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Four Decades of Breeding for Varietal Improvement of Irrigated Lowland Rice in the International Rice Research Institute

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Abstract : Since the establishment of the International Rice Research Institute (IRRI) in 1960, IRRI's breeding effort in varietal improvement for irrigated lowland has passed four decades. Breeding of semi-dwarf rice varieties such as IR8 at IRRI during first decade from 1960 to 1969 resulted in quantum leaps in yield potential, which marked the green revolution in Asia. During the second decade from 1970 to 1979, the primary emphasis of rice improvement has been directed towards incorporation of multiple disease and insect resistance and shortening of growth duration. Grain quality was the main target of crop improvement at IRRI during the third decade from 1980 to 1989. The fourth decade from 1990 to 1999 and beyond was focused again on the improvement of yield potential by developing hybrid rice and new plant type. Up to 1999, 46 indica inbred varieties and 2 indica/indica hybrid rice varieties were developed by IRRI and released in the Philippines for the irrigated lowland rice systems. Large-scale adoption of these improved varieties under modern crop management practices has resulted in a dramatic increase in rice production in major rice-growing countries. The hybrid varieties between indicas increased yield potential by 9% under the tropical conditions. New plant type (NPT) breeding has not yet resulted in an increase in yield potential. The second generation NPT developed by crossing tropical japonica with indica has demonstrated some promising results in terms of improvements in yield potential, disease and insect resistance, and grain quality.

Key words : Breeding, Disease resistance, Grain quality, Insect resistance, Irrigated rice, Yield potential.

Rice is the most important food crop in the world. Rice accounts for more than 40% of calorie intake in tropical Asia. Global rice production must reach 800 million tons of paddy rice to meet projected demand in 2030, which is 200 million tons more than the rice production in 2000 (FAOSTAT, 2003). This additional rice must come mainly from irrigated land in Asia because improving rice yields in most rainfed regions is constrained by drought, flooding, and poor soil quality (Cassman, 1999). Moreover, the scope for expansion of irrigated rice area is limited. Irrigated riceland contributes more than 75% of total rice production although it accounts for about 55% of total rice area. Therefore, the average yield of Asia's irrigated riceland must increase from 5.0 to 8.0 tons per hectare in the 30-year period from 2000 to 2030. Rice varieties with higher yield potential must be developed to enhance the average farm yields.

Yield potential is defined as the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water non-limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled (Evans, 1993). Potential yield refers to maximum yield that could be achieved by a crop in given environments (Evans and Fischer, 1999). Crop simulation model estimates potential yield with plausible physiological and agronomic assumptions. Therefore, yield potential is used mainly for measured comparison of varieties while potential yield for comparisons between different crops and environments (Evans and Fischer, 1999).

Since the establishment of the International Rice Research Institute (IRRI) in 1960, IRRI's breeding effort for improving rice yield potential of irrigated lowland has passed four decades (Table 1). The first decade from 1960 to 1969 emphasized on dwarf breeding by introducing dwarf genes from Taiwanese varieties to tropical tall land races. During the second decade from 1970 to 1979, the primary emphasis of rice improvement has been directed towards incorporation of multiple disease and insect resistance and shortening of growth duration. Grain quality was the main target of crop improvement at IRRI during the third decade from 1980 to 1989. The fourth decade from 1990 to 1999 and beyond was focused again on the improvement of yield potential by developing hybrid rice and new plant type.

In 1966, IRRI released IR8, the first high-yielding

Table 1. Breeding obectives in irrigated rice at IRRI during the last four decades.

Decade	Years	Breeding objective
1st	1960-1969	Dwarfism
2nd	1970-1979	Multiple disease and insect resistance
3rd	1980-1989	Grain quality
4th	1990-1999	High yield with hybrid and new plant type

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Abbreviations : CMS, cytoplasmic male sterility; DS, dry season; IRRI, International Rice Research Institute; NPT, new plant type; WS, wet season.

Table 2. General information on the 46 inbred and 2 hybrid varieties developed by the International Rice Research Institute and released in the Philippines for irrigated lowland in the tropics (modified from Khush and Virk, 2002).

