed 1,688 Asian traditional varieties using isozymes and identified six genetically distinct groups, which were called groups I–VI. Group I encompasses the varieties of the tropical regions classified by Oka (1958) as the "*indicas*". At the other extreme is group VI where there are the varieties adapted to temperate climates called "*japonicas*" by Oka (1958). The latter group includes most of the upland rice varieties.

As rice is cultivated all over the world, its diversity is also due to the wide range of ecosystems the crop is adapted to. According to IRRI (2002) one way of categorizing it is to distribute the ecosystems in four broad categories: irrigated, lowland, upland, and flood-prone. A combination of these ecosystems with different agro-ecological zones gives a very complex matrix in which rice genetic diversity has become available adapting naturally to meet farmers' demands.

Even though rice is a rich crop in terms of its genetic diversity, there are several reports in the literature indicating that the varieties released by the breeding programs in different parts of the world have a narrow genetic diversity basis. Cuevas-Pérez et al. (1992) and Montalban et al. (1998) presented results on irrigated and upland rice in Latin America, respectively, indicating that commercial varieties released for both systems had a narrow genetic base. Guimarães (2002) dissected the Brazilian rice varieties and arrived at the same conclusion. Mishra (2002), considering the breeding approaches used in India and the varieties released in the last 30 years, concluded: "the genetic base is narrowing and this is a matter of concern". Evidence was added by Rai (2003) when analyzing the 29 varieties released in the Indian Kerala State. He also pointed out that in Nigeria there is genetic uniformity within the upland rice varieties. Dilday (1990) showed similar results when analyzing the genetic diversity of the rice varieties released in the USA as well as Kaneda (1985) in Japan. However, as indicated before, these results do not suggest that this is true when looking at the rice species. For example, Sun et al. (2001) analyzed *O. rufipogon* and *O. sativa* using molecular markers and concluded that they still have a wide genetic variability with regards of number of alleles, number of genotypes, heterozygosity, and diversity among genes. In the cultivated species, they found only 4 exclusive alleles but in the wild species there were 78 of these alleles. These results indicate the wide genetic variability still present in the species, mainly in the wild relatives.

Second (1982) found large differences in allelic frequency between the *indica* and *japonica* species. Oka (1964) concluded that the genetic diversity is maintained within groups independent of whether there are crosses and recombination in the segregating generations. Junjian et al. (2002) used simple sequence repeat (SSR) markers and studied the genetic diversity between *indica* and *japonica*. They found similar average numbers of alleles: 4.4 and 4.3, respectively. However, the average genetic distance was greater for the *indicas*, which suggested a higher level of genetic variation for this group in relation to the *japonica*. The two wild species included in the study (*O. rufipogon* and *O. nivara*) fall outside of the range of cultivated species, suggesting the presence of unique alleles still to be used by breeders to exploit the between species variability. This knowledge has been exploited to increase the yield potential of commercial varieties (Xiao, Li, Grandillo, Ahn, Yuan, Tanksley, and McCouch 1998; Moncada, Martínez, Borrero, Gauch, Guimarães, Tohme, and McCouch 2001; Brondani, Rangel, Brondani, and Ferreira 2002).

The importance of having genetic diversity available is the possibility of making it useful to develop products that will have an impact at farmers' field level. Rice breeders have been exploiting this potential in many different and creative ways. There are a few examples where exploitation of wild relatives has produced significant results. The first opportunity to take advantage of the wild relatives' unique characteristics was through exploiting the existence of genes for disease and insect resistance. Khush (1977) used *O. nivara* as a source of resistance to grass stunt virus resistance and introduced it into IR28, IR29, and IR30 cultivars; also, from *O. rufipogon* the resistance to the viral disease called "tungro" was obtained.

Rice bacterial blight resistance was obtained from *O. longistaminata* and introduced in the commercial variety IR24 (Khush et al., 1990).

The first hybrid rice was developed based on a genetic cytoplasm male sterility system identified in the *O. sativa* L. *f. spontanea* in China (Shih-Cheng and Loung Ping, 1980). Khush (1994) combined different genetic groups (tropical *japonicas*, temperate *indicas*, and *japonicas*) in order to create a new rice type expected to increase the grain yield of commercial varieties by ~30%.

Rice is rich in genetic diversity and breeders have a wide choice when looking for parental materials.

3   Choice of Germplasm

One of the most difficult tasks in carrying out a successful breeding program is the choice of germplasm. To be able to develop a variety with a set of desirable characteristics rice breeders need to be sure that the source germplasm has desirable genetic variability. After the parents are chosen and the crosses are made there are almost no chances of new alleles appearing in the segregating populations.

To make the right choice of parental material to be used in a breeding program, breeders must clearly know the type of product to be developed; the characteristics of the species to be bred; the combining ability of the parents in case of hybrid cultivars; the environmental conditions of the target area; the social and economic aspects of the farmers and markets; and the different breeding approaches available to achieve the proposed goals. Today, an additional element to be considered is the legal aspect in relation to the materials to be used as parents.

In general, rice breeding programs have two major different end products. The first and the most common one is a pure line, which will be evaluated and released as a commercial variety. The second one is an inbred line that will be the parent of a commercial hybrid. An intermediate product may be a population with certain desirable characteristics that could be used for further improvement, for cultivars per se, or for line extraction.

If the target of breeders is to develop pure lines it is important to know the ability of the progenitor to transfer its characteristics to the segregating populations. An interesting example is the rice variety "Ceysvoni" from Surinam; it has a high level of resistance to blast and a good plant type as well as excellent grain type to Brazilian standards. However, when used in crosses with other upland and irrigated varieties, the different combinations do not produce high quality breeding lines. In general, all segregating populations are discarded before reaching homozygosis. It seems that some materials when used in crosses produce undesirable changes in the genetic composition of the resulting population. Another example is the cultivar BG90–2, a high-yielding irrigated rice variety. Every time this genotype was used in crosses, the resulting segregating populations did not seem to retain its yield potential and they were discarded before producing homozygous lines. Brondani et al. (2002) proposed combining this cultivar with wild species to identify yield-

related quantitative trait loci (QTLs). More information on combining ability of the progenitors is desirable to achieve the proposed goal.

