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RICE BREEDING AT THE CALIFORNIA RICE EXPERIMENT STATION

K.S. MCKENZIE*, V.C. ANDAYA, F. JODARI, S.O. PB. SAMONTE, J.J. OSTER and C.B. ANDAYA

Rice Experiment Station, California Cooperative Rice Research Foundation, Inc. Biggs, California 95917, USA
*Corresponding author's email: ksmckenzie@crrf.org

SUMMARY

Commercial rice production in California has been underway since 1912 initially relying on selections from japonica plant introductions from Japan and China followed by release of the founding medium grain Calrose in 1948. The establishment of a grower-funded accelerated rice breeding program at the Rice Experiment Station in 1969 has supported California rice production with the release of 45 rice cultivars including medium-, short-, long-grains as well as specialty market types. Support, structure, methods, and objectives of the RES Rice Breeding Program are described.

Keywords: Temperate japonica rice, yield, quality, milling, cold tolerance, disease resistance, grower funded research

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INTRODUCTION

California rice production

Rice production in California is concentrated in the Sacramento Valley of Northern California. This is a temperate Mediterranean climate with low humidity, essentially no summer rainfall, and relatively high day time temperatures. Low night time temperatures may occur periodically causing pollen sterility and yield loss. Thus indica and tropical varieties have not been successful. Cold tolerant japonica types adapted to a high intensity water-seeded lowland production system on heavy clay soils are grown. Approximately 90% of the California production is planted to medium grains, 8% short grains, and 2% long grains. The production system is highly mechanized which includes aircraft seeding, precision fertilizer application, and chemical pest control. There are relatively few diseases and insect pests, but weed control is a major production challenge and expense for growers. There is organic rice production on about 5% of the area. Planting begins in mid-April and is concluded by early June, with harvest beginning in September and usually completed by early November. The California Rice Industry is subject to considerable government regulations and restrictions; including pesticide registration, use, and application; management practices (burning residue and water management); approval of rice cultivars for commercial production as well as rice research activities (importation of seed into California, transgenic rice and types with potential commercial impact). It is an expensive crop to grow and requires considerable capital and equipment. California rice growers are typically innovative, quick to adopt new technology, active in the industry and government, and fund the grower-owned Rice Experiment Station (RES) as well rice research by the University of California (UC) and the USDA-ARS.

RICE BREEDING PROGRAM

History

Although rice production for California had been proposed and attempted since the mid-1800s, the event that seems to have launched California rice production and RES was the maturing of a successful rice crop on 16 hectares on the Crane Ranch, southwest of Biggs, California. The 1908 experiment was the work of W.W. Mackie (a soil specialist with the USDA's Bureau of Soils Survey), and led to the founding of RES in 1912. In the previous few years, scientists with the USDA's Bureau of Plant Industries tested and identified a few plant introductions that successfully produced a rice crop in small plantings in the heavy clay soils of the Northern Sacramento Valley. In the following few years, selections of two of the best adapted selections short grain introductions were identified and named 'Caloro' and 'Colusa' (Johnson, 1958). They became the predominant California rice cultivars for the next 45 years.

By the 1930s, there had been rapid development in related disciplines, and applied plant breeding was beginning to emerge and make its mark in areas like hybrid corn and cereal breeding. Genetics, with its laws of inheritance, were better-understood and scientific breeding methods helped develop new cultivars through hybridization and selection. This brought plant breeders knowledge and tools to use "directed evolution" to develop improved cultivars, rather than just relying on introductions from other places and random variability created in materials due to natural out-crossing or mutations. Planned cross-pollination, followed by the natural self-pollination and selection of rice until the traits became fixed, was used to develop rice cultivars in the Southern United States and undertaken at RES. This pedigree breeding method led to the 1948 release of the medium grain 'Calrose' (Johnson, 1958) and continues to be the predominant method for varietal improvement at RES. By 1960, Calrose was grown on 30% of California rice acreage and by 1975 that number had risen to 70%. Although the cultivar Calrose is no longer grown commercially today, the name has become a market class for rice cultivars that have been developed from Calrose with the same or improved medium grain quality characteristics.