Variety	Year of release	Line designation	Parents	Variety	Year of release	Line designation	Parents
IR5	1967	IR5-47-2	Peta Tangkai Rotan	IR58	1983	IR9752-71-3-2	IR28/Kwang-chang-ai IR36
IR8	1966	IR8-288-3	Peta Dee-geo-woo-gen	IR60	1983	IR13429-299-2-1-3	IR4432-53-33/PTB33 IR36
IR20	1969	IR532-E576	IR262-24-3 TKM6	IR62	1984	IR13525-43-2-3-1-3-2	PTB33/IR30 IR36
IR22	1969	IR579-160-2	IR8 Tadukan	IR64	1985	IR18348-36-3-3	IR5657-33-2-1 IR2061-465-1-5-5
IR24	1971	IR661-1-140-3	IR8 IR127-2-2	IR65	1985	IR21015-196-3-1-3	Batatais/IR36 IR52
IR26	1973	IR1541-102-7	IR24 TKM6	IR66	1987	IR32307-107-3-2-2	IR13240-108-2-2-3 IR9129-209-2-2-2-1
IR28	1974	IR2061-214-3-8-2	IR833-6-2-1-1 IR1561-149-1//IR24*4/*O. Nivara*	IR68	1988	IR28224-3-2-3-2	IR19660-73-4/IR2415-90-4-3-2 IR54
IR29	1974	IR2061-464-4-14-1	IR833-6-2-1-1 IR1561-149-1//IR24*4/*O. Nivara*	IR70	1988	IR28228-12-3-1-1-2	IR19660-73-4/IR54 IR9828-36-3
IR30	1974	IR2153-159-1-4	IR1541-102-6-3 IR20*4/*O. Nivara*	IR72	1988	IR35366-90-3-2-1-2	IR19661-9-2-3/IR15795-199-3-3 IR9129-209-2-2-2-1
IR32	1975	IR2070-747-6-3-2	IR20*2/*O. Nivara* CR94-13	IR74	1988	IR32453-20-3-2-2	IR19661-131-1-2 IR15795-199-3-3
IR34	1975	IR2061-213-2-17	IR833-6-2-1-1 IR1561-149-1//IR24*4/*O. Nivara*	PSBRc2	1991	IR32809-26-3-3	IR4215-301-2-2-6/BG90-2 IR19661-131-1-2
IR36	1976	IR2071-625-1-252	IR1561-228-1-2/IR1737 CR94-13	PSBRc4	1991	IR41985-111-3-2-2	IR4547-4-1-2/IR1905-81-3-1 IR25621-94-3-2
IR38	1976	IR2070-423-2-5-6	IR20*2/*O. Nivara* CR94-13	PSBRc10	1992	IR50404-57-2-2-3	IR33021-39-2-2 IR32429-47-3-2-2
IR40	1977	IR2070-414-3-9	IR20*2/*O. Nivara* CR94-13	PSBRc18	1994	IR51672-62-2-1-1-2-3	IR24594-204-1-3-2-6-2 IR28222-9-2-2-2-2
IR42	1977	IR2071-586-5-6-3	IR1561-228-1-2/IR1737 CR94-13	PSBRc20	1994	IR57301-195-3-3	IR35293-125-3-2-3/IR32429-47-3-2-2 PSBRc4
IR43	1978	IR1529-430-3	IR305-3-17-1-3 IR661-1-140-3	PSBRc26H	1994	IR64615H	IR62829A IR29723-143-3-2-1R
IR44	1978	IR2863-38-1-2	IR1529-680-3/CR94-13 IR480-5-9-3	PSBRc28	1995	IR56381-139-2-2	IR28239-94-2-3-6-2 IR64
IR45	1978	IR2035-242-1	IR1416-128-5/IR1364-37-3-1 IR1824-1	PSBRc30	1995	IR58099-41-2-3	IR72 IR24632-34-2
IR46	1978	IR2058-78-1-3-2	IR1416-131-5/IR1364-37-3-1 IR1366-120-3-1/IR1539-111	PSBRc52	1997	IR59682-132-1-1-2	IR48613-54-3-3-1 IR28239-94-2-3-6-2
IR48	1979	IR4570-83-3-3	IR1702-74-3-2/IR1721-11-6-8-3 IR2055-481-2	PSBRc54	1997	IR60819-34-2-1	IR72 IR48525-100-1-2
IR50	1979	IR9224-117-2-3-3-2	IR2153-14-1-6-2/IR28 IR36	PSBRc64	1997	IR59552-21-3-2-2	PSBRc2 IR39292-142-3-2-3
IR52	1980	IR5853-118-5	Nam Sa-gui 19/IR2071-88 IR2061-214-3-6-20	PSBRc72H	1997	IR68284H	IR58025A IR34686-179-1-2-1R
IR54	1980	IR5853-162-1-2-3	Nam Sa-gui 19/IR2071-88 IR2061-214-3-6-20	PSBRc80	1999	IR62141-114-3-2-2-2	IR50401-77-2-1-3 IR42068-22-3-3-1-3
IR56	1982	IR13429-109-2-2-1	IR4432-53-33/PTB33 IR36	PSBRc82	1999	IR64683-87-2-2-3-3	IR47761-27-1-3-6 PSBRc28

