Chapter 19

Rice

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Rice feeds half the world's people, mainly in Asia. Their food security and crop biodiversity depend upon continued access to seed developed from thousands of locally adapted varieties of *Oryza sativa* and *O. glaberrima* that Asian and African farmers have grown for generations, the more than 20 species of wild rice native to Asia, Africa, Latin America and Oceania, and the related genera in the tribe Oryzeae. Worldwide, about 80 million ha of rice are grown under irrigated conditions, the most important rice production system, with average yields of 3-9 t/ha. Athough four CGIAR centres (IRRI, WARDA, CIAT and IITA) hold and use rice germplasm, only IRRI has a global mandate to conserve and improve germplasm. Other centres have regional or continental mandates in Africa and Latin America.

The aggregate population of the less-developed countries grew from 2.3 billion in 1965 to 4.1 billion in 1991. Asia accounted for 59% of the global population, about 92% of the world's rice production and 90% of global rice consumption. Bangladesh, China, India, Indonesia, Myanmar, Thailand and Vietnam are the world's largest rice producers, accounting for about 78% of world production (IRRI 1995). Even with rice providing 35-80% of total calories consumed in Asia and with a slowing of growth in total planted area, production has so far kept up with demand. The world's annual rough rice production, however, will have to increase by almost 70% over the next 35 years to keep up with population growth and income-induced demand for food. The urban poor in Asia spend a large part of their income on rice and the consumption of rice will continue to increase as incomes and urbanization increase.

BOTANY AND DISTRIBUTION

Besides domesticated *Oryza*, other wild *Oryza* and related genera of the tribe Oryzeae are distributed throughout the tropics (Tables 19.1 and 19.2). The basic chromosome number is n=12. *Oryza* species are generally grouped into four complexes of closely related species (Chang and Vaughan 1991; Vaughan 1989, 1994). Species of the *O. ridleyi* complex inhabit lowland swamp forests, and species of the *O. meyeriana* complex are found in upland hillside forests. The *O. officinalis* complex consists of diploid and tetraploid species found throughout the tropics. The *O. sativa* complex consists of the wild and weedy relatives of the two rice cultigens as well as the cultigens themselves. The wild relatives of *O. glaberrima* in Africa consist of the perennial rhizomatous species *O. longistaminata*, which grows throughout sub-Saharan Africa, and annual and weedy relatives are found primarily in West Africa. Among the wild relatives of *O. sativa*, the perennial *O. rufipogon* is widely distributed over South and Southeast Asia, southeast China and Oceania. Other forms are found in South America, usually in deepwater swamps (Chang 1976a).

Table 19.1. Taxa in the genus *Oryza*: the species complexes and genome groups (adapted from Chang and Vaughan 1991 and Vaughan 1994).

Species complex	Taxon	Genome group	Distribution
O. sativa	*O. glaberrima*	A^gA^g	West Africa
	O. barthii	A^gA^g	Sub-Saharan Africa
	O. longistaminata	A^lA^l	Sub-Saharan Africa, Madagascar
	O. sativa	AA	Worldwide
	O. nivara	AA	Tropical and subtropical Asia
	O. rufipogon	AA	Tropical and subtropical Asia
	O. meridionalis	AA	Northern Australia
	O. glumaepatula	A^gA^g	South and Central America
O. ridleyi	*O. longiglumis*	Tetraploid	Indonesia (Irian Jaya), Papua New Guinea
	O. ridleyi	Tetraploid	Southeast Asia, Papua New Guinea
O. meyeriana	*O. granulata*	Diploid	South and Southeast Asia
	O. meyeriana	Diploid	Southeast Asia
O. officinalis	*O. officinalis*	CC	Tropical and subtropical Asia
	O. minuta	BBCC	Philippines, Papua New Guinea
	O. eichingeri	CC	Sri Lanka, Sub-Saharan Africa
	O. rhizomatis	CC	Sri Lanka
	O. punctata	BBCC, BB	Sub-Saharan Africa, Madagascar
	O. latifolia	CCDD	South and Central America
	O. alta	CCDD	South and Central America
	O. grandiglumis	CCDD	South America
	O. australiensis	EE	Northern Australia
Species not yet assigned to a complex	*O. schlechteri*	Diploid	Indonesia (Irian Jaya), Papua New Guinea
	O. brachyantha	FF	Sub-Saharan Africa

Table 19.2. Genera in the tribe Oryzeae (adapted from Chang and Vaughan 1991).

Genus	No. of species	Distribution	Environment
Oryza	22	Pan-tropical	tropical
Leersia	17	Worldwide	temperate / tropical
Chikusiochloa	3	China, Japan	temperate
Hygroryza	1	Asia	temperate / tropical
Porteresia	1	South Asia	tropical
Zizania	3	Europe, Asia, North America	temperate / tropical
Luziola	11	North and South America	temperate / tropical
Zizaniopsis	5	North and South America	temperate / tropical
Rhynchoryza	1	South America	temperate
Maltebrunia	5	Tropical and southern Africa	tropical
Prosphytochloa	1	Southern Africa	temperate
Potamophila	1	Australia	temperate / tropical

Origin, Domestication and Diffusion

The centre of origin of rice and the exact time and place of its first development may never be known. The most convincing archaeological evidence for domestication, dated to 4000 BC, was discovered in Thailand (Solheim 1972). In the early Neolithic era, rice was grown in forest clearings under a system of shifting cultivation; puddling the soil and transplanting seedlings were likely refined in China (Chang 1976b, 1976c). In Southeast Asia rice originally was produced under dryland conditions in the uplands and only recently came to occupy the vast river deltas. Diffusion has carried rice to every continent except Antarctica.

Wetland rice cultivation came to the Philippines during the second millennium BC and Deutero-Malays carried the practice to Indonesia about 1500 BC. The crop was introduced to Japan no later than 100 BC (Chang 1976a, 1976c). It reached India in early times and by 1000 BC was a major crop in Sri Lanka. Rice was introduced about 344-324 BC to Greece and the Mediterranean by returning members of Alexander the Great's expedition to India and spread gradually throughout southern Europe and to a few locations in North Africa (Huke and Huke 1990). Rice cultivation was introduced to the New World by early European settlers (Grist 1986). Early in the 18th century rice spread to Louisiana, but not until the 20th century did it reach California's Sacramento Valley (Adair *et al.* 1975). The California introduction corresponded with that of the first successful crop in Australia's New South Wales (Huke and Huke 1990).

The primary centre of diversity for *O. glaberrima* is in the swampy basin of the upper Niger River (Chang 1976a). Two secondary centres lie to the southwest near the Guinean coast. In West Africa, *O. glaberrima* is a dominant crop grown in the flooded areas of the Niger and Sokoto River basins (Chang 1985). Ecological diversification in *O. sativa*, which involved cycles of hybridization, differentiation and selection, was enhanced when ancestral forms of the cultigen were carried by farmers and traders to higher latitudes, higher elevations, dryland sites, seasonably deepwater areas and tidal swamps (Chang 1985). Two major ecogeographic races differentiated as a result of isolation and selection: indica, adapted to the tropics, and japonica, adapted to the temperate regions and tropical uplands. Selections made to suit cultural and socioreligious traditions added diversity, especially grain size, shape, colour and endosperm properties (Chang 1985). Today, thousands of rice varieties are grown in more than 100 countries.

Reproductive Biology

The morphology of rice is divided into the seedling, vegetative organs and reproductive organs (Chang and Bardenas 1965; Vergara 1991). Growth duration is 3-6 months and potential grain yield is primarily determined before heading. The life history of rice has three growth phases: vegetative, reproductive and ripening (Fig. 19.1). A 120-day variety, when planted in a tropical environment, spends about 60 days in the vegetative phase, 30 days in the reproductive phase and 30 days in the ripening phase (Yoshida 1981; Vergara 1991). Heading is considered a synonym for anthesis in rice. It takes 10-14 days for a rice crop to complete heading because there is variation in panicle exsertion among tillers of the same plant and among plants in the same field (Yoshida 1981). Agronomically, heading is usually defined as the time when 50% of the panicles have exserted. The length of ripening varies among varieties from about 15 to 40 days. Ripening is also affected by temperature with ranges from about 30 days in the tropics to 65 days in cool, temperate regions such as Hokkaido, Japan and Yanko, NSW, Australia (Yoshida 1981; Vergara 1991).