Through the 1960s California rice growers began asking for more progress on varietal development. "The Green Revolution" in cereals was starting and California rice growers wanted to participate and remain competitive. There was also a need for expanded rice research to address production issues. Several California grower groups visited the rice research stations in the Arkansas, Louisiana, and Texas and also the newly formed International Rice Research Institute in the Philippines. They recognized the benefits of a well-funded and productive research program and in 1969 established a grower-funded rice marketing order, or check-off. Growers elected to annually collect funds ($0.05/100 kg) based on their production of paddy rice to support research. This provided funds for an accelerated rice breeding program at RES, and breeders began to improve the adaptation and productivity of Calrose as well as develop cultivars for the other market classes (long, short, waxy, etc.).

Organization, funding and facilities

The California Cooperative Rice Research Foundation (CCRRF) is a private, nonprofit research foundation and the membership consists of California rice growers. The Rice Experiment Station is owned and operated by CCRRF. RES was established at its present site between Biggs and Richvale, California in 1912 through the cooperative efforts of the Sacramento Valley Grain Association and the United States Department of Agriculture (USDA). Policy and administration of RES is the responsibility of an 11-member Board of Directors (rice growers) elected by the CCRRF membership. CCRRF works to serve all California rice growers.

Rice variety development at RES is funded through annual grants to RES by the California Rice Research Board (CRRB) that manages funds received from all California rice producers through assessments on rice production (http://www.carrb.com). The CRRB acts under the authority of the California Department of Food and Agriculture and growers must vote to continue the program every 5 years. The CRRB finances approximately 80% of the total RES annual budget through an annual grant. The remaining 20% is derived from the sales of foundation rice seed to seed growers, grants, and revenues from investments. RES foundation seed production is self-supporting and not funded by the CRRB. RES however does receive grants from the Rice Research Trust (RRT) to fund research capital expenditures and research related activities. The RRT is a tax-exempt trust established in 1962 to receive tax-deductible contributions for support of rice research. RES is not government supported. The RES research budget for 2013 was $2M.

RES facilities are summarized in Table 1. Activities at RES are devoted primarily to breeding and production of foundation seed of RES cultivars for California seed growers. RES has 18 full time employees. The scientific staff includes a Station Director, Director of Plant Breeding, Long Grain Breeder, Short Grain and Premium Quality Breeder, and DNA Lab Research Scientist (PhDs); Rice Pathologist and DNA lab technician (MS); a Breeding Nursery Manager and 4 Breeding Assistants. Operations are supported by a field/maintenance staff of 4 and an administrative assistant. Part-time labor of up to 25 workers is used at planting, harvest, and nursery seed processing. In addition, RES provides research land, facilities, and support to University of California researchers in weed science, agronomy and entomology at no charge.

Breeding methods

The RES plant breeding program aims to develop rice cultivars of all grain types and market classes with high and stable grain yields and quality that will sustain the profitability of rice with minimum adverse environmental impact. Important breeding objectives include the incorporation of high yield potential, seedling vigor, cold tolerance, early maturity, lodging resistance, and disease resistance into future rice cultivars. Improved milling yield, grain appearance, and cooking characteristics relative to consumer preference, are also major components of the plant breeding program.

Table 1. Land and facilities of the Rice Experiment Station.

Land	Area (ha)	Comment	Facilities	Area (m^2)
Total Facility	193		Greenhouses	
			5 Breeding& Pathology	1100
			1 Weed research	210
Breeding Nursery	30	1 year rotation	2 Cold Screening Greenhouses	115
Other Nurseries	18	Weed, Agronomy, Insects research	Research Building and Seed House	1200
Foundation Seed	83	Some fields fallowed annually	DNA, Pathology, Quality, Weed labs	210
Cold Tolerance Nursery	2	Grower field	Seed Drying, Storage and Cleaning	850
Hawaii Winter Nursery	1	1 year rotation	Office, Shop and Storage	1615
			Seed Drying/Storage Bins (18-127 Mg and 5-25 Mg)	