modern rice variety for the irrigated tropical lowlands. Up to 1999, 46 indica inbred varieties and 2 indica/indica hybrid rice varieties were developed by IRRI and released in the Philippines for the irrigated lowland rice systems (Table 2). These varieties were named as "IR" series until 1988, after which they have been designated as Philippine Seed Board Rice (PSBRc) varieties. Agronomic traits of the 48 varieties were summarized in Tables 3 and 4. These varieties and their derivatives have been widely grown in South and Southeast Asia and account for more than 80% of total rice production in this region (Khush, 1990).

The objectives of this review paper are to summarize what has been achieved in breeding for irrigated rice varieties at IRRI during the first three decades and to describe the progress in developing hybrid rice and new plant type at IRRI in the fourth decade for increasing yield potential of irrigated rice crop.

1. First decade : Development of first tropical semi-dwarf variety, IR8

Scientists at IRRI discovered soon after IRRI's founding in 1960 that the main constraint to grain yield was the architecture of the traditional tropical rice varieties, which were tall and lodged easily with fertilizer-N application (Khush et al., 2001). Tall varieties yielded essentially the same as the lodging-resistant varieties if they were supported with bamboo sticks. The supported tall varieties also responded positively to fertilizer-N application. Therefore, lodging was the primary cause of low yield when the traditional tropical rice varieties were subjected to modern crop management practices (Khush et al., 2001). The success in semi-dwarf wheat proved that breeding rice varieties with short stature could solve the lodging problem. Some semi-dwarf rice varieties were available in the subtropical area of Mainland China in the 1950s. Taichung Native 1 (TN1), a semi-dwarf variety from Taiwan, was first planted in the tropics in the late 1950s. However, TN1 was highly susceptible to major diseases and insects in the tropics. Development of semi-dwarf rice varieties for tropical conditions became the breeding objective of IRRI in the early 1960s (IRRI, 1962).

Plant breeders at IRRI made crosses in 1962 for

Table 3. Growth duration and plant height of 46 inbred and 2 hybrid varieties developed by the International Rice Research Institute and released in the Philippines for irrigated lowland in the tropics. Measurements were taken at maturity. All varieties were grown at IRRI farm in the dry season of 2001.

Variety	Growth duration (day)	Plant height (cm)
IR5	133	141
IR8	133	115
IR20	119	105
IR22	116	91
IR24	125	103
IR26	133	118
IR28	110	102
IR29	116	87
IR30	116	84
IR32	134	104
IR34	126	126
IR36	110	84
IR38	119	96
IR40	116	95
IR42	133	109
IR43	125	96
IR44	133	102
IR45	125	102
IR46	125	109
IR48	126	124
IR50	110	94
IR52	116	97
IR54	119	106
IR56	110	89
IR58	110	85
IR60	110	90
IR62	110	89
IR64	116	97
IR65	116	93
IR66	116	92
IR68	126	119
IR70	133	109
IR72	116	88
IR74	133	104
PSBRc2	133	105
PSBRc4	116	97
PSBRc10	116	82
PSBRc18	120	110
PSBRc20	116	97
PSBRc26H	125	109
PSBRc28	116	93
PSBRc30	120	96
PSBRc52	116	96
PSBRc54	116	98
PSBRc64	133	112
PSBRc72H	127	115
PSBRc80	116	103
PSBRc82	116	102

introducing dwarfing genes from Taiwanese varieties to tropical tall land races. The short statured parents from Taiwan were Dee-geo-woo-gen (DGWG), TN1, and I-geo-tse. The eighth cross that IRRI breeders made in late 1962 was between Peta, a tall, vigorous variety from Indonesia, and DGWG. From that cross, IR8, the first semi-dwarf, high yielding modern rice variety for the irrigated tropical lowlands, was selected (Fig. 1). After the release of IR8, three semi-dwarf varieties, IR5, IR20, and IR22 were developed and released in the Philippines during the first decade from 1960 to 1969.