GERMPLASM CONSERVATION AND USE

The full spectrum of germplasm in the genus *Oryza* consists of the following:

- Wild *Oryza* species, which occur throughout the tropics, and related genera, which occur worldwide in both temperate and tropical regions.
- Natural hybrids between the cultigens and wild relatives and primitive cultivars of the cultigen in areas of rice diversity.
- Commercial varieties, obsolete varieties, minor varieties and special-purpose types in the centres of cultivation.
- Pure line or inbred selections of farmers' varieties, elite lines of hybrid origin, F_1 hybrids, breeding materials, mutants, polyploids, aneuploids, intergeneric and interspecific hybrids, composites, cytoplasmic sources from breeding programmes and, more recently, transgenic lines produced through genetic engineering.

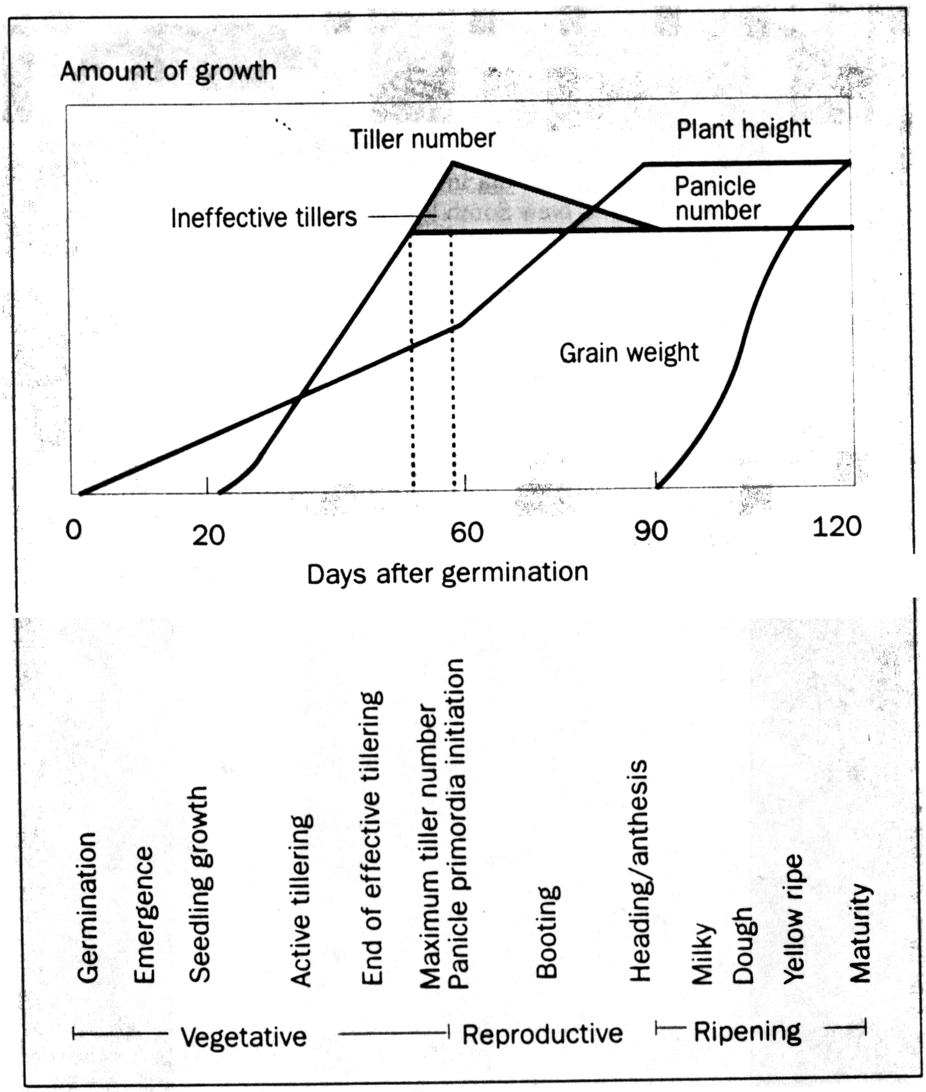

Fig. 19. Schematic growth of a 120-day rice variety in the tropics.

Conservation *ex situ* is a safe and efficient way to conserve rice genetic resources and to make the germplasm readily available to breeders and other researchers (Ford-Lloyd and Jackson 1986). Orthodox rice seed can be dried to a moisture content of ±6% and stored at subzero temperatures to keep them viable for decades and longer.

More than 219 000 accessions of cultivated and wild rices are stored in genebanks in more than 40 countries (Bettencourt and Konopka 1990). In Latin America and Europe, the accessions of *O. sativa* represent germplasm that has been introduced or developed as part of national rice breeding efforts. Accessions of *O. sativa* and *O. glaberrima* in Asia and Africa mostly represent indigenous landrace varieties that comprise the important germplasm heritage of these countries. The widespread distribution of wild rices throughout the tropics of Asia, Africa, South America and the Caribbean is reflected in their representation in national germplasm collections. The number of rice germplasm accessions does not necessarily reflect the genetic diversity of the rice crop because of the considerable exchange and duplication of genetic materials among genebanks.

Almost 100 000 samples of cultivated and wild rices are held in India, at the National Bureau of Plant Genetic Resources, and in the People's Republic of China, at the National Genebank of the Institute of Crop Germplasm Resources, Chinese Academy of Agricultural Sciences. Important collections are maintained in many other Asian countries, including the Philippines, Thailand and Indonesia. Japan holds about 12 000 accessions at the National Institute of Agrobiological Resources, in Tsukuba, which has a particular responsibility for the temperate-adapted japonica rices.

The most geographically diverse collections of rice germplasm are held in trust in the genebanks of two CGIAR centres, IRRI and IITA (Table 19.3). Together these institutes carry the responsibility for the long-term preservation of more than 86 100 samples of *O. sativa*, 3750 samples of *O. glaberrima* and 2900 samples of the 20 wild species in the genus *Oryza* – a total of almost 93 000 accessions. Add to these the several thousand accessions that WARDA maintains in working collections, many of them derived from its own breeding programmes, and the figure for rice germplasm in the CGIAR centres approaches 100 000 samples. About 34% of the germplasm conserved at IITA is a duplicate of accessions in the collection at IRRI.

Germplasm Collecting and Acquisition

Germplasm collecting has traditionally been a collaborative activity between the CGIAR centres and national programmes, and in Africa the effort has also involved other organizations such as ORSTOM, IRAT, IDESSA and IPGRI. Between 1972 and 1993, IRRI scientists have participated in 84 collecting missions in Bangladesh, Bhutan, India, Nepal and Sri Lanka in South Asia; in Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Papua New Guinea, Philippines, Thailand and Vietnam in Southeast Asia; and in Botswana, Zambia and Madagascar in Africa. These missions resulted in the collection of more than 11 900 cultivated rice samples and 1908 wild species samples.

Beginning in 1978, WARDA scientists at the Mangrove Swamp Rice Program in Rokupr, Sierra Leone, collected traditional mangrove swamp rice varieties. By 1986, the collection stood at 754 accessions of mainly *O. sativa* and a few *O. glaberrima* from the Gambia, Guinea, Guinea Bissau, Nigeria, Senegal and Sierra Leone. The WARDA Continuum Program at Bouaké in Côte d'Ivoire also collected and received upland rice varieties from NARS between 1985 and 1993. Many accessions were also received from IRAT, IITA and ORSTOM. This collection now encompasses more than 4800 samples of *O. sativa*, more than 1200 samples of *O. glaberrima* and some wild species. Samples have been collected from most of the major West Africa rice-growing countries, including Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, The Gambia, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo. Between 1976 and 1990, IITA carried out 60 exploration missions in more than 30 countries in Africa and collected more than 6000 cultivated and wild rice samples.