The breeding program has basically followed a pedigree method, pure line selection with some modifications, and some backcrossing. Induced mutation, especially for semi dwarfism and some endosperm traits has been used directly and through cross breeding. Crosses are made in greenhouse independently in spring and fall by each project. Crossing blocks are planted over about 4 dates comprising of ~100 potential parents. Plant breeders make daily selections of the crosses to be made at flowering. Each new cross is assigned a unique continuing consecutive R# after the season is complete and seed is set and harvested. F_1s are then grown by transplanting in the field in the summer or Hawaii nursery, or may go back to the greenhouse for crossing. F_2 populations are grown at RES and may be duplicated at cold tolerance nursery (San Joaquin County). Greenhouses are used for rapid generation advance and cold tolerance screening. Grain and quality types/objectives within projects are grouped together throughout the rest of the breeding and nursery process. Bundles of panicles for advancement are selected from the F_2 populations for lab examination as brown rice during the winter. From these F_2 panicles, a panicle-to-row advancement process proceeds involving several panicles being selected from a row and advanced or discarded by visual or other criteria. The program has developed the capability to grow a large water-seeded nursery. This allows selections and evaluations in the commercial production system used in California from the F_3 generation forward. After a few generations, the row may be cut (after panicles are selected) for quality testing and the seed from the row used to begin small plot testing. Small plots are assigned to each project, and may or may not be replicated and have many checks included. Preliminary yield tests are 4 replicates planted at 2 seeding dates at RES (3 x 6 m plots) and a drilled seed maintenance plot is grown for a pure seed source. Statewide Yield Test entries are grown in the same manner and are conducted by the University of California Cooperative Extension. Table 2 presents a summary of activities in the breeding program and Table 3 contains an example report summary of one of the maturity groups from the 2012 UC Statewide Yield Tests.

Yield

The climate, soils, and production system of California's rice growing regions do support high field yields with state rice yields averaging over 9 t ha^{-1}. Since the establishment of the RES accelerated breeding program in 1969, statewide average yields have increased from 6.1 to 9.3 t ha^{-1}. Yield potential continues to be a primary breeding objective at the RES. Yield gain in US rice was recently reviewed (McKenzie *et al*., 2014). H.L. Carnahan (RES Director of Plant Breeding 1969-89) estimated that 60% of this increase was attributed to improved rice cultivars (McKenzie *et al*., 1994). Genetic gain was estimated at 25 and 50 kg ha^{-1} yr^{-1} for the periods 1981-2011 and 1996-2011, respectively (McKenzie *et al*., 2014).

With the relatively high yield potential, achieving incremental yield increases are becoming more difficult and there is growing concern about reaching a yield plateau. Experimental materials however are still being recovered with increased yield potential. Hybrid rice, as an approach to increase yield, has been considered, but RES has not initiated a breeding effort in this area. Obstacles to hybrid rice development for RES include: (1) a temperate japonica cultivar base with low heterosis, (2) already high commercial yields with current inbred cultivars, (3) cold tolerance, (4) limited acreage and resources to support a hybrid breeding effort, (5) a water-seeded production system requiring high seeding rates, (6) grain quality and market acceptance, and (7) seed production and seed import restrictions (McKenzie *et al*., 2014). Non-transgenic herbicide tolerant rice (Clearfield ™) has been widely adopted in the southern US and contributed to increased commercial yields in that region. While weed control is a major issue for California rice growers; this technology has not been made available in California. Improvements using transgenic technology would currently be rejected as unacceptable by marketers and thus California growers. Marker-assisted selection is being used at RES, but currently only for grain quality factors and for blast resistance that involve major genes, but it is hoped that it may contribute to facilitating further yield increases in the future.

Table 2. Summary of RES 2012 rice breeding and seed production activities.