Table 4. Yield components of 46 inbred and 2 hybrid varieties developed by the International Rice Research Institute and released in the Philippines for irrigated lowland in the tropics. Measurements were taken at maturity. All varieties were grown at IRRI farm in the dry season of 2001.

Variety	Panicles per m^2	Spikelets per panicle	Spikelet filling %	1000-grain weight (g)
IR5	357	126	65	21
IR8	323	111	63	27
IR20	337	117	77	19
IR22	419	71	81	22
IR24	312	98	77	26
IR26	380	106	74	21
IR28	414	77	74	23
IR29	469	57	78	22
IR30	462	66	79	21
IR32	411	77	70	22
IR34	308	114	66	25
IR36	451	75	69	21
IR38	333	71	82	24
IR40	435	75	86	19
IR42	397	96	77	19
IR43	328	83	76	28
IR44	409	65	75	25
IR45	348	82	79	27
IR46	388	93	82	22
IR48	235	122	74	27
IR50	485	88	70	19
IR52	341	77	81	24
IR54	293	103	71	24
IR56	388	76	81	24
IR58	417	70	85	21
IR60	458	77	80	20
IR62	435	80	73	22
IR64	371	78	84	25
IR65	376	81	73	22
IR66	384	89	79	21
IR68	271	112	73	30
IR70	389	92	76	20
IR72	390	70	75	22
IR74	415	93	72	24
PSBRc2	353	95	77	24
PSBRc4	394	81	83	23
PSBRc10	381	92	77	23
PSBRc18	427	86	70	22
PSBRc20	394	89	74	22
PSBRc26H	277	128	64	24
PSBRc28	412	88	75	22
PSBRc30	369	74	69	24
PSBRc52	514	81	70	20
PSBRc54	372	113	62	21
PSBRc64	347	90	76	23
PSBRc72H	235	114	75	27
PSBRc80	375	99	70	23
PSBRc82	420	93	74	23

IR8 has semi-dwarf stature (about 115 cm tall), a profuse tillering growth habit, stiff culm, and erect, moderately sized, dark-green leaves (Chandler, 1969). It is responsive to fertilizer and is photoperiod insensitive compared with many traditional varieties. It has medium growth duration of 130 to 135 d. The birth of IR8 resulted in quantum leaps in yield potential from 6 to 10 tons per hectare in the tropics (Chandler, 1982). The increase in yield potential was due to the improvement in harvest index. Although selections were guided by short stature, and resistance to lodging, breeders were unintentionally selecting for improved canopy architecture, light penetration, and efficient biomass partitioning

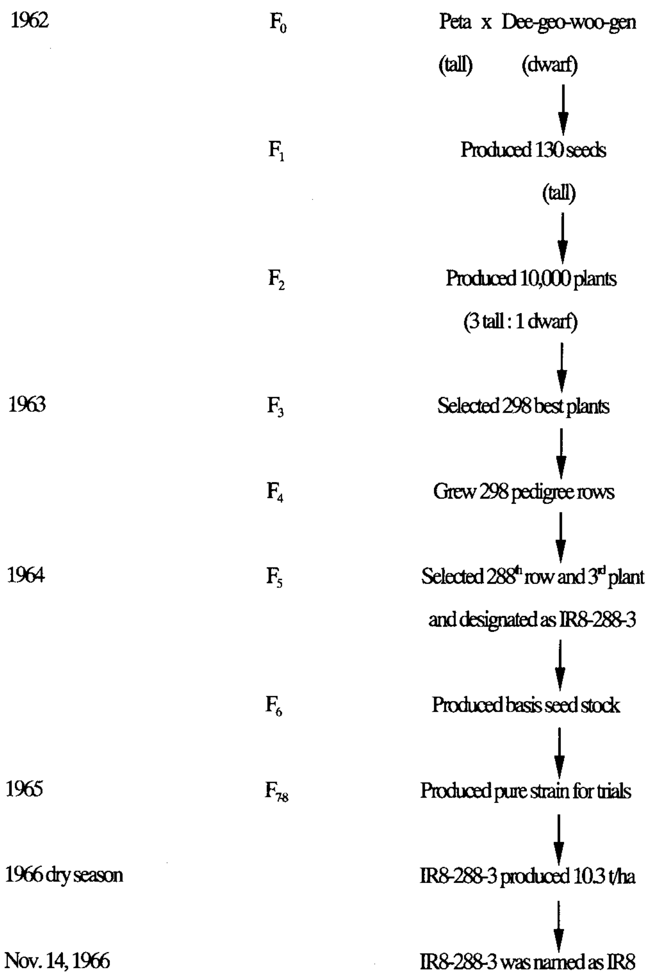

Fig. 1. Scheme of breeding procedure for the development of IR8.