In general, rice breeders, as well as breeders for other crops, tend to recycle and cross high-performing parents (e.g., elite × elite) among themselves and conduct maximum inbreeding when aiming at developing new commercial varieties. This strategy is based on the concept that self-pollinated crops have a large part of their genetic variance as additive variance. In addition, high-performing parents with reduced genetic variance present a higher probability of generating superior genotypes.

Another important aspect to consider is the genealogy of the parental material. In general, breeders avoid crossing parents with similar genetic make-up, because their combination will not produce a broad genetic variability limiting the possibilities of obtaining desirable gene combinations (desired genotype). If the final product is a hybrid, knowledge about the genealogy of the parents is crucial, since heterosis relies on genetic differences. Hybrid rice is produced based on cytoplasmic-genetic male sterility. It requires three types of breeding lines: a cytoplasmic-genetic male sterile line (A line), a maintainer line (B line), and a restore line (R line). Therefore, if the objective is to produce hybrid rice, knowledge of the general and the specific combining ability of lines becomes essential. Heterosis is based on genetic differences (among other factors), thus information on the genetic distance between A and R lines is fundamental to produce high-performing hybrids. Therefore, knowledge about the genealogy of the parental material is crucial.

To facilitate the development of economically high-yielding hybrids with all of the desirable agronomic traits it is also important to consider other characteristics when selecting the parental material such as aspects related to difference in grain type and shape, plant height, resistance to biotic and abiotic stresses. Hybrid rice seed production depends on a series of factors, including the coincidence in the flowering period of the male and female lines. It is important to have parents that complement each other well, with good specific and general combining abilities. This terminology was introduced by Sprague and Tatum (1941) to differentiate between the mean performance of a parent in crosses (general combining ability) and the deviations of individual combinations from the mean (specific combining ability). Knowledge of this behavior is more important when the non-additive effects are predominant.

To create a rice population, it is important to choose parental materials with high levels of genetic differences for the traits under selection. However, it is desirable to have also a low genetic divergence for the traits the breeder wants to keep in the population. An example of the use of such information in deciding between rice parents with tolerance to iron toxicity was presented by Khatiwada et al. (1996). "Azucena", IRAT 104, and "Moroberekan" were the cultivars with the best general combining ability for iron toxicity tolerance and were the recommended ones for elite × elite crosses.

The choice of parental material depends on the breeders' objectives, the desired type of product, the existing genetic diversity, and the information available, as well as the combining ability of the parents.

4 Major Breeding Achievements

4.1 The Rice Green Revolution

In the 1960s, scientists quickly realized that most tall traditional rice varieties lodged easily when nitrogen fertilization was applied, which was the major limitation to grain yield (Khush et al., 2001). The semi-dwarf (sd_1) IR8 was the first high-yielding rice variety developed from a combination between the Indonesian variety "Peta" and "Dee Geo Woo Gen" from Taiwan. The key factor responsible for the increase in yield potential was the improvement of the harvest index. However, even though IR8 had a major drawback regarding its poor grain quality, it still became the symbol of the green revolution in rice. Within a few years, many countries around the world were replacing their traditional cultivars with the modern high-yielding varieties.

The icon of the rice green revolution, when compared to traditional varieties, exhibits certain distinct characteristics; it has shorter stature, a shorter growth cycle, higher tillering ability, higher photosynthetic capacity, responsiveness to fertilizers (mainly nitrogen), and consequently much higher yield potential to high-input environments.

In the following decades IRRI developed IR36, which became the most widely planted variety in the 1980s and IR64 was the most used in the 1990s (Peng and Khush, 2003). In addition to these varieties, IRRI released a large series of IR-coded varieties. However, while these newer materials were characterized by their resistance to disease and insects, they did not contribute significantly to genetic gains for grain yield. Scientists then believed that a new breakthrough in yield potential had to come through a new plant type.

4.2 The New Plant Type

Donald (1968) was one the pioneers in the discussion of breeding for ideotype plants. Yang et al. (1996) suggested that in order to develop super high-yielding rice varieties it was essential to increase the biological yield. Searching for a second green revolution IRRI had been working on a new rice ideotype or new plant type (NPT) with a harvest index of 0.6 (60% grain: 40% straw weight) and with an increased ability for photosynthesis to increase total biological yield. Peng et al. (2005) considered the following components on this NPT: low tillering capacity, few unproductive tillers, from 200 to 250 grains per panicle, from 90 to 100 cm of plant height, thick and strong stems, vigorous root system, and from 100 to 130 days of growth cycle. These traits would allow the rice plant to transform more energy into grain production, increasing the yield potential by about 20% but with more input and cost.

Even before IRRI, Japan was the first country to pursue research on the NPT idea. In 1981, Japan launched a project aiming at combining varieties from *indica* and *japonica* groups to develop a super high-yielding rice cultivar (Wenfu et al., 2001). Dingkuhn et al. (1991) carried out physiological studies to understand the yield potential limitations of the *indica* varieties. They observed that under direct-seeded systems rice plants produced an excessive leaf area, which caused mutual shading and reduction in the canopy photosynthesis and sink size. In addition, they developed a large number of unproductive tillers.