Between 1977 and 1985 IRAT and ORSTOM collected samples around Lake Chad, the Senegal River basin, Mali, Côte d'Ivoire, Guinea and Guinea Bissau. Their collection consists of three main species: *O. glaberrima* (222), *O. breviligulata* (=*O. barthii*) (19) and *O. longistaminata* (53), the perennial allogamous wild species (Bezançon *et al.* 1984; De Kochko 1985; Charrier and Hamon 1991).

Seed Conservation Facilities

The genebank at IRRI has operated since 1977 and after extensive renovation in 1993-94 was renamed the International Rice Genebank (IRG). It operates in accordance with the internationally accepted standards adopted by the FAO Commission on Plant Genetic Resources.

Table 19.3. The number of germplasm accessions of cultivated and wild rice species at IRRI and IITA in December 1995 (*O. sat.*=*Oryza sativa*; *O. glab.*=*Oryza glaberrima*).

	IRRI			IITA		
Country	*O. sat.*	*O. glab.*	Wild	*O. sat.*	*O. glab.*	Wild
Afghanistan	69			2		
Argentina	73		1	1		
Australia	94		66	16		
Austria	2					
Bangladesh	5462		77	23		
Belize	3					
Benin	4		2	75	16	
Bhutan	229					
Bolivia	11			1		
Botswana			2	7		11
Brazil	849		38	143		
Brunei	159		13			
Bulgaria	27					
Burkina Faso	457	52	2	861	180	1
Burundi	36					
Cambodia	1398		84			
Cameroon	66	27	49	84	69	1
Canada						
Central African Rep.	9			61	1	7
Chad	32	21	56	43	22	12
Chile	7					
Colombia	160		3	10		
Congo	1	1		1		
Costa Rica	12		7	1		
Côte d'Ivoire	841	10	11	79	209	5
Cuba	161		4	1		
Dominican Republic	10					
Ecuador	45			2		
Egypt	62	1		130	2	
El Salvador	37			24		
Ethiopia	6		12			
Fiji	26					
Former Yugoslavia	2					
France	192					
French Guiana			1			
Gabon	1					
Gambia	180	4	6	337	47	1
Ghana	198	15	6	163	44	
Greece	3					
Guatemala	13		8			
Guinea-Bissau	52	12	1	70	15	
Guinea-Conakry	549	110	14	484	77	3
Guyana	80		1			
Haiti	47					
Honduras	1					
Hong Kong	10					
Hungary	64					
India	14948		635	157		
Indonesia	8454		96	34		
Iraq	15					
Islamic Republic of Iran	195					
Italy	170					
Jamaica	6			4		
Japan	1103			16		
Kenya	253		10			
Republic of Korea	1098			104		

Country	IRRI O. sat.	IRRI O. glab.	IRRI Wild	IITA O. sat.	IITA O. glab.	IITA Wild
Korea DPR	7					
Lao PDR	1396		25	10		
Liberia	1413	416	1	1021	627	
Madagascar	1000		3	743		
Malawi	11			280		
Malaysia	2741		56	21		
Mali	46	271	121	53	136	8
Mauritania	2		1	3		
Mauritius	1					
Mexico	119		3	4		
Micronesia	7					
Morocco	2					
Mozambique	54					
Myanmar	1727		142	9		
Nepal	1472		16			
Netherlands	14					
New Zealand	1					
Nicaragua			1			
Niger	3	1	12	13	35	5
Nigeria	323	176	35	1092	1076	68
Pakistan	1073					
Panama	11		1	3		
Papua New Guinea	12		46	2		
Paraguay			1			
People's Rep. of China	7774		58	5		
Peru	65			16		
Philippines	4454		115	178		
Poland	9					
Portugal	69					
Puerto Rico	40			14		
Romania	32					
Russia & CIS	337			14		
Rwanda	2					
Saudi Arabia	1					
Senegal	552	85	18	548	81	11
Sierra Leone	775	24	18	358	28	1
Solomon Islands	2					
Spain	42					
Sri Lanka	2010		104	11		
Sudan	15	2	6			
Surinam	96		7	17		
Taiwan	1681		79	12		
Tanzania	125	2	37	328	4	6
Thailand	5084		522	21		
Togo	6			5	15	
Tunisia	1					
Turkey	53					
Uganda			15			
United Kingdom	8					
United States	1106			40		
Uruguay	5					
Venezuela	27		3	2		
Vietnam	1588		49			
Zaire	56		2	28		
Zambia	30		7	484	18	
Zimbabwe	93			44	2	
(Unknown)	1059	25	56	330	104	24
Total	**76614**	**1255**	**2765**	**9343**	**2808**	**164**

The IRG facilities include:

- An Active Collection for medium-term storage and distribution of samples maintained at a temperature of +4°C, 927 m^3, capacity for about 110 000 accessions of ±500 g each.
- A Base Collection for long-term (50->100 yr) conservation maintained at a temperature of −20°C, 164 m^3, capacity for 108 000 accessions, each with two aluminium cans, ±60 g each.
- Two screenhouses with a combined area of >4000 m^2. One is used for the cultivation of low viability or low seed stock accessions of cultivated rice. The other is used exclusively for the cultivation of the wild rices, in pots or special seedbeds.
- A seed drying room at 15°C and 15% RH, where seeds equilibrate to ±6% moisture content.
- A seed testing and germplasm characterization laboratory.
- A data management laboratory, with four computer work stations connected to the IRRI local area network.
- A conservation support laboratory for tissue culture of low viability and seed stock accessions, for cytological and biosystematic studies of the collection.
- A molecular marker laboratory, for studies of isozymes, random amplified polymorphic DNA (RAPD) and other markers.
- Access to >10 ha of field space on the IRRI Central Research Farm - upland site, with assured irrigation facilities for the multiplication and rejuvenation of germplasm and also field characterization.

The IITA also has both active and base collection seed storage facilities for rice germplasm conservation. The germplasm maintained by WARDA, however, including breeding lines, is currently stored in three working collections at each of its research sites: the Continuum Program at Bouaké, Côte d'Ivoire; the Irrigated Sahel Program at St. Louis in Senegal, and at WARDA's lowland breeding unit at IITA.

Rice can be grown almost throughout the year at the IRRI Central Research Farm, which is located at 121°15′E longitude and 14°13′N latitude. Germplasm is multiplied or rejuvenated for long-term conservation from November to May. Studies are conducted to determine optimal conditions for seed quality and longevity. In recent research at Los Baños, Kameswara Rao and Jackson (1996a, 1996b) identified the environmental factors that affect seed quality and therefore potential longevity of storage. Extending the work of Ellis *et al.* (1993) conducted under controlled conditions at the University of Reading in the UK, the field research in the Philippines included more rice varieties and a range of environmental conditions. Changes in seed quality during the ripening stage were studied in 16 rice cultivars, representing the three main types of *O. sativa* – indica, japonica and javanica – and one cultivar of *O. glaberrima*, grown during the 1992-93 dry season (November-May) at Los Baños, Philippines (Kameswara Rao and Jackson 1996a). Kameswara Rao and Jackson (1996b) also studied changes in seed quality during development and maturation in three japonica cultivars and one indica cultivar planted on three different dates in October and November 1993 and early January 1994. The changes in germplasm multiplication and rejuvenation that have been introduced at IRRI, coupled with the post-harvest handling of the seeds, have significantly enhanced the quality of rice germplasm stored in the IRG. If seeds do not germinate after 7 days under optimal conditions, their viability is determined using the topographical tetrazolium test (Ellis *et al.* 1985). Dehulling often improves germination, but studies indicate that different species respond to different temperature regimes (F.C. de Guzman, pers. comm.). For export of germplasm to some countries, a hot water treatment of seeds at 57°C for 15 minutes is a seed health requirement to control the seedborne nematode *Aphelenchoides besseyi*. Checking seed health before conservation has permitted the preparation of 10-g packs of seeds in the Active

Collection, ready for distribution. In the case of the wild species, only 10-20 seeds are distributed per sample.