between grain and straw, that resulted in an increase in harvest index (Takeda, 1984). Adoption of the high-yielding variety IR8 occurred rapidly in South, East and Southeast Asia because farmers obtained a yield advantage of 1 to 2 t ha^{-1} on irrigated land compared with traditional varieties (Chandler, 1972). IR8 together with modern wheat varieties developed by Norman E. Borlaug and his team at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico ushered in the green revolution in the world in the 1960s.

Although IR8's improved yield potential increased farmers' yield, its poor grain quality was a major concern. In 1969, IR532-E576 and IR579-160-2 were released as IR20 and IR22 in the Philippines, respectively. Compared with IR8, IR20 and IR22 had attractive and translucent grains with high milling recovery (Khush et al., 2001).

2. Second decade : Development of first variety with multiple resistance, IR36

Tropical climate is more conducive for infestation of the rice crop by diseases and insects as compared to the temperate climate. Crop management practices for improved modern high yielding varieties such as fertilizer application and increased population density, resulted in increased disease and insect damages. In tropical Asia, the most common diseases of the rice crop were blast, bacterial blight, sheath blight, tungro virus and grassy stunt virus; the most common insects were brown planthopper, green leafhopper, stem borer, and gall midge. The main emphasis in the IRRI's breeding program in the 1970s was incorporation of disease and insect resistance and shortening of growth duration (Khush et al., 2001). Large germplasm collections were screened at IRRI to identify donors for resistance to most of the diseases and insects. Varieties with resistance to as many as four diseases and four insects have been bred using those donors.

During the second decade from 1970 to 1979, 17 rice varieties were developed and released in the Philippines for tropical lowlands. Most notable was IR36. IR36 was bred using 12 varieties and one wild species from six countries (Khush et al., 2001). In 1971, IR1561 was crossed with a plant from the *Oryza nivara*/IR24 back-cross. This F_1 was topcrossed with a third parent (CR94-13). In 1972, F_2 population was grown. In December 1972, 937 plants were grown in a pedigree nursery as F_3 rows. In 1973 and 1974, F_4 and F_5 progenies were evaluated. IR2071-625-1-252 was selected among these progenies and was named as IR36 by the Philippine Seed Board in 1976. IR36 was the first IRRI improved variety with multiple disease and insect resistance (bacterial blight, blast, tungro, grassy stunt, brown planthopper, green leafhopper, stem borer, and gall midge). It had other desirable agronomic traits such as short growth duration of 110 days, good grain quality (long, slender and translucent grains), and tolerance to abiotic stresses. Its yield potential was evaluated at IRRI, in Philippine Seed Board trials conducted at 10 sites, and in the International Rice Testing Program nurseries. It outyielded the IR30 check during both the dry and wet seasons. Because of the desirable combination of these adaptive traits, IR36 was accepted widely and became the most widely planted rice variety in the 1980s, grown on about 11 million hectares annually from 1980 to 1989 (Khush et al., 2001). IR36 was gradually replaced by IR64 but is still planted in Indonesia, India, and the Philippines. Until today, IR36 is still the variety of rice or any other food crop species that is planted on largest accumulated area in the world.

3. Third decade : Development of variety with high grain quality, IR64

The earliest IRRI varieties such as IR5 and IR8 had poor grain quality with bold and chalky grains that were easily broken during milling (Khush and Virk, 2002). All the varieties released after IR5 and IR8 had improved milling quality with slender and translucent grains and good milling recovery. However, improvement in cooking quality was slow because the donors for disease and insect resistance used during 1970s had high amylose content and low gelatinization temperature. Rice consumers in Southeast Asia prefer rices with intermediate amylose content, soft gel consistency, and intermediate gelatinization temperature, while preference in South Asia was high amylose content. Most of the varieties developed during the second decade had high amylose content.