The development of this NPT was based on tropical *japonica* germplasm derived from Indonesia, being the source of low tillering, large panicles, thick stems, vigorous root system, and short stature. According to Peng et al. (2005) the process of developing the NPT was more complicated than originally thought. The first generation of breeding lines with the above mentioned traits did not perform as expected. New crosses were made combining the tropical *japonicas* with elite *indica* breeding lines. The expectation was that lines coming out of these crosses would increase the yield potential of irrigated lowland rice by about 10%.

The development of super high-yielding rice varieties following the concepts proposed by Khush and Peng (1996) have encountered various technical difficulties. However, the basic principles remain the same. Horie (2001), Sheehy et al. (2001), and Murchie et al. (2001) looked at several of these physiological limitations and made technical arguments aimed at addressing them. Even though the results of these strategies are not yet producing an impact at the farmers' field level, it is important to highlight how rice breeders have been combining knowledge in creative ways on genetic diversity, plant physiology, and rice breeding methods to address these challenges.

4.3   Hybrid Rice

The hybrid rice technology concept dates back to 1964 in China. However, only in 1970, when a wild abortive pollen plant was identified in Southern China, did the idea begin to materialize. In 1980, Shih-Cheng and Loung Ping (1980) published one of the first articles indicating the potential of hybrid rice. The proposed strategy then relied on the male sterility produced by the abortive pollen system identified in the wild species *O. sativa* L. *f. spontanea*. Hybrid rice would then be produced through a so-called three-line system, where one line would have the genetic–cytoplasmic male sterility; the second line would be responsible for maintaining the sterility, and a third one would be used as the matching parent for the hybrid with the responsibility of restoring the fertility.

The first set of genetic–cytoplasmic male sterile lines was produced in 1970, while the first hybrid rice was released in 1974, with the hybrids outyielding, on average, the conventional rice varieties by 20%. In 1999, the area planted to hybrids was about 15.5 million ha, representing 50% of the total rice area and 60% of the total Chinese rice production (Guohui and Longping, 2003). Since 1994, hybrids

have been released in India, Philippines, Vietnam, Bangladesh, and Indonesia. The yield gains of the released hybrids in relation to the conventional varieties vary from 20% in Philippines to 30.2% in Vietnam (Virmani, 2003). India has released six hybrids since 1989, however, the pace of adoption by farmers has been slower than expected and only 200,000 ha are cultivated (Mishra et al., 2003). Among the above mentioned countries, Vietnam was the first to begin releasing hybrids, initially in 1979. By 2001, it had around 480,000 ha planted to hybrids (Hoan and Nghia, 2003). Indonesia began its hybrid production in 1998 and has released two public and five private hybrids. The projection is for more than 500,000 ha to be planted in the years to come (Suwarno et al., 2003). Bangladesh followed in close collaboration with IRRI, and released two IRRI hybrids. While the area planted is not significant yet, the government has put in place a hybrid rice master plan to boost its adoption (Julfiquar et al., 2003).

To simplify the hybrid rice production system, the concept of environmental genetic male sterility (EGMS) was introduced. The two environmental factors considered were the photoperiod (PGMS) and the temperature (TGMS) sensitivities, which are controlled by recessive nuclear genes. This technology allows, according to Mou et al. (2003), the use of any genotype with good traits as male parent, to obtain *japonica* hybrids (e.g., it is difficult to identify restorers for this group), and to develop inter-group hybrids such as *indica/japonica* (e.g., there is no restriction regarding the restorer–maintainer relationship). The first two-line hybrid was released in China. It represented 17.2% of the total hybrid rice area in the country in 2001, some 2.67 million ha (Guohui and Longping, 2003).

4.4   NERICA Rice

Upland and lowland dry land environments are the two most important rice production ecosystems in Africa, where it is staple food for the sub-Saharan population. Certain challenging problems and environmental conditions as well as production practices common to these ecosystems limit rice production, such as weeds, diseases, and insect pressure, soil fertility decline, soil acidity, and drought stress. WARDA began a program to combine the two cultivated rice species *O. sativa* and *O. glaberrima* in 1991. Their genetic dissimilarity needed the use of a different breeding approach. Embryo rescue technique was employed to obtain viable segregating populations (Jones et al., 1997). The newly developed materials were called "new rice for Africa" and were popularized as NERICA varieties. There are not many technical publications about the development of these varieties. Information is gathered in the form of press releases, on the WARDA web page (www.warda.cgiar.org/) and in articles such as that of Jones and Wopereis-Pura (2001). The main features of these new varieties, when compared to the traditional *O. glaberrima*, cultivated by farmers, are their improved ability to compete with weeds, their larger panicles with around 400 grains and a higher yield potential. In addition, shattering is reduced, stems are stronger thus preventing lodging, maturity

occurs around 30 days earlier than other conventional cultivars, and they have greater resistance to the most common biotic and abiotic stresses, as well as improved adaptability to the poor African rice growing soils. The success story of the NERICA varieties includes a strong participation of the farmers in the process of evaluation of the breeding lines as well as in the development of the materials (e.g., farmer–breeder inititatives, participatory plant breeding, see Chapter 14). Information on the impact of this technology can be found at WARDA (2003).

5 Current Breeding Goals

An increase in productivity is always one of the main goals of any crop breeding program including rice. However, a long list of goals can be identified for this crop varying in importance from region to region, country to country, and even within a given country. A few examples of current breeding goals are described in the sequence.

Increase grain yield potential is the major goal of almost all rice breeders programs around the world. The major impacts, listed elsewhere in this chapter, are related to the development of new strategies to increase the genetic grain yield potential of the varieties. Nonetheless, there are still regions in the world where rice leaves and straws play a major role in farmers' livelihoods.

Resistance to blast disease has been among one of the most researched rice breeders' goals for decades. This disease is the most widespread pest of rice. It is present in almost all countries and agro-ecological zones where rice is grown. It causes leaf and panicle damages. Improvement strategies have to rely either on gene pyramiding or multiple long-term resistance and/or tolerance because the fungus has a complex set of races and single gene resistance is frequently overcome in a very short time by the pathogen.