In West Africa, seed is produced at each of WARDA's main research stations during the post-rainy season. The standing crop is inspected by experts and only disease- and insect-free seed is harvested. The moisture content is brought down to 6-8% before storage in the cold room. At each station, a 500-2000 g seed sample of each accession is kept in appropriate containers in air-conditioned rooms with temperatures ranging from 18 to 20°C and 20-30% RH. IITA maintains a collection of over 12 500 accessions, which include some accessions from WARDA and IRRI. Rice germplasm maintained at IITA was multiplied at rice paddies on site at IITA's station in Ibadan. During the growing season, rice plants were inspected by plant quarantine officers. Seeds harvested from healthy plants were certified for distribution.

For the active collection, up to about 500 g of seeds of each accession are stored in a plastic screw-top jar in a cold store conditioned at 5°C and 30% RH. Requests for germplasm samples from rice researchers are taken from this collection. For the base collection, about 150 g of seeds of each accession with seed germination rate known to be greater than 85% is dried to 5% moisture content in a drying cabinet or room conditioned at less than 10% RH and 20°C, and then sealed into aluminium cans or aluminium foil envelopes and stored in a cold room at –20°C.

At IRRI, the wild species are grown in pots in a restricted-access screenhouse. All wild species accessions are grown under a quarantine agreement with the Philippine Bureau of Plant Industry. Perennial species are maintained as living plants when seeds are difficult to produce. Since the panicles of wild rices shatter at maturity, they are bagged with nylon nets after pollination and mature seeds accumulating in the nets are collected for conservation. The seeds are dried to 6% moisture content, and small samples are stored in the Active and Base Collections.

For many years, the National Seed Storage Laboratory (NSSL) at Fort Collins, Colorado, USA, has provided a 'black box' duplicate safety storage for the germplasm from the IRG. In 1993 IRRI signed a formal agreement with USDA-ARS under which this 'black box' facility has operated. Sealed boxes of rice accessions in aluminium foil packs (20 g per accession) are placed in the –20°C vaults at NSSL, and remain sealed. The IITA, WARDA and IRRI also duplicate a proportion of the rice germplasm they hold in trust among the three institutes.

For several countries, including Sri Lanka, Cambodia and the Philippines, the germplasm conserved in the IRG represents a more or less complete duplicate of national rice collections. For other countries, such as India and the People's Republic of China, only a proportion of national collections are duplicated at IRRI. The IRG has provided an important safety net for several national conservation efforts, when for one reason or another, national collections were lost or where a genebank has not been established within a country. In this respect the germplasm conserved at IRRI has had a significant impact on national conservation efforts and whole collections have been restored to the country of origin. A notable example is Cambodia, where the cultivation of deepwater rices was actively discouraged during the period of political and civil strife of the 1970s. As a consequence, these rices were abandoned and lost in several provinces. Fortunately, earlier germplasm had been collected and conserved at IRRI and when the political climate changed, it was possible to return samples of each accession to Cambodia. In the cases of the Philippines and Sri Lanka, duplicate storage of national germplasm was an essential step during the development of a germplasm conservation infrastructure within each country. Once a medium-term genebank had been constructed in 1992 at the Philippine Rice Research Institute (PhilRice) located in Nueva Ecija Province on the island of Luzon, IRRI was requested to make available a complete set of Philippine accessions that now form the basis of the national rice germplasm collection. In Sri Lanka, a modern genebank was opened in the late 1980s at

Table 19.4. Germplasm restored to donors from the IRRI genebank.

Country	Year	No. of samples
Cambodia	1981-1989	524
India	1986, 1988, 1993, 1994	7111
Indonesia	1994	416
Mexico	1995	110
Nepal	1981	537
Pakistan	1982, 1984, 1985, 1994	3678
Philippines	1987, 1988	1973
Senegal	1988	517
Sri Lanka	1989, 1991	1950
Thailand	1994	392

Peradeniya, near Kandy, and local germplasm was restored to that country from accessions conserved at IRRI.

In 1994, IRRI received a request from the National Bureau of Plant Genetic Resources (NBPGR) in India for samples of the Assam Rice Collection which had been sent to IRRI for duplicate storage in the 1960s. Within a few months of receipt of this request, the IRG was able to return more than 5000 samples of this valuable germplasm to India, where it once again forms part of that country's germplasm heritage. In the same year, the IRG also restored rice germplasm to Thailand and Indonesia. In 1995, the Pakistan Agricultural Research Council requested the restoration of Pakistani accessions stored in the IRG. A list of all germplasm restoration is given in Table 19.4.

Germplasm Characterization and Evaluation

The IRRI and IITA germplasm has been characterized using 44 morphological and agronomic characters and according to the IRRI-IBPGR descriptors for *O. sativa*, published in 1980. Scientists have screened thousands of accessions and identified those having resistance to biotic stresses (Tables 19.5 and 19.6). Resistance to some stresses like grassy stunt virus was not found in *O. sativa*, but its identification in one accession (IRGC 101508) of *O. nivara* from India and its use in rice breeding led to the release of IR36 that at one time was the most widely cultivated variety of any cereal, occupying more than 11 million ha in its heyday (Swaminathan 1982). Based on extensive evaluation and analysis of resistance genes, researchers found distinct 'hot spots' for different pests and diseases (Table 19.7). Resistance to bacterial blight was found in Bangladesh and the Philippines; for blast in Vietnam, Lao PDR, Myanmar, Thailand; and brown planthopper in Sri Lanka. Vaughan (1991) also has indicated that the frequency of resistance genes to major pests and diseases is not uniformly spread throughout Asia. These areas deserve further collecting to acquire more sources and possibly new sources in a different genetic background.

Characterization of rice germplasm at WARDA's main research station at M'be, near Bouaké in Côte d'Ivoire, showed very wide variation in important morphological and agronomic traits within the traditional landraces of *O. sativa* and *O. glaberrima* as well as within some wild rice populations (Jones *et al.* 1993). In their evaluation studies, germplasm with rapid and vigorous vegetative growth to suppress weeds, tolerance for and resistance to major stresses such as drought, blast, African rice gall midge (ARGM), RYMV, nematodes and soil acidity has been identified. Growth duration (days from planting to maturity) of West African rice germplasm ranged from 80 to 140 days (Jones *et al.* 1993). Several accessions with very early duration of between 65 and 75 days to maturity were also identified, confirming earlier reports that some accessions of *O. glaberrima* evaluated during the dry season at Los Baños, Philippines matured within 50-60 days (Ng *et al.* 1991). Of 123 *O. glaberrima* entries screened in 1993 at WARDA, 14 were rated as resistant to leaf and neck blast (Jones *et al.* 1993). Forty-four accessions of

Table 19.5. The value of rice genetic resources: resistance to 13 disease and insect pests in *Oryza sativa* germplasm evaluated at IRRI.

Biotic stress	*O. sativa* accessions: Number	% resistant
Bacterial blight (*Xanthomonas oryzae* pv. *Oryzae*)	48203	11.2
Blast (*Pyricularia oryzae*)	36305	26.2
Sheath blight (*Thanatephorus cucumeris* (*Rhizoctonia solani*))	22754	9.2
Rice tungro disease	15795	3.5
Rice ragged stunt virus	13759	4.7
Brown planthopper biotype 1 (*Nilaparvata lugens*)	47268	1.6
Brown planthopper biotype 2	13652	1.5
Brown planthopper biotype 3	16643	1.9
Whitebacked planthopper (*Sogatella furcifera*)	56237	1.6
Green leafhopper (*Nephotettix* spp.)	57437	2.7
Rice whorl maggot (*Hydrellia philippina*)	22598	3.0
Zigzag leafhopper (*Recilia dorsalis*)	2732	10.1
Rice leaf folder (Cnaphalocrosis medinalis; Marasmia patnalis)	8005	0.6

Table 19.6. Rice germplasm accessions tested against major insect pests and diseases of rice by IITA scientists for the development of resistant varieties in Africa.