During the third decade from 1980 to 1989, IRRI breeders made significant progress in improving the grain quality, especially cooking quality. Thirteen varieties were developed for irrigated tropical lowlands during this period. Among them, IR64 was the first variety with a desirable combination of intermediate amylose content, soft gel consistency, intermediate gelatinization temperature, translucent, and long slender grains. IR64 was a descendant of 20 land races from eight countries (Khush et al., 2001). It inherited its superior grain quality from a popular pre-green revolution Philippine variety BPI 76. IR64 was another widely grown rice variety in the world, grown on 8 to 9 million hectares of rice land annually in Asia in late 1980s and 1990s. It is still a very popular variety in many countries. Although yield potential remained the same for varieties developed in the second and third decades, their average yield per day was higher due to reduction in growth duration.

4. Fourth decade : Development of hybrid rice and new plant type

Annual rice production increased at the rate of 2.8% between 1975 and 1985 through the use of fertilizer-responsive improved varieties. However, signs of slower growth were evident in the late 1980s when the growth in grain production fell below that of population. In the late 1980s, IRRI's strategic plan focused again on the improvement of yield potential by developing hybrid rice and new plant type (IRRI, 1989). During the fourth decade from 1990 to 1999, 12 varieties were developed for irrigated tropical lowlands and released in the Philippines. Among the 12 varieties, two were indica hybrids developed using the three-line system.

(1) Development of hybrid rice

Hybrid rices have been grown in China since 1976 and today more than 50% of China's rice area is now planted to rice hybrids (Yuan et al., 1994). In the late 1970s, these Chinese rice hybrids were evaluated in tropical lowland environments of Southeast Asia. They were poorly adapted and were susceptible to diseases and insects (Virmani et al., 1982). In 1978, IRRI began to develop hybrids for the tropical lowlands (Khush, 1995). Cytoplasmic male sterility (CMS) and the fertility restoration system are the most common tools used for breeding rice hybrids for the tropics. During the third and fourth decades from 1979 to 1999, IRRI has bred many CMS, maintainer, and restorer lines. Two IRRI CMS lines, IR58025A and IR62829A, are the most popular parents for development of rice hybrids in the tropics. In 1994, the Philippine government released PSBRc26H, the first hybrid combination for cultivation in irrigated lowlands in the Philippines. This rice hybrid used IR62829A as the sterile parent. In 1997, Philippine government released another hybrid combination, PSBRc72H, whose sterile parent was IR58025A. Both combinations are hybrid varieties between indica parents and were developed by IRRI using the three-line system.

Some hybrid rices developed at IRRI have shown a yield advantage of about 15% compared to the best inbred varieties when grown in farmers' fields (Virmani, 2001). Farmers usually produce 1 to 1.5 t/ha additional yield by growing hybrid rice. Peng et al. (1999) compared the yield potential of hybrids and indica inbred varieties grown in several field experiments. The results suggest an increase in yield potential of indica hybrids of about 9% compared with the best indica inbred varieties under tropical conditions. The higher yield potential of indica hybrids compared with indica inbred varieties was attributed to the greater biomass production rather than harvest index.

Commercialization of hybrid rice has been initiated in Vietnam (1992), India (1994), the Philippines (1998), and Bangladesh (1999) (Virmani, 2001). Currently, about 280,000, 150,000, 5,000, and 250,000 ha were planted with hybrids in these countries, respectively. However, the area planted to hybrid rice is still quite small in the tropical countries. Major limitations to the large-scale adoption of hybrid rice technology in the tropics are : inadequate level of standard heterosis for grain yield, poor agronomic management of hybrid rice, low yield of hybrid seed production, high seed cost, and poor grain quality. Once these limitations are eliminated by extensive research, area planted to hybrid rice should increase in the tropics.

(2) Development of new plant type

Development of semi-dwarf rice varieties in the 1960s is the most striking example of a successful improvement in plant type. In the late 1980s, it was postulated that the stagnant yield potential of semi-dwarf indica inbred rice varieties might be the result of the plant type common to all of this germplasm. They produce a large number of unproductive tillers and have excessive leaf area which may cause mutual shading and a reduction in canopy photosynthesis and sink size, especially when grown under direct-seeded conditions (Dingkuhn et al., 1991). Most of these varieties have high tillering capacity and small panicles. A large number of unproductive tillers, limited sink size and lodging susceptibility were identified as the major constraints to yield improvement in these varieties. Simulation models predicted that a 25% increase in yield potential was possible by modification of the following traits of the current plant type (Dingkuhn et al., 1991) : (1) enhanced leaf growth combined with reduced tillering during early vegetative growth, (2) reduced leaf growth and greater foliar N concentration during late vegetative and reproductive

Table 5. Yield and yield components of second and first generation new plant type lines and indica checks grown at IRRI farm in the dry season of 2001.