Grain quality characteristics vary from region to region and market requirements. Very often varieties are discarded by farmers because they do not meet their required quality standards. One example of the importance of the trait in determining the success of a breeding program is upland rice in Brazil. Until the 1980s, the most wanted grain type in the Brazilian mid-west region was the upland type (medium to long bold grains). However, due to the market pressure made by the industry from the Brazilian south (irrigated rice grain type – long and slender grain type) the upland grain type lost market. The upland rice program had to quickly shift its grain type objective and only when upland varieties with long and slender grains were released, only then upland rice became popular again. Specialty grain quality rice types are also an objective of many breeding programs around the world today.

Drought tolerance is another trait highly researched in rice. The increase trend in global water scarcity, the gradual seriousness of water shortage around the world due to climate change, and the high water demand of rice varieties make this a highly important objective of rice breeding programs. In addition, due to the urbanization and pressure from other more important cash crops rice cultivation

has been pushed to less favorable areas with larger water availability problems. The complexity of the trait and the difficulties in developing a reliable and simple screening system make the development of tolerant varieties an important challenge. The use of biotechnology tools is making a significant contribution to identify genes and strategies to incorporate them in new varieties. However, the progress is still below the required level to produce significant impact in rice production due to the genetic complexity of the trait.

An important point to make is that breeders have a tremendous challenge to cope with farmers and markets demands. Other challenging goals include resistance to bacterial and sheath blight, and several viruses; resistance to insects such as brown plant hopper, green leafhopper (vector of *tungro* viruses) and gall midge; and tolerance to salinity, iron toxicity, and low temperatures.

6   Breeding Methods and Techniques

6.1   Conventional Rice Breeding Methods

If one makes a global literature review on the breeding methods commonly used to develop rice varieties around the world pedigree selection is always at the top. More than 85% of the released rice varieties published in Crop Science Society of America have been developed through pedigree selection. When there are possibilities to carry out more than one generation per year (e.g., winter nurseries) the method is combined with modified bulk or even single-seed descent to speed up the process of having pure lines for agronomic evaluation.

This chapter will focus on methods that are more unique or that can bring new elements into the attention of the readers.

6.2   Population Improvement Through Recurrent Selection

This section will not try to dissect rice population improvement through recurrent selection but it will highlight the experiences of using such methods in Latin America where the method has been employed for more than 15 years. There are breeding programs with different capacities run by international organizations such as the CIAT, the "Centre de cooperation internationale en recherche agronomique pour le developpement" (Cirad), and several national programs such as the Brazilian Agricultural Research Corporation (Embrapa), and the "Fundación para la Investigación Agricola" (Danac), among others.

A question one could ask is why population improvement strategies including genetically broad-based populations should be considered for a self-pollinated crop such as rice. The answer to this question is simple: several reports indicate that the genetic gains obtained by different breeding programs around the world and

particularly in Latin America (Santos et al., 1997; Muralidharan et al., 2002) are stagnating or even decreasing. In addition, other reports indicate that the genetic base of the rice varieties is narrowing (Dilday, 1990; Cuevas-Pérez et al., 1992; Rangel et al., 1996).

Population improvement through recurrent selection is a traditional breeding method that has been used in maize for over 50 years (Hull, 1945; Dudley and Lambert, 2004). However, it has not been a common breeding methodology choice in self-pollinated crops. Fujimaki (1979) suggested its application in rice using male sterility. In soybean, Werner and Wilcox (2004) reported the results of male sterility facilitated population improvement for yield characteristics. Wang et al. (1996) used the *Tai Gu* gene to induce sterility and apply recurrent selection in wheat. These are other successful examples of the utilization of population improvement facilitated by the existence of male sterile genes. However, fewer cases are shown in the literature in which male sterility was induced by the application of chemical products (Picard et al., 2004).

Hand crossing in rice is a laborious task as described by Guimarães (1999). Some of the requirements when using recurrent selection methods are to produce progenies (sometimes crossing when using full or half-sib families) and recombine the selected ones after replicated experiment trials across environments. Therefore, the utilization of population improvement methods in rice only became feasible after the discovery of the male sterile gene obtained by Singh and Ikehashi (1981) through induced mutation of the rice variety "IR36". The recessive male sterile gene was employed in 1984 by Embrapa and Cirad to create populations with broad genetic bases (Taillebois and Guimarães, 1989; Rangel and Neves, 1997). Moreover, the simplification of the crossing method developed by Taillebois and Castro (1986) and described by Sarkarung (1991) made a significant contribution to promoting the use of breeding methods that require a large number of crosses each year.

Population improvement through recurrent selection in rice is a methodology widely used in Latin America; however, it is not as popular elsewhere. In rice, as probably happens in almost all self-pollinated crops, breeders tend to use pedigree selection which is a complement to recurrent selection if well managed. The genetic improvement process is cyclical, aiming at taking advantage of the progress made in the previous years. In general, each year breeders select the best breeding lines to make new elite crosses between them and/or with new germplasm. Guimarães et al. (1996), analyzing the upland rice breeding program at CIAT, which is based on pedigree and modified bulk selection, found that "even though CIAT did not follow the recurrent selection method, a modified approach, similar to the proposed methodology, was used" during the period 1984–1993. The aim of having such cycles is to capitalize on the genetic gains made in previous years; however, through pedigree selection this is done in a non-systematic way.

The main feature of recurrent selection is to increase the frequencies of the favorable alleles, as was pointed out by Hull (1945) when describing the process of recurrent selection. Thus, by applying the recurrent selection method in rice,

breeders are following the same principle but in a systematic and long-term way. Therefore, recurrent selection allows defined and shorter breeding cycles, the possibility of a more precise follow-up of genetic gains, and opportunities to develop breeding lines with a wide genetic make-up.