2012 Nursery	Number	Method	Plots	Location	Comments
Crosses	1418	Vacuum-approach	4 Crossing blocks in	Greenhouse	Primarily 3 way, BC, and
F_1	1400	Transplant	>5 space planted	RES/Hawaii	Single to BC/3 way
F_2	RES-1685 Cold Nursery-960	Precision Drilled	12 x 1.8 m 0.15 m spacing	RES/Cold nursery	Brown rice visual selection
$F_{3\text{-}5}$	~70,000	Water seed vials	1.2 m row 0.5 m spacing	RES/ Hawaii	Brown rice visual selection
Small plots	1915 2112	Water seed Vials/sacks	1.2 x 1.8 m 3 x 3 m	RES	Brown/milled/cooking
Preliminary yield test	959 entries	Water seed sacks	3 x 6 m 2 reps	RES	Brown/milled/cook/ Harv. H_20 /cold
Statewide	44 Adv. entries 96 Pre. entries	Water seed, sacks 1 drilled	3 x 6 m Adv. 4 rep Pre. 2 rep	UC/Growers & RES (7)	Brown/milled/cook/Harv. H_20/cold tolerance
Experimental Headrow Breeder	5	 vials sacks	1.5 m row 0.5 m spacing, Broadcast	RES	Brown/milled/Harv. H_20 /cold tolerance/cook/ market-quality
Foundation Seed Production (68 ha)	15 cultivars	Dry seed to permanent flood	68 ha	RES	Seed allocated to CA growers by CA Crop
	4 headrows 2 experimentals	Water seeded rows Water seeded rows	400 per variety Breeder increase		Release & IP Protection

Table 3. Very early advanced variety tests (4 location average) in UC cooperative extension statewide yield tests (2012).

Entry	Grain Type[1]	Grain Yield (kg/ha)	Harv. H_20 (%)	Seedling Vigor[2] (score)	Days to 50% Heading	Lodging[3] (%)	Height (cm)
09Y2141	SWX	11220	20.9	4.9	90	35	97
M206	M	10820	20.6	5.0	92	20	94
09Y2036	S	10760	19.1	4.9	89	60	97
10Y3286	M	10750	19.0	4.9	88	2	91
11Y1005	L	10620	18.0	4.8	93	2	94
08Y3310	M	10520	20.8	5.0	94	1	89
M104	M	10450	19.6	5.0	86	10	91
08Y2049	SSR	10350	19.5	4.1	89	10	86
06Y575	L	10320	19.0	4.0	99	10	97
CH202	SWX	10160	17.9	4.9	89	60	86
L206	L	10140	16.8	4.6	92	1	81
08Y3269	M	10140	21.7	4.9	96	25	94
M202	M	9880	21.4	5.0	95	20	97
CH201	SPQ	9770	17.6	5.0	94	50	89
S102	S	9640	15.6	5.0	84	30	91
M205	M	9250	22.8	5.0	99	25	89
CM101	SWX	8770	16.5	5.0	85	35	91
MEAN		10200	19.2	4.8	91	23	91
CV		4.7	5.5	2.5	1.2	66.4	4
LSD (.05)		340	0.7	0.1	0.1	NA	2.5

[1] M = medium grain. S = short grain, L = long grain, SWX = short grain waxy, SPQ = short grain premium quality, SSR = Stem rot resistant
[2] Subjective rating of 1-5 where 1 = poor and 5 = excellent seedling emergence
[3]Subjective rating of 1-99 where 1 = none and 99 = completely lodged.

Cold tolerance

Seedling vigor, facilitating rapid emergence for the water seed production system, and resistance to low temperature induced pollen sterility prior to heading are important cold tolerance traits needed in California rice cultivars. Visual evaluation on water-seeded rows or plots and seedling vigor scores (Table 3) are collected on the breeding materials from the F_3 generation forward. The shift to semi dwarf cultivars posed a concern that these types would have considerably weaker seedling vigor. Some initial studies (McKenzie *et al*., 1980) suggested this would not be a problem in RES germplasm and this has proven to be the case in the medium grain project. When foreign germplasm has been introduced as a parent, particularly in the short grain and long grain projects, low levels of seedling vigor have been encountered. Most RES germplasm has acceptable level of seedling vigor for water seeding. Efforts were made to achieve high level of seedling vigor observed in introductions, like Italica Livorno (Williams and Peterson, 1973). This was not successful after several attempts at RES as the material recovered was very early maturing, lodged severely, and stem rot susceptible making it unacceptable for release. The wide spread use of precision laser leveled fields by growers (providing improved water depth control), has lessened the demand for higher level of seeding vigor in new cultivars. The breeding program also has begun monitoring advanced lines for phytotoxicity to several of the rice herbicides that are applied at planting or in the first two weeks after water seeding.