Insect	Number of accessions/lines: Tested	Identified as resistant
Stalk-eyed fly (*Diopsis longicornis*)	3767	35
Pink stem borer (*Sesamia calamistis*)	1369	8
White stem borer (*Maliarpha separatella*)	2415	5
Striped stem borer (*Chilo zacconius*)	600	10
Gall midge (*Orseola oryzivora*)	635	11
Whorl maggot (*Hydrellia prosternalis*)	430	2
Case worm (*Nymphula stagnalis*)	700	4
Angoumois grain moth (*Sitotroga cerealella*)	234	2
Rice yellow mottle virus	1531	95
Rice blast	1531	167

Sources: IITA 1975, 1976, 1977, 1982, 1983, 1984, 1985, 1986; Soto and Siddiqi 1976; Ng *et al.* 1980a, 1991; John *et al.* 1985; Alam and Masajo 1986; Abifarin 1991; Thottappilly and Rossel 1993; Paul *et al.* 1995.

Table 19.7. 'Hot spots' of useful resistance to diseases and pests in *Oryza sativa* germplasm.

Disease or pest	Country
Bacterial blight (*Xanthomonas oryzae* pv. *Oryzae*)	Bangladesh, Philippines
Blast (*Pyricularia oryzae*)	Vietnam, Lao PDR, Myanmar, Thailand
Sheath blight (*Thanatephorus cucumeris* (*Rhizoctonia solani*))	Malaysia, Sri Lanka, Vietnam
Rice tungro disease	Bangladesh
Brown planthopper (biotypes 1, 2 and 3) (*Nilaparvata lugens*)	Sri Lanka
Whitebacked planthopper (*Sogatella furcifera*)	Lao PDR
Green leafhopper (*Nephotettix* spp.)	Bangladesh

O. glaberrima inoculated with RYMV were highly resistant at IITA (Ng *et al.* 1980b). Jones *et al.* (1993) indicated that *O. glaberrima* could serve as a source of increased biomass, grain yield and improved grain quality.

Table 19.8. Varietal classification of *Oryza sativa* L. based on isozyme polymorphism (adapted from Glaszmann 1986).

Isozyme group	Germplasm
I	Typical indica: Aman (Bangladesh, northeast India), Tjereh (Indonesia), Hsien (China)
II	Varieties from foothills of Himalayas, from Iran to Assam
III	Bhadoia, Aswina (two deepwater varieties from Bangladesh)
IV	Rayada varieties (Bangladesh)
V	Very diverse group (along Himalayas from Iran to Myanmar): basmati rices (Pakistan, India, Nepal); some special rices from Myanmar
VI	Japonica rices (Japan, Korea), keng (China), bulu (Indonesia), upland rices (Southeast Asia), high-altitude varieties (Himalayas)

The application of isozyme and molecular techniques now permits further insight into genetic diversity. Glaszmann (1986) developed a classification of *O. sativa* based on the allelic pattern of 21 isozyme loci. Varieties of *O. sativa* were classified into six groups based on isozyme polymorphism that showed distinct geographic distribution (Table 19.8). The indica and japonica rices are placed in Groups I and VI, respectively, and this classification has proved extremely useful for the effective utilization of different germplasm in rice breeding because of the potential reproductive barriers. The javanica rices also fall within Group VI, and are often now referred to as tropical japonicas for this reason. They have become the basis of the new plant types being developed at IRRI and described by Khush (1993). The other isozyme groups II, III, IV and V include rice varieties with rather restricted distribution, such as the Rayada varieties of Bangladesh (Group IV) and the Basmati rices from Pakistan (Group V) renowned for their aroma. Analysis of nuclear and mitochondrial DNA has also added a new dimension to our understanding of the pattern of differentiation and diversity in rice (Second 1985; Second and Wang 1992).

The identification of duplicate accessions is a major concern for the IRG because the size of the collection is not necessarily a true reflection of genetic diversity of its germplasm. Efforts are underway to identify germplasm based on passport information, morphological comparison and molecular markers. In a collaborative research project between the University of Birmingham (UK) and IRRI, Virk *et al.* (1995a, 1995b) have demonstrated the utility of the PCR-based technique of analysis of RAPD. In one study, 'true' duplicates were included for comparative purposes, as well as suspected duplicate accessions and several that just represented a broad range of rice varieties and were not expected to be duplicates of any of the samples included in the study (Virk *et al.* 1995b). Not only did the study demonstrate that duplicate accessions could be identified, but it also raised the probability of identifying duplicate accessions with a given number of primers, and it indicated how many primers must be used to have confidence that duplicate accessions can be identified. In another study, these researchers showed that RAPD markers could be used to predict quantitative traits in the field (Virk *et al.* 1996).

Germplasm Exchange

Rice researchers throughout the world consider the IRG as a reliable source of rice germplasm. Since 1973, more than 740 000 samples of 10 g of seeds of each (for wild species just 10-20 seeds per packet) have been distributed to rice researchers free of charge, which includes more than 18% to collaborators outside IRRI. The requests are increasing every year, and during 1990 to 1994 alone, 157 363 samples of the cultivated and 9644 samples of wild relatives were supplied in response to requests from diverse sources. The major recipients were universities, research institutes and NARS. The germplasm is used most frequently by scientists at IRRI to identify sources of resistance to biotic and abiotic stresses. To send rice germplasm outside the Philippines requires an import permit from the requesting country and a Philippine phytosanitary certificate to accompany all shipments. Although it no longer has a mandate for rice improvement, IITA continues to distribute rice germplasm on request from its genebank.

Properties and Uses

Table 19.9 lists the caloric properties of rice for human use. Rice provides 20% of global human per capita energy and 15% of per capita protein (Juliano 1993). Unmilled (brown) rice of 17 587 cultivars in the IRRI germplasm collection averages 9.5% protein content, ranging from 4.3 to 18.2%. Rice also provides minerals, vitamins and fibre, although all constituents except carbohydrates are reduced by milling. Milling also removes roughly 80% of its thiamine. Environmental factors (soil fertility, wet or dry season, solar radiation and temperature during grain development) and crop management (added N fertilizer, plant spacing) affect rice protein content (Juliano and Bechtel 1985).

Where rice is the main item of the diet, it is frequently the basic ingredient of every meal and is normally prepared by boiling or steaming. In Asia, bean curd, fish, vegetables, meat and spices are added to rice. A small proportion of rice is consumed in the form of noodles, which serve as a bed for highly spiced specialities and as the bulk ingredient in soups.

Most rice is consumed in its polished state and when it constitutes a high proportion of food intake, dietary deficiencies may result (Juliano 1993). By contrast, parboiling rough rice before milling, a common practice in India and Bangladesh, allows a portion of the vitamins and minerals in the bran to permeate the endosperm and be retained in the polished rice (Juliano 1993). This treatment also lowers protein loss during milling and increases whole grain recovery.

Breeding

Landraces have become widely adapted to a range of agro-ecological conditions and to some pests and diseases. Initial rice breeding activities were limited to selection and purification of locally adapted landraces, which resulted in marginal gains of 10-15% increase in yield (Parthasarathy 1972). The first success in international rice breeding, which led to the release of Mahsuri and ADT27, was achieved at the Central Rice Research Institute, Cuttack, India, by crossing the tall tropical indica varieties with shorter japonicas from Japan and other regions of Eastern Asia. Rice breeding at IRRI began in 1962 following the acquisition of an array of rice germplasm from different sources. A major advance in rice breeding was the development of semidwarf varieties. These possessed high yield potential (10-11 t/ha), shorter crop duration from 150 days or longer to around 100 days, and greater yield stability through genetic resistance or tolerance for pests, diseases and problem soils. The first significant rice breeding achievement was the release of IR8 from a cross between the Chinese dwarf variety Dee-geo-woo-gen and the Indonesian variety Peta. Rice germplasm has been used to develop new plant types, reduce crop duration and incorporate resistance to biotic stresses (Chang 1985; Plucknett *et al.* 1987; Khush 1987, 1993; Chang and Li 1991; Jackson and Huggan 1993; Jackson 1995).

Breeding objectives vary from one rice ecosystem to another, but all emphasize high yield potential, good grain quality and yield stability (Khush 1993). IRRI breeders use pedigree breeding to develop germplasm with multiple resistance to diseases and insects important to Asian rice. Major genes control resistance to blast, tungro, grassy stunt, green leafhopper, brown planthopper and gall midge. Recurrent selection is the preferred method for quantitative trait loci (QTLs). In Latin America and the Caribbean (LAC), breeding aims to stabilize yields and reduce production costs by developing

Table 19.9. Rice consumption, caloric intake and percent of calories from rice, 1990.

Country	Milled rice consumption† (kg capita⁻¹ yr⁻¹)	Calories capita⁻¹ year⁻¹ Total‡	Rice	% calories from rice
Myanmar	190	2448	1893	77
Bangladesh	155	2100	1580	75
Indonesia	138	2631	1519	58
Thailand	128	2271	1258	55
Madagascar	104	2162	1091	50
Philippines	99	2452	995	41
People's Rep. of China	94	2706	959	35
India	66	2243	673	30
Japan	62	2926	699	24
Brazil	43	2723	448	16
Egypt	28	3318	300	9
Pakistan	19	2377	189	8
Nigeria	12	2147	130	6
South Africa	8	3158	86	3
Mexico	6	2986	64	2
USA	6	3680	69	2
Turkey	6	3262	57	2
CIS	6	3391	56	2
World	**55**	**2712**	**574**	**21**

Source: IRRI 1993.

† Amount available for human consumption.

‡ Data include all food available for human consumption

lines with higher and more stable resistance to major diseases and insects (particularly blast, RHBV, *Tagosodes oryzicolus* and leaf scald), grain discolouration, greater lodging resistance and better grain quality. A recurrent selection programme to increase the yield potential of lowland rice was initiated by CIAT-Palmira in 1993, using several genepools developed by CIRAD and CNPAF. Breeding for upland rice in LAC is concentrated in Brazil, Colombia and Mexico, and each programme deals with a different set of constraints. The Mexican group working on upland rice improvement for unfavourable environments is exploiting an Asian upland indica genetic base to identify drought tolerance and blast resistance. The semidwarf varieties have been adopted in 65% of the rice areas of the world and have doubled rice production from 256 million t in 1965 to 520 million t in 1990 (Khush 1993). The subsequent breeding efforts done by CIAT's Rice Program steadily improved the semidwarf prototype obtained from IRRI, particularly for early maturity, improved grain type and better pest resistance while maintaining the yield potential. Pests rapidly evolve to overcome resistances, however, and breeders constantly bring in new resistance sources just to maintain varietal performance. To increase yield potential further, IRRI scientists have developed a new plant type based on crosses between indica rices and the bulu rices of Indonesia – the so-called tropical japonicas. The discovery of cytoplasmic male sterility wild abortion type (CMS-WA) has permitted exploitation of hybrid vigour, which is reported to produce a 10-20% increase in yield (Virmani 1994).

The wild rices represent a reservoir of useful genes for resistance to diseases, insect pests and tolerance for abiotic stresses. Several useful traits from wild species (Table 19.10) have been transferred into elite breeding lines of rice through backcross breeding (Jena and Khush 1990). Four varieties (MTL98, MTL103, MTL105, MTL110) with resistance to the brown planthopper and whitebacked planthopper from *O. officinalis* (IRGC 100896) have been released in Vietnam. Two new CMS lines – IR66707 A and IR69700 A having cytoplasm from *O. rufipogon* and *O. glumaepatula*, respectively, and in the nuclear background of IR64 – also have been developed. The CMS source of these

Table 19.10. Transfer of useful characteristics from wild species into *Oryza sativa* using embryo rescue.

Species (genome)	Resistance to / tolerance for pests and diseases
O. brachyantha (FF)	Yellow stemborer, bacterial leaf blight (BB)
O. australiensis (EE)	Brown planthopper (BPH), BB
O. latifolia (CCDD)	BPH
O. minuta (BBCC)	BPH, blast, BB; sheath blight
O. officinalis (CC)	BPH, whitebacked planthopper, tungro
O. ridleyi (4x)	Yellow stemborer
O. nivara (AA)	BB, grassy stunt virus
O. longistaminata (A'A')	BB (*Xa-21*)
O. rufipogon (AA)	Tungro, acid sulphate, elongation ability

Source: D.S. Brar, pers. comm.

lines is different from WA cytoplasm, the most commonly used source in hybrid rice breeding (Virmani 1994).

Founded in 1975 as the International Rice Testing Program (IRTP), the International Network for Genetic Evaluation of Rice (INGER) today still provides an important mechanism for the safe exchange of elite germplasm.

Prospects

The collaborative efforts of the IARCs and scientists in many countries over more than three decades have contributed significantly toward the safe preservation of the rice genepool. Without this collaboration, much of the diversity of rice would have been lost altogether. Although much has been accomplished, the task has not yet been completed. Many countries in Asia are aiming to complete the task of collecting rice varieties before the end of the decade. In some countries, this means only collecting in a few remote areas that have not been surveyed in the past. In others, such as the Lao PDR, where collecting activities have been limited and few modern varieties have been introduced, much of the cultivation of rice is based on traditional varieties. During collecting in the second half of 1995, it was possible to identify many hundreds of different rice landraces being grown by farmers under rain-fed lowland and upland conditions.

As the economies of Asian countries in particular grow rapidly and as long as population growth remains unchecked, the demand for rice production from improved varieties will increase, thereby placing further pressure on traditional farming systems. On-farm conservation or farmers' management of diversity is being actively promoted as an alternative, and even better, strategy to *ex situ* conservation in genebanks. Beyond the generally accepted advantage of continued evolution of diversity, there is opportunity for seed exchange in dynamic systems, varietal improvement and the establishment of linkages between farmers' management of diversity and *ex situ* conservation (Bellon *et al.* 1997). Advocating these linkages is necessary, but developing a sustainable strategy is essential. There is a remarkable lack of research to back up the claims of the most ardent proponents of on-farm conservation. IRRI has initiated a research project to remedy this situation, and a multidisciplinary team led by a social anthropologist and population geneticist will evaluate the social and genetic consequences of different farmer management systems.

A question that is often asked concerns the value of rice genetic resources and what has been the return on investment for genetic conservation. Since genetic conservation does not aim to establish museum collections, the assumption has been that germplasm collections have value and genetic conservation has had an impact on rice improvement. Yale economist Robert Evenson and his colleague, Doug Gollin, made a study of the flows of rice germplasm and their impact on national rice production in a number of countries (Evenson and Gollin 1994). They showed that the use of landrace varieties had indeed increased over the past 10-15 years. Plucknett *et al.* (1987) also described IR36, in which no fewer than 15 landraces and one wild species figure in this variety's pedigree. The impact of particular alleles, such as that conferring grassy stunt virus from *O. nivara* (accession IRGC 101508), is easy to demonstrate. Unfortunately, such examples are few and far between.

We should not restrict our definition of use or value of germplasm to whether or not a particular accession has been used in breeding or appears in the pedigree of a released rice variety. Generating knowledge for rice science is equally important. The use of rice germplasm in research contributes to our knowledge about rice genetics, physiology, biochemistry, molecular biology and the reaction of this important crop to its many pests and diseases. All of these factors affect rice production.

The genebanks of the world contain much of the diversity of the rice genepool. This diversity has been used effectively by plant breeders to increase the productivity of rice varieties and thereby contribute to the well-being of growing populations in Asia and elsewhere in the world. It remains to be seen whether the application of biotechnology and molecular biology, which now permit the exploitation of novel and even alien genes to transfer important traits to rice varieties, will supersede the use of rice genetic resources. We do know that these tools are helping rice scientists to understand better the nature of genetic diversity in rice. In future they should help us to produce new varieties and to make the conservation of rice genetic resources more efficient.

Limitations

Irrigated rice production problems in Latin America and the Caribbean differ in many respects from those observed in Southeast Asia, South Asia and West Africa. Rice *hoja blanca* virus (RHBV) and its vector *Tagosodes oryzicolus* are present only in this region, whereas some constraints found in Asia, such as tungro and grassy stunt virus diseases and the brown planthopper, are not present. Similarly, yellow mottle virus found in Africa is not found in Latin America and the Caribbean. Some pests like blast are common to all rice-growing regions, but virulence diversity and frequencies are different. Direct seeding has always been a prevalent feature of rice in Latin America and the Caribbean, which together with often poor water control has resulted in serious weed problems that have led to the widespread use and abuse of herbicides in the region.

About one-fourth of the world's total riceland or approximately 40 million ha is rain-fed, contributing 18% of the global rice supply. Adverse climate, poor soils, a lack of suitable modern varieties and poverty keep farmers from being able to increase productivity. Technologies for the irrigated rice sector can also be applied in the favourable rain-fed lowland subecosystem.

Although upland rice constitutes a relatively small proportion of the total rice area, it is the dominant rice culture in Latin America and West Africa. In Asia, the area of the upland ecosystem is much larger than the area under rice, because rice is grown in rotation with many other crops (De Datta 1981). Upland rice soils range from erodible, badly leached alfisols in West Africa to fertile volcanic soils in some areas in Southeast Asia (Oldeman and Woodhead 1986). In Brazil, where upland rice is a major crop, soils have extremely low CEC values, high P fixation and high levels of exchangeable Al. Upland rice soils in most of Africa have low available water-holding capacity because of coarse texture, are often kaolinitic and have severe nutrient deficiencies and Al and Mg toxicities (Kang and Juo 1984).

Around 10 million ha of ricelands in South and Southeast Asia are subject to uncontrolled flooding. Although average yields are only about 1.5 t/ha, these areas support more than 100 million people. Farmers deal with problems of excess water in places ranging from stagnant >50 cm deep to the very deeply flooded (up to as much as 8 m) areas where floating rice is grown and the cropping systems vary depending upon the time, depth and duration of flooding (Catling 1992). Boro rices are grown in flood-prone ecosystems during the dry season in Bangladesh and India. Traditionally, boro rices were cultivated only in local land depressions that contained sufficient residual water in the soil for a crop during the dry season. With improved irrigation, mainly from tube wells, boro rice cultivation has now spread to other floodplains having low water percolation. Irrigated boro is fast replacing floating rices and has become a second rice crop in some young deltas. Such changes in rice cropping also have occurred in Vietnam after the construction of river canals.

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REFERENCES

Abifarin, A.O. 1991. Rice evaluation in Africa. Pp. 187-195 *in* Crop Genetic Resources of Africa. Vol. 1 (F. Attere, H. Zedan, N.Q. Ng and P. Perrino, eds.). IBPGR, UNEP, IITA, CNR, Rome.

Adair, C.R. , J.H. Martin, T.H. Johnston, C.N. Bollich, J.R. Gifford, N.E. Jodon, R.J. Smith, Jr., E.C. Tullis, B.D. Webb and J.N. Rutger. 1975. A summary of rice production investigations in the U. S. Department of Agriculture, 1898-1972. I-II. Rice J. 78 (3):26-29.

Alam, M.S. and T.M. Masajo. 1986. Resistance of rice varieties to gallmidge *Orseolia oryziora* H. & G. Abstract paper in Annual Plant Resistance to Insect Newsletter, Volume 12, June 1986, Purdue University, USA.

Bellon, M.R., J.L. Pham and M.T. Jackson. 1997. Rice farmers and genetic conservation. *In* Plant Conservation: the *In Situ* Approach (N. Maxted, B.V. Ford-Lloyd and J.G. Hawkes, eds.). Chapman & Hall, London. (in press).

Bettencourt, E. and J. Konopka. 1990. Directory of germplasm collections. 3. Cereals: *Avena*, *Hordeum*, Millets, *Oryza*, *Secale*, *Sorghum*, *Triticum*, *Zea* and Pseudocereals. IBPGR, Rome.

Bezançon, G., A. De Kochko and K. Goli. 1984. Cultivated and wild species of rice collected in Guinea. Plant Genet. Resour. Newsl. 57:43-46.

Catling, D. 1992. Rice in deep water. IRRI, Manila, Philippines and Macmillan, London and Basingstoke.

Chang, T.T. 1976a. Rice. Pp. 98-104 *in* Evolution of Crop Plants (N.W. Simmonds, ed.). Longman, London.

Chang, T.T. 1976b. The rice cultures. Phil. Trans. R. Soc. Lond. B. 275:143-157.

Chang, T.T. 1976c. The origin, evolution, cultivation, dissemination, and diversification of Asian and African rices. Euphytica 25:425-441.

Chang, T.T. 1985. Crop history and genetic conservation: rice—a case study. Iowa State J. Res. 59:425-456.

Chang, T.T. and E.A. Bardenas. 1965. The morphology and varietal characteristics of the rice plant. Technical Bull. 4. IRRI, Manila, Philippines.

Chang, T.T. and C.C. Li. 1991. Genetics and breeding. Pp. 23-101 *in* Rice: Production, Vol. I, 2nd edn. (B.S. Luh, ed.). Van Nostrand Reinhold, New York.

Chang, T.T. and D.A. Vaughan. 1991. Conservation and potentials of rice genetic resources. Pp. 531-552 *in* Biotechnology in Agriculture and Forestry, Vol. 14. Rice (Y.P.S. Bajaj, ed.). Springer-Verlag, Berlin, Heidelberg.

Charrier, A. and S. Hamon. 1991. Germplasm collection, conservation and utilization activities of the Office de la recherche scientifique et technique outre-mer (ORSTOM). Pp. 41-52 *in* Crop Genetic Resources of Africa, Vol. II (N.Q. Ng, P. Perrino, F. Attere and H. Zedan, eds.). Sayce Publishing, UK.

De Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley and Sons, New York.

De Kochko, A. 1985. Collecting rice in the Lake Alaotra region in Madagascar. Plant Genet. Resour. Newsl. 63:6-7.

Ellis, R.H., T.D. Hong and M.T. Jackson. 1993. Seed production environment, time of harvest, and the potential longevity of seeds of three cultivars of rice (*Oryza sativa* L.). Ann. Bot. 72:583-590.

Ellis, R.H., T.D. Hong and E.H. Roberts. 1985. Handbook of Seed Technology for Genebanks. Vol. I. IBPGR, Rome, Italy.

Evenson, R.E. and D. Gollin. 1994. Genetic resources, international organizations, and rice varietal improvement. Center Discussion Paper No. 713, Economic Growth Center, Yale University, New Haven, Connecticut, USA.

Ford-Lloyd, B. and M. Jackson. 1986. Plant Genetic Resources: an Introduction to their Conservation and Use. Edward Arnold, London.

Glaszmann, J.C. 1986. A varietal classification of Asian cultivated rice (*Oryza sativa* L.) based on isozyme polymorphism. Pp. 83-90 *in* Rice Genetics. IRRI, Manila, Philippines.

Grist, D.H. 1986. Rice. 6th edn. Tropical Agriculture Series. Longman, London and New York.

Huke, R.E. and E.H. Huke. 1990. Rice: then and now. IRRI, Manila, Philippines.

IITA. 1975. Annual Report for 1974. IITA, Ibadan, Nigeria.

IITA. 1976. Annual Report for 1975. IITA, Ibadan, Nigeria.

IITA. 1977. Annual Report for 1976. IITA, Ibadan, Nigeria.

IITA. 1982. Annual Report for 1981. IITA, Ibadan, Nigeria.

IITA. 1983. Annual Report for 1982. IITA, Ibadan, Nigeria.

IITA. 1984. Annual Report for 1983. IITA, Ibadan, Nigeria.

IITA. 1985. Annual Report for 1984. IITA, Ibadan, Nigeria.

IITA. 1986. Annual Report for 1985. IITA, Ibadan, Nigeria.

IRRI. 1993. IRRI rice almanac, 1993-1995. IRRI, Manila, Philippines.

IRRI. 1995. World rice statistics, 1993-1994. IRRI, Manila, Philippines.

Jackson, M.T. 1995. Protecting the heritage of rice biodiversity. GeoJournal 35:267-274.

Jackson, M.T. and R. Huggan. 1993. Sharing the diversity of rice to feed the world. Diversity 9 (3):22-25.

Jena, K.K. and G.S. Khush. 1990. Introgression of genes from *Oryza officinalis* Well ex Watt to cultivated rice, *O. sativa* L. Theor. Appl. Genet. 80 (6):737-745.

John, V.T., G. Thottappilly, Q. Ng, K. Alluri and J.W. Gibbons. 1985. Varietal reaction to rice yellow mottle virus disease. FAO Plant Prot. Bull. Vol. 33, No. 3.

Jones, M.P., E.A. Heinrichs, D.E. Johnson and C. Riches. 1993. Characterization and utilization of *Oryza glaberrima* in upland rice improvement. Pp. 3-12 *in* WARDA Annual Report 1993. Bouaké, Côte d'Ivoire.

Juliano, B.O. 1993. Rice in human nutrition. FAO Food and Nutrition Series, No. 26. FAO, Rome, Italy and IRRI, Manila, Philippines.

Juliano, B.O. and D.B. Bechtel. 1985. The rice grain and its gross composition. Pp. 17-57 *in* Rice: Chemistry and Technology, 2nd edn. (B.O. Juliano, ed.). American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Kameswara Rao, N. and M.T. Jackson. 1996a. Seed longevity of seventeen rice cultivars and strategies for germplasm conservation in genebanks. Ann. Bot. 77:251-260.

Kameswara Rao, N. and M.T. Jackson. 1996b. Seed production environment and storage longevity of japonica rices (*Oryza sativa* L.). Seed Sci. Res. 6:17-21.

Kang, B.T. and A.S.R. Juo. 1984. Review of soil fertility management and cropping systems for wetland rice production in West Africa. Pp. 493-502 *in* An Overview of Upland Rice Research. IRRI, Manila, Philippines.

Khush, G.S. 1987. Rice breeding: past, present and future. J. Genet. 66 (3):195-216.

Khush, G.S. 1993. Breeding rice for sustainable agricultural systems. Pp. 189-199. *in* International Crop Science I (D.R. Buxton, R. Shibles, R.A. Forsberg, B.L. Blad, K.H. Asay, G.M. Paulsen and R.F. Wilson, eds.). Crop Science Society of America, Madison, USA.

Ng, N.Q., I.W. Buddenhagen and S. Sarkarung. 1980a. Screening of rice germplasm for rice yellow mottle virus resistance. *In* The role of genetics in food and health in the eighties. Abstract of the Genetic Societies of Nigeria, 4th Annual Conference, University of Benin, Benin City, 4-5 December, 1980.

Ng, N.Q., T.T. Chang, D.A. Vaughan and C. Zuno-Alto Veros. 1991. African rice diversity: conservation and prospects for crop improvement. Pp. 213-227 *in* Crop Genetic Resources of Africa, Vol. II (N.Q. Ng, P. Perrino, F. Attere and H. Zedan, eds.). Sayce Publishing, UK.

Ng, N.Q., A.T. Perez and S. Sarkarung. 1980b. Screening of rice germplasm for leaf blast resistance. *In* The role of genetics in food and health in the eighties. Abstract of the Genetic Societies of Nigeria, 4th Annual conference, University of Benin, Benin City, 4-5 December, 1980.

Oldeman, L.R. and T. Woodhead. 1986. Physical aspects of upland rice environments (an introductory statement). Pp. 3-5 *in* Progress in Upland Rice Research. IRRI, Manila, Philippines.

Parthasarathy, N. 1972. Rice breeding in tropical Asia up to 1960. Pp. 5-29 *in* Rice Breeding. IRRI, Manila, Philippines.

Paul, C.P., N.Q. Ng and T.A.O. Ladeinde. 1995. Diallel analysis of resistance to rice yellow mottle virus in African rice *Oryza glaberrima* Steud. J. Genet. & Breed. 49:217-222.

Plucknett, D.L., N.J.H. Smith, J.T. Williams and N. Murthi Anishetty. 1987. Gene Banks and the World's Food. Princeton University Press, Princeton, USA.

Second, G. 1985. Geographic Origins, Genetic Diversity and the Molecular Clock Hypothesis in the *Oryzeae*. NATO Adv. Stud. Inst. Ser. G5:41-56.

Second, G. and Wang. Z.Y. 1992. Mitochondrial DNA-RFLP in genus *Oryza* and cultivated rice. Genet. Res. Crop Evol. 39:125-140.

Solheim, W.G. 1972. An earlier agricultural revolution. Sci. Am. 226 (4):34-41.

Soto, P.E. and Z. Siddiqi. 1976. Screening for resistance to African insect pests. Paper presented at the WARDA Varietal Improvement Seminar. Bouaké, Ivory Coast.

Swaminathan, M.S. 1982. Beyond IR36 - Rice research strategies for the 80s. Paper presented at the International Centers' Week, World Bank, November 10, 1982, Washington, D.C.

Thottappilly, G. and H.W. Rossel. 1993. Evaluation of resistance to rice yellow mottle virus in *Oryza* species. Indian J. Virol. 9(1):65-73 (January 1993).

Vaughan, D.A. 1989. The genus *Oryza* L.: current status of taxonomy. IRRI Res. Paper Ser. No. 138. IRRI, Manila, Philippines.

Vaughan, D.A. 1991. Choosing rice germplasm for evaluation. Euphytica 54:147-154.

Vaughan, D.A. 1994. The wild relatives of rice—a genetic resources handbook. IRRI, Manila, Philippines.

Vergara, B.S. 1991. Rice plant growth and development. Pp. 13-22 *in* Rice. Vol. I (2nd edn.) (B.S. Luh, ed.). Van Nostrand Reinhold, New York.

Virk, P.S., B.V. Ford-Lloyd, M.T. Jackson and H.J. Newbury. 1995a. The use of RAPD for the study of diversity within plant germplasm collections. Heredity 74:170-179.

Virk, P.S., B.V. Ford-Lloyd, M.T. Jackson, H. Pooni, T.P. Clemeno and H.J. Newbury. 1996. Predicting quantitative traits in rice using molecular markers and diverse germplasm. Heredity 76:296-304.

Virk, P.S., H.J. Newbury, M.T. Jackson and B.V. Ford-Lloyd. 1995b. The identification of duplicate accessions within a rice germplasm collection using RAPD analysis. Theor. Appl. Genet. 90:1049-1055.

Virmani, S.S. 1994. Heterosis and hybrid rice breeding. Monographs on Theoretical and Applied Genetics 22. Springer-Verlag Berlin and Heildelberg and IRRI, Manila, Philippines.

Yoshida, S. 1981. Fundamentals of Rice Crop Science. IRRI, Manila, Philippines.