Population genetic improvement through recurrent selection in Latin America is, unlike maize, recent and dates back to 1996. This is due in part to the support of the Organization of American States (OSA), Embrapa, Cirad, and CIAT who offered the first training course to introduce the subject to breeders in the region. As the next step, broad genetic base populations were made available to them by Embrapa and CIAT. In addition, a close follow-up was provided by more experienced breeders from both institutions. Moreover, Chatel and Guimarães (1997) prepared a handbook providing guidance to rice population development and improvement. Guimarães (1997) was the first to report the progress made by the different breeding programs in the region. Similar reports were produced in 2000 (Guimarães, 2000) and 2004 (Guimarães, 2005). During the last 15 years these programs have made significant progress. There are currently more than 50 genetically broad base rice populations developed in the region (GRUMEGA Grupo de Mejoramiento Genético Avanzado en Arroz, 2006a). In Argentina, breeding programs developed *indica* populations PARG-1 and PARG-2 (Marassi et al., 2000) and PARG-3 (Marassi et al., 2004) aiming at improving cold tolerance. For the same trait, breeding programs in Chile developed *japonica* populations PQUI-1 and PQUI-2 (Hernaiz-L et al., 2004). Graterol (2000) described how PFD-1 and PFD-2 populations were produced in Venezuela to adapt to two different environmental conditions (winter and summer growing seasons). In Cuba, the national program developed the populations IACuba-1 and IACuba-2 searching for a genetically diverse population adapted to local challenges (Pérez-Polanco et al., 2000). The cultivar CG-91 with resistance to rice blast for upland conditions was developed by Guimarães and Correa-Victoria (2000). Similar research has been conducted by Courtois et al. (1997) for upland rice.

Breeders in Latin America highlighted the following advantages of using population genetic improvement through recurrent selection: (a) the possibility of creating and managing their own segregating populations without incurring any additional expenses necessary to evaluate potential parents every year; having a structured crossing program; keeping detailed information on lines and parents; (b) the possibility of having improved and diverse breeding lines available at the end of every recurrent cycle as well as continuing to make progress in increasing the frequency of favorable genes in the population; (c) the national programs can have more than one population improvement program with minimal additional resources, avoiding the duplication of similar activities in a given year (instead of having to evaluate hundreds of line of two populations in one year, the program can be organized in such a way that in a given year one population is in the recombination phase and the other in line evaluation phase); and (d) as in (b) varietal development process can be integrated with the population improvement program and become a unique and more powerful project.

An extra advantage that is worth highlighting is the possibility of integrating different rice breeding programs within countries. In Brazil the evaluation phase of the different populations being managed for the irrigated and the upland ecosystems are shared among state organizations, Embrapa units, and universities. Each partner carries out the evaluation of progenies at fewer locations than in evaluations carried out by single breeding programs. All locations are pooled and a combined analysis is performed. Selection of the best families for the recombination phase is done through discussion of the results in a joint meeting. The best lines at each location are kept by the local breeding program for further selection and line development. A similar strategy was adopted in Venezuela through the "Fundación Danac", who developed populations PFD-1 and PFD-2 and evaluates families through the national program, universities, and the private sector.

Many rice programs in Latin America did not have a fully operational breeding project. In general, they were dependent on ad hoc introductions of pure lines from other stronger national programs or international organizations. Today, these programs are releasing improved varieties obtained from segregating lines used for recombination and development of new recurrent cycles. A good example of this progress can be seen in Bolivia, which recently released the variety "Esperanza" (GRUMEGA, 2006b). Chile has collaborated closely with CIAT for a long time and has always had a strong breeding program. In 1990 the country decided to add to its portfolio of breeding methods recurrent selection for genetic improvement (Alvarado-A, 1997), and in 2007 it has released R-Quila 23 (GRUMEGA, 2006c). In the region, countries are carrying out their population improvement programs using different recurrent selection strategies for genetic improvement. Most countries utilize the S_1–S_2 recurrent selection procedure, evaluating and selecting S_0 plants, advancing to the $S_{0:1}$ generation outside the normal growing season, and evaluating and selecting $S_{0:2}$ families for recombination. In temperate countries, where two growing seasons per year are not feasible unless using winter nurseries, scientists evaluate and select $S_{0:1}$ and $S_{1:2}$ families. Very seldom do scientists in these countries use a different selection scheme, therefore, non-additive effects are not considered in genetic improvement. In almost all cases there have been reported genetic gains for the target traits when comparing more advanced generations with the original populations or less advanced recurrent cycles. Brazil has a very strong rice breeding program and has been one of the promoters of this methodology. The first variety derived from a genetically broad-based population under recurrent selection was released in 2002 (GRUMEGA, 2006d). The breeding programs are currently managing five populations for irrigated conditions (Rangel et al., 2000) and eight for upland ecosystems (Castro et al., 2000). Evaluation studies were carried out in different populations in order to assess the efficacy of the method in rice. Rangel et al. (2005) reported 6.65% genetic gain after evaluating two cycles of recurrent selection in the irrigated rice population CNA-IRAT 4. Badan et al (2005) reported 6.2% gains after selecting for rice blast resistance when comparing cycles 1 and 2 of the upland rice population CNA-7. Moreover, evaluation of three cycles of recurrent selection for grain yield and neck blat in CG-3

upland rice population showed 3.6% and 3.4% genetic gain per year, respectively (Morais et al., 2008).