Resistance to low temperature pollen sterility (blanking) has been a necessity in California rice due to low nighttime temperatures (< 13° C) that can periodically occur at about two weeks before heading. F_2 populations are grown at a cold nursery location and low blanking lines selected. Refrigerated greenhouses at RES are used to evaluate and select advanced lines for resistance to blanking. The Hawaii winter nursery is also a low temperature location used for selecting and evaluating blanking tolerance. Cold tolerance is a difficult trait to evaluate, but through selection in these nurseries over the years quantitative improvements have been made in all grain types. 'Calmochi-101' (Carnahan *et al*., 1986) is still considered one of the most blanking resistant cultivars, and some of this tolerance is credited to a parent 'Tatsumimochi' from Hokkaido. 'M-104' (Johnson, 2002), 'M-206' (Johnson, 2005) and 'S-102' (McKenzie *et al*. 1997) show less blanking than their predecessors although it is difficult to quantify. The release and commercial production of long grain cultivars in California, like 'L-206' (Jodari, 2008), reflects the improvements in cold tolerance that has been made in long grains. Specialty grain types, like aromatics, still represent a continuing challenge for blanking resistance and are restricted to the warmer production areas of California. Efforts have been made recently to evaluate a few elite materials from the Cold Tolerance Group of the Temperate Rice Research Consortium (TRRC) at RES. High levels of blanking were observed in these materials at the Hawaii winter nursery, RES cold tolerance nursery, and refrigerated greenhouses. Likewise, evaluations of some of RES most cold tolerant materials by members of the TRRC group demonstrated little blanking resistance in their screening nurseries. This illustrates the complexity and difficulties often encountered in breeding for cold tolerance.

Quality

Breeding for rice quality in the USA was previously reviewed (McKenzie, 1992). Table 4 contains a summary of grain quality evaluations currently used by the RES Rice Breeding Program. Beginning in the F_2 generation, harvested panicles are discarded that show high blanking or poor panicle characteristic and those selected are hulled and examined as brown rice. This allows the breeder to evaluate the size, shape, defects, and translucency (chalk) of the kernels. It was shown that there was a very high correlation (R^2 > 0.9) between the number of broken brown rice kernels and the whole kernel white rice milling yield (McKenzie, 1992b). Actual milling tests (% whole kernel and % total milled rice) are conducted in progeny rows (F_4 or higher). Milling tests are conducted on advanced lines over a series of harvest moistures. The harvest moisture milling studies identify lines with high and stable whole kernel milling yields. Figure 1 shows the results of harvest moisture studies on an experimental line 05Y471 compared to its medium grain parent cultivars M-104 and M-206. 05Y471 which was later released as 'M-105' (Johnson and McKenzie, 2013), shows a much higher and more stable whole-kernel milling yield than M-104. A progression of improvements in the milling yield of the long-grain releases has been achieved as well.

Physiochemical tests like apparent amylose content and alkali spreading value (gelatinization temperature type) are determined in all grain types in advanced generations. There is limited variation in these traits and also in cooking quality performance in the standard medium and short grains. Thus, testing for these traits is only done for verification or when exotic germplasm is used. Physiochemical tests including starch viscosity (RVAs) and cooking tests do receive more emphasis in the long grain and specialty types. DNA markers are used in the long grain project for apparent amylose content class, gelatinization temperature type, and RVA profile. Micro-cooking taste tests (12 g) followed by cooking and testing advancing

Table 4. Quality evaluation testing by grain type in the RES rice breeding program.*

Grain Type	Size, Shape and Appearance	Milling Yield	Amylose, ASV., RVA viscosity	Cook Test	Other	Marketer & Expert Evaluation
Medium	x	x	x	x		x
Short	x	x	x	x		x
Premium	x	x	x	x x x	protein	x x
Long	x	x	x x	x x x		x
Aromatics	x	x	x x	x x x	2-AP, elongation	x x
Others	x	x	x	x		x x

*Lab testing for amylose and gelatinization temperature type (ASV) provided by USDA Rice Quality Unit; protein from the California Wheat Commission Milling and Baking Lab; RVA, Cooking tests at RES; 2-AP and aroma testing USDA, UC Davis, and RES.