Genotype	Grain yield (t ha^{-1})	Panicles m^{-2}	Spikelet/ Panicle	Grain filling (%)	Grain wt (mg)
Second generation new plant type lines					
IR72158-16-3-3	10.3	345	144	70	26.9
IR72158-16-3-3-1	10.1	308	151	72	27.0
IR73459-120-2-2-3	10.0	360	126	78	25.5
IR72967-12-2-3	9.8	300	138	75	28.4
IR72985-65-3-1	9.4	391	115	79	24.2
IR73707-45-3-2-3	9.3	306	140	77	25.3
First generation new plant type lines					
IR68552-100-1-2-2	9.2	220	179	79	25.9
IR65564-44-2-3	6.6	217	181	60	25.3
Indica checks					
IR72	6.7	453	82	76	21.5
PSBRc18	7.1	372	102	73	23.1

growth, (3) a steeper slope of the vertical N concentration gradient in the leaf canopy with a greater proportion of total leaf N in the upper leaves, (4) increased carbohydrate storage capacity in stems, and (5) a greater reproductive sink capacity and an extended grain-filling period.

To break the yield potential barrier, IRRI scientists proposed modifications to the high-yielding indica plant type in the late 1980s and early 1990s. The proposed new plant type (NPT) has low tillering capacity (3 to 4 tillers when direct seeded), few unproductive tillers, 200 to 250 grains per panicle, a plant height of 90 to 100 cm, thick and sturdy stems, leaves that were thick, dark green, and erect, a vigorous root system, 100 to 130 days growth duration, and increased harvest index.

Breeding work began in 1989 when about 2,000 entries from the IRRI germplasm bank were grown during the dry (DS) and wet (WS) seasons to identify donors for the desired traits (Khush, 1995). Donors for low tillering trait, large panicles, thick stems, vigorous root system, and short stature were identified in the "bulu" or javanica germplasm mainly from Indonesia. This germplasm is now referred to as the tropical japonica (Khush, 1995). Hybridization was initiated in the 1990 DS. The F_1 progenies were grown in the 1990 WS, F_2 progenies in the 1991 DS, and the first pedigree nursery in the 1991 WS. Since then, more than 2,000 crosses were made, 100,000 pedigree lines were produced, breeding lines with the desired morphological ideotype traits were selected, and about 500 NPT lines have been evaluated in observational yield trials.

The NPT lines based on tropical japonicas were developed in less than 5 years. They were grown in a replicated observational trial for the first time in late 1993. As intended, the NPT lines had large panicles, few unproductive tillers, and lodging resistance. Grain yield was disappointing, however, because of low biomass production and poor grain filling. Reduced tillering capacity might contribute to low biomass production because the crop growth rate during vegetative stage of NPT lines was lower than the indica varieties. Less biomass production was also associated with poor grain filling, but the cause-and-effect relationship has not been established. The poor grain filling of NPT lines was probably due to lack of apical dominance within a panicle (Yamagishi et al., 1996), compact arrangement of spikelets on the panicle (Khush and Peng, 1996), a limited number of large vascular bundles for assimilate transport (S. Akita, personal comm.), and source limitation due to early leaf senescence (Ladha et al., 1998). The NPT lines are also susceptible to diseases and insects and have poor grain quality.

In 1995, development of second-generation NPT lines was initiated by crossing tropical japonica NPT lines with elite indica parents. Multiple site-year comparisons of NPT lines with highest yielding indica varieties have shown that the original NPT design did not have sufficient tillering capacity. An increase in tillering capacity is needed to increase biomass production and to improve compensation when tillers are lost to insect damage or other causes during the vegetative stage. A slightly smaller panicle size without change in panicle length also appeared to be advantageous to reduce the compact arrangement of spikelets. Some second generation NPT lines (F_5 generation) with the above refinements have then been selected and were planted in a replicated observation trial for the first time in the 1998 WS. These second-generation NPT lines have been tested in breeder's replicated yield trial in the 2001 DS (Table 5) and in a replicated agronomic trial in the 2002 DS (Fig. 2) and results are promising. In the 2001 DS, yield components were measured from small plots and based on 12-hill samples (0.5 m^2 harvest area). We could see relative difference in grain yield and its attributes among first generation NPT, second generation NPT and indica checks from this study. It was not reliable to determine the yield potential of second-generation NPT lines from Table 5 because of small plots and small harvest areas. In the replicated agronomic trial conducted in the 2002 DS, plot size was 25 m^2 and grain yield was measured from 5 m^2 harvest area. Yield potential of second generation NPT lines, hybrid varieties, and indica inbred