6.3 Hybrid Rice

To cope with future demand for rice production, yield per unit area has to be increased rapidly in the major rice producing countries. As stated before, hybrid rice was first released in China in 1974 with the promise of increasing yield potential beyond the level of the traditional varieties through the exploitation of heterosis. The initial breeding strategy to produce hybrids relied on three breeding lines known as A line (the male sterile line), B line (responsible to maintain the genetic male sterility of the A line), and R line (used to restore the fertility of the A line and to produce the hybrid seed). The technique evolved to a two-line process using environmental genetic male sterility (EGMS) counting on photoperiod (PGMS) and temperature (TGMS) sensitivity to induce sterility. The ideal system for these and other cross-pollinated crops would be the one-line method utilizing the apomixis system that allows preserving the right cultivar.

According to Virmani et al. (1997) the development of a hybrid breeding program has to go through the following stages of identification and development of the A, B, and R breeding lines: identification and evaluation of male-sterile lines and their restorers; testcross phase to select heterotic combinations and to initiate conversion of maintainer lines into male-sterile lines; backcrosses to transfer the cytoplasmic male-sterility to elite maintainer lines; trials to study the combining ability (general and specific) of the parental lines; and foundation seed production of all three lines. Production of breeding lines for the three- or two-line methods is still a difficult task for most of the breeding programs outside of China. One of the bottle necks for spreading the technology worldwide is the seed production process. In general, the production system relies on planting a few rows of the male line (R line) and rows of the female (A line) in such way that the maximum hybrid seed production per unit area occurs in the A line. Few ratios of female to male line seed production have been used (e.g., the 6:2, 8:2, and/or the 10:2 ratios). Mao (2001) reported that the average hybrid seed production in rice lines is between 2.5 and 3.0 t ha^{-1}, however, outside of China it is much lower (1.0–1.5 t ha^{-1}, according to Virmani et al., 2001). In Argentina, RiceTec is producing hybrid rice for southern South America. The company is using three- and two-line systems. Their seed production varies tremendously from year to year with an average around 1.2 t ha^{-1}.

In addition to the seed production of the female parent, the success of a hybrid is dependent on the level of heterosis it can express after crossing their parental varieties. The combination between different varieties is the first step to obtain heterosis, but its expression improves as combinations between varieties belonging to different groups (*indica* and *japonica*) are explored. An alternative to develop hybrids with higher potential might be the use of yield enhancing genes from other

species (Yuan, 2003). Molecular markers are trying to identify restorer genes in *japonica* background (Tan et al., 1998) and thermo-sensitive genetic male sterility genes (Yamaguchi et al., 1997; Latha et al., 2004). In addition, marker-assisted selection (MAS) has been reported to assist in the development of hybrids with disease and insect resistance in China (He et al., 2004).

6.4 Mutation Breeding

The use of different sources derived from induced mutations was a popular choice to generate genetic diversity for specific traits in rice in the 1980s. Today the technique became part of the tools kit breeders have to enhance specific rice characteristics in well-adapted varieties. The intention of this section is not to discuss all aspects related to the use of mutation breeding, but to highlight a few successes and flag the importance of mutations to rice improvement.

According to Wang (1992) during the period 1966–1990, there were 78 varieties released in China originated from mutation breeding. More recently, from 1991 to 2004, there was a similar number (77) of new releases coming from application of mutation (Chen et al., 2006). The most popular mutagen is still the gamma rays and the mutated characteristics are the ones responsible for the expression of agronomic (e.g., resistance to pests) and grain quality phenotypes.

In Indonesia the first mutant variety (Atomita 1) was released in 1982 and up to today there are 14 officially released varieties, 13 of them were improved for biotic stresses such as resistance to brown plant hopper; in all cases the mutagen agent was the gamma rays (Ismachin and Sobrizal, 2006).

Vietnam is one of the most important rice producing country in the world. Reports from Tran et al. (2006) indicated that during the period 1990 and 2002 the Agricultural Genetic Institute developed and released 10 varieties, most of them have better grain quality, in addition to other agronomic traits; once more the gamma rays were the most common mutagen agent used.

Maluszynski et al. (1998) summarized the number officially released mutant varieties and came up with "cereals" as the group with the largest numbers followed by legumes and industrial crops. Among cereals rice presented the highest number with barley in second. In rice the main improved traits were early maturity, plant height, and disease resistance. It is worth mentioning that the famous gene sd_1 (see section on major breeding achievements) is a mutant. However, the most commonly mutated trait over all crops was "semi-dwarfness". Table 1 summarizes the number of varieties released around the world, which were developed by the use of mutagens. The Food and Agriculture Organization of the United Nation (FAO)/ International Atomic Energy Agency (IAEA) Mutant Varieties Database indicates that there were 2,541 releases up to March 2007. The largest numbers are from cereals (1,212), followed by legumes and industrial crops. Among cereals rice presented the highest number (525) with barley in second (303) and wheat in third (200).

Table 1 Officially released mutant varieties of rice in the FAO/IAEA Mutant Varieties Database, March 2007

Country	Varieties released (#)	Country	Varieties released (#)
Bangladesh	5	Japan	70
Brazil	28	Korea	7
Burkina Faso	3	Myanmar	5
China	222	Nigeria	3
Costa Rica	2	Pakistan	10
Ivory Coast	26	Philippines	8
France	5	Portugal	1
Guyana	26	Romania	1
Hungary	3	Senegal	2
India	40	Sri Lanka	1
Indonesia	6	Thailand	4
Iraq	3	USA	23
Italy	2	Vietnam	28

7 Integration of New Biotechnologies in Breeding Programs

The first and most important aspect to successfully take advantage of the variety of biotechnology tools available to rice breeders is to have a well-structured, efficient, and effective breeding program. This statement may seem obvious for many readers but it does not reflect the reality of a large portion of the rice breeding programs in developing countries around the world.

FAO has started a worldwide plant breeding and associated biotechnology assessment in 2002. This work has been concluded in a sample of more than 50 developing countries in all the different rice growing regions. Among other things, the results indicate that almost every country has made investments in the area of biotechnology recently. However, only a very limited number of them have reinforced their breeding activities and worse still, the great majority do not even have well-structured and fully operational breeding programs that can incorporate biotechnology tools. To add to this, very seldom have they ensured linkages between biotechnology efforts and breeding priorities or strategies.

Anther culture is a simple biotechnology tool that has been around for quite a long time. The technique allows the development of double haploid lines or true breeding lines, which shortens the breeding cycle and helps produce new rice varieties. One of the main uses of double haploid lines is for the development of mapping populations for molecular analysis and mapping of DNA markers (Lu et al., 1996).

As mentioned previously in this chapter, rice has a series of species that can and have been used to address specific breeding problems such as resistance to pests and tolerance to abiotic stresses. However, one of the main limitations on the use of wild relatives in breeding programs is the lack of crossability between species due to

chromosomal and genetic differences. One alternative to overcome these sexual barriers is to use embryo rescue and protoplast fusion, which are simple biotechnology techniques that have been used successfully in rice. Fertile *O. sativa* and *O. glaberrima* progenies were obtained through backcrossing and double haploid production by Jones et al. (1997). The NERICA varieties, mentioned elsewhere in this chapter, provide a good example of how these techniques were used to help address some specific breeding objectives.

Plant breeders want to use of molecular markers. Several different types of markers are being used in rice, among which one may find the following: restriction fragment length polymorphisms (RFLPs); randomly amplified polymorphic DNA markers (RAPDs); amplified fragment length polymorphisms (AFLPs); diversity array technology (DArT); simple sequence length polymorphisms (SSLPs) also known as SSRs or microsatellites; transposable elements (TEs); and/or single nucleotide polymorphisms (SNPs). If genes of interest are identified and linked to some of these markers they can be used to aid selection in a process known as MAS. Knowledge of gene and marker location, linkage strength, and stability is essential. Therefore, basic information is required and molecular linkage maps play a major role. Rice maps have been developed to that end; the first RFLP map was published in 1988 and was constructed at Cornell University by McCouch et al. (1988). Breeders are interested in transferring genes of interest from one parent to the other. This process can be facilitated by tagging such genes, which means identifying a tight linkage between the targeted gene and a molecular marker. By selecting the marker the breeder is indirectly selecting the trait of interest using MAS with the limitations of indirect selection. In the literature, there are examples of application of MAS in rice to aid backcrossing programs; in fact, theoretical studies have indicated that MAS can help reduce from 6 to 3 the number of backcrosses necessary to transfer a targeted gene (Frisch et al., 1999). In hybrid rice, Chen et al. (2000) transferred a resistance gene for bacterial leaf blight into a widely used parent. Huang et al. (1997b) successfully pyramided four bacterial blight resistance genes through MAS into a rice variety. Nevertheless, the application of this tool in conventional breeding programs has been limited. The rice genome is one of the most studied by scientists around the world. Arumuganathan and Earle (1991) described it as having 430 Mb. Chen et al. (2002) described it as 400 Mb once re-evaluated. Goff et al. (2002) sequenced the *japonicas* genome and Yu et al. (2002) did the same for the *indicas*. Having the rice genome sequenced brings a new and more important challenge that is to use this information to identify the biological functions of these genes and their interactions with other genes and environments. Therefore, the matching between genotyping and phenotyping plays an important role and the existence of breeding programs with excellent screening techniques and capable breeders are essential to capture the best advances of modern biotechnology and discard the rest. The introduction of an alien gene into rice by production genetically engineered rice allows breeders to target problems that without this technology it was not feasible. The golden rice is the most well known case of application of genetic engineering in rice in the 1990s. This specific project genetically engineered the provitamin A pathway into rice. Most cases, however,

were related to the production of transgenic rice for resistance to diseases, insects, and abiotic stresses. Khush and Brar (2003) presented a table with 19 examples of transgenic rice.

In closing this section it is not redundant to reiterate the need of integrating biotechnology tools and certain successful techniques into the existing breeding programs. Decision-makers responsible for allocation of resources for research should not have two choices – biotechnology or plant breeding – but only one integrative way forward which is to ensure the integration of these activities towards producing improved varieties to solve farmers' demands.

8   Foundation Seed Production

Seed production is one of the key steps for the success of a variety. Thus, it has to be considered as an integral part of the breeding programs. The objective of this section is to indicate the linkages between foundation seed production and the phases involved in a breeding program. As an example of how this can be done I will use the past experience of the Embrapa Rice and Beans Centres in Brazil.

The segregating populations produced by the hundreds of crosses made every year are taken to the field and advanced through pedigree selection or modified bulk selection. As soon as the breeders identify potential breeding lines in the F_4, F_5, or F_6 generations they are included in the observational trials, which are planted across locations throughout the country. The best 50–100 lines are promoted to preliminary yielding tests planted across several locations also throughout the country. This is the stage when the breeders start considering lines for the foundation seed production. Headquarters seed specialists, together with breeders, select around 100 panicles to initiate the seed production process using the panicle-row process. As the breeding lines move from preliminary yield trials to advanced and regional yield trials the seed multiplication process advances from 2 to 3 kg of foundation seed to the required amount of high quality seeds necessary to attend the seed producers. This strategy requires high resource mobilization since it starts based on 20–30 breeding lines with potential to be released as varieties and ends on one or two released varieties. However, it speeds up the process of varietal release allowing to arriving at the moment of release with a large amount of high quality seeds. In addition it links breeders and seed specialists in the early stages of the seed production process ensuring the high quality of the final product.