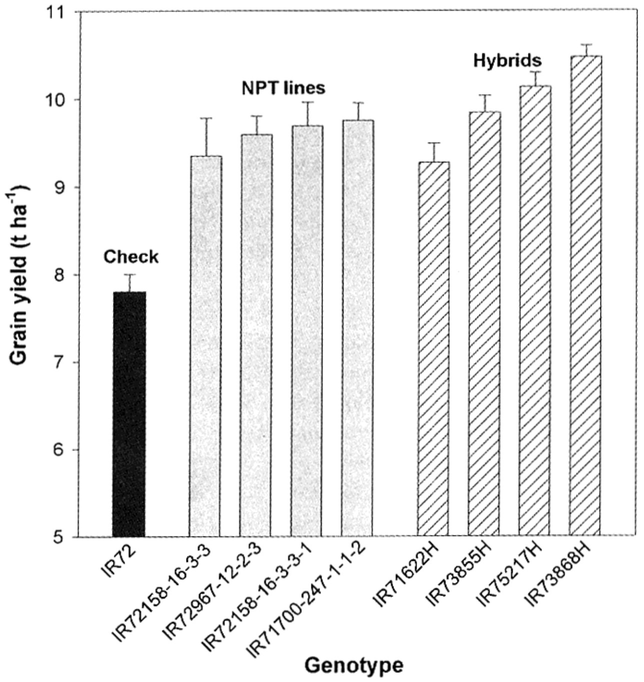

Fig. 2. Grain yield of second generation new plant type lines and hybrid rice varieties grown at IRRI farm in the dry season of 2002. Error bars represent standard error of mean (SE).

check can be compared from this study. Although second generation NPT lines did not break the yield barrier of 10 t/ha as did by some hybrid varieties, they produced significantly higher yield than indica inbred check variety (Fig. 2). It was observed that some second generation NPT lines produced more biomass than indica inbred varieties due to their taller stature and larger leaf area. They also had larger panicles (more spikelets per panicle) as compared with indica inbred varieties. The simulated climatic yield potential for the 2001 DS is 7.9 t ha^{-1}, but 10 t ha^{-1} for the 2002 DS. The yield attributes of second generation NPT for achieving 11.0 t ha^{-1} are listed in Table 6.

Indica germplasm also helped improve other NPT attributes such as grain quality and disease and insect resistance. As the effort of breeding for second generation NPT continuous, it is expected that more elite second generation NPT lines with improved yield potential, disease and insect resistance, and grain quality will be developed at IRRI. These elite second generation NPT lines should increase the yield potential of irrigated lowland rice by about 10% in the tropics.

5. Conclusion

Breeding of semi-dwarf rice varieties at IRRI during first decade from 1960 to 1969 resulted in quantum leaps in yield potential, which marked green revolution in Asia. During the second and third decades, IRRI breeders improved disease and insect resistances; grain quality and shortened growth duration while maintaining the yield potential. Large-scale adoption of these improved

Table 6. Yield attributes of second generation new plant type lines.

Traits	Values
Panicles per m^2	330
Spikelets per panicle	150
Grain filling	80%
Grain weight (oven dry weight)	25 mg
Aboveground total biomass (at 14% moisture content)	22 t ha^{-1}
Harvest index	50%
Grain yield (at 14% moisture content)	11.0 tha^{-1}

varieties under modern crop management practices has resulted in a dramatic increase in rice production in major rice growing countries. During the fourth decade, IRRI developed hybrid rice and new plant type for the tropical environments. The hybrid varieties between indicas increased yield potential by 9%. New plant type breeding has not yet resulted in an increase in yield potential. The second generation NPT developed by crossing tropical japonica NPT lines with elite indica parents is expected to improve yield potential, disease and insect resistance, and grain quality. Further increase in yield potential is possible through inter-subspecific hybrid (indica x tropical japonica NPT) and biotechnology.

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