9   Rice Breeding Capacity Around the World

FAO, in collaboration with CGIAR centers and other stakeholders has been assessing the national plant breeding and related biotechnology capacity, as proposed in the Global Plant of Action (FAO, 1996) of the International Treaty on Plant Genetic

Resources for Food and Agriculture (FAO, 2002). The mechanism to gather information on countries' capacity is a survey focusing on several breeding and biotechnology issues. For this chapter the analysis will consider the number of full-time equivalent[1] (FTE) plant breeders[2] available in all private and public institutions in each surveyed country and the resource allocation per crop (rice in this case). The organizations were asked to provide the total number FTE breeders and the percentage of the total resources that was allocated to rice breeding activities. The numbers in Table 2 were obtained by multiplying the total number of FTEs by the percentage of resource allocations to rice. Preliminary survey results for a sample of countries in Central Asia were published by Guimarães et al. (2006a) and in Africa by Guimarães et al. (2006b). These results covered all crops; however, in this chapter the focus will be on rice only (Table 2). As one might expect, because of the importance of the rice crop for the Asian population, the largest number of FTE breeders was observed in Asia, even though that was the region with the least number of countries surveyed (only four countries were sampled). The results indicated that there were 84.9 rice breeders, representing 21.6% of the total FTE breeders in the region, the highest percentage of all the regions. The next highest result was found for Latin America, which had 46 FTE rice breeders, some 17.1% of the total number of FTE breeders in the region. As rice is the staple food for the majority of the countries in these two regions, these results reflect the importance that the national programs give to the development of improved varieties.

The total number of rice breeders in Brazil represents 50% of the number of rice breeders present in all seven countries sampled in Latin America. Embrapa has two-thirds of the total number of FTE rice breeders in the country. The state organizations follow with much lower numbers while the private sector has only two breeders working in the country. Considering the whole country's breeding capacity, rice represents only 4.4% (Table 2).

In Africa, for many countries, mainly in West Africa, rice is the staple food and one of the most important sources of calories. The results in Table 2 reflect its importance by the total number of FTE rice breeders working in Africa. An important part of the 28.4 FTEs rice breeders are in West Africa. The West African countries all have, with the exception of Niger and Senegal, more than two breeders working in national rice breeding programs. However, looking at the total number of FTE breeders in Africa rice represents a very small fraction (3.6%). The potential that rice has in West African countries is due to its increasing popularity in consumption patterns although the gap between supply and demand is still significant. Nevertheless, some countries have invested in rice breeding to contribute to the growth of local rice production (Oladele and Sakagami, 2004).

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[1] A Full Time Equivalent (FTE) is the work done by a person who has any responsibility linked to plant breeding (genetic enhancement, line development, line evaluation, or genetic studies) during one year (365 days).

[2] The survey considered as plant breeders all scientific personnel with a plant breeding degree and also the ones directly involved in plant breeding activities.

Table 2 Distributions of the number of Full Time rice breeders' equivalent of selected organizations obtained through a survey carried out in Brazil in 2005

Organization	Rice breeders	Breeders for other crops	Breeders (#)	Rice breeders (%)
Brazil	20.5	446.5	467.0	4.4
Embrapa[a]	13.0	201.0	214.0	6.1
State Institutions[b]	4.0	123.0	127.0	3.1
Universities[b]	1.5	89.5	91.0	1.6
Private companies[b]	2.0	33.0	35.0	5.7
Latin America[c]	46	222.6	268.6	17.1
Africa[d]	28.4	770.6	799.0	3.6
Near East and North Africa[e]	6.1	595.5	601.6	1.0
Central Asia and Caucasus[f]	16.9	1,240.0	1,257.0	1.3
Asia[g]	84.9	307.5	392.4	21.6
East Europe[h]	7.7	1,022.0	1,030.0	0.7

[a]Embrapa is the largest public research organization in the country with 37 research centers (www.embrapa.br)

[b]The sample included 8 state institutions, 20 universities, and 7 private companies distributed through out the whole country

[c]The eight countries sampled were Argentina, Bolivia, Costa Rica, Dominican Republic, Ecuador, Nicaragua, Uruguay, and Venezuela. All data refer to 2004 except for Venezuela that has data for 2001

[d]The 15 countries sampled were Angola, Cameroon, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Senegal, Sierra Leone, Uganda, Zambia, and Zimbabwe. All countries refer to 2001, with the exception of Ethiopia and Sierra Leone (2004) and Angola and Cameroon (2003)

[e]The seven countries sampled were Algeria, Sudan, Jordan, Lebanon, Oman, Tunisia, and Turkey. All countries have data for 2004 except for Algeria and Sudan (2001)

[f]The seven countries sampled were Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, Armenia, Georgia, and Azerbaijan. All data are for 2004

[g]The four countries sampled were Bangladesh, The Philippines, Thailand, and Sri Lanka. All data are for 2004

[h]The five countries sampled were Albania, Bulgaria, Macedonia, Moldova, and Slovak Republic. All data are for 2004

Rice is not an important crop in Central Asia and Caucasus which is why only 1.3% of the total FTE breeders in the region are working with the crop. Kazakhstan, the largest producer in the region, cultivated only 83,000 ha in 2006 (FAOSTAT, 2006) and had 12.1 FTE rice breeders in 2004. The smallest numbers were found for Eastern Europe, and Near East and North Africa regions, yet they have a sizeable total number of FTE breeders. Rice production does not have the same high priority in these regions as it does in Asia or Latin America. Therefore, the resources allocations for rice breeding activities can be expected to be limited compared with other crops such as wheat and maize.

In conclusion, different regions allocate their breeding resources according to their crop priorities. Moreover, rice breeders are widely distributed across all regions. What is more important, the aforementioned genetic diversity and the

wise choice of germplasm help bring about food security in countries where rice is a staple. This, however, depends on applying creativity to different breeding approaches and the wise use of biotechnology tools.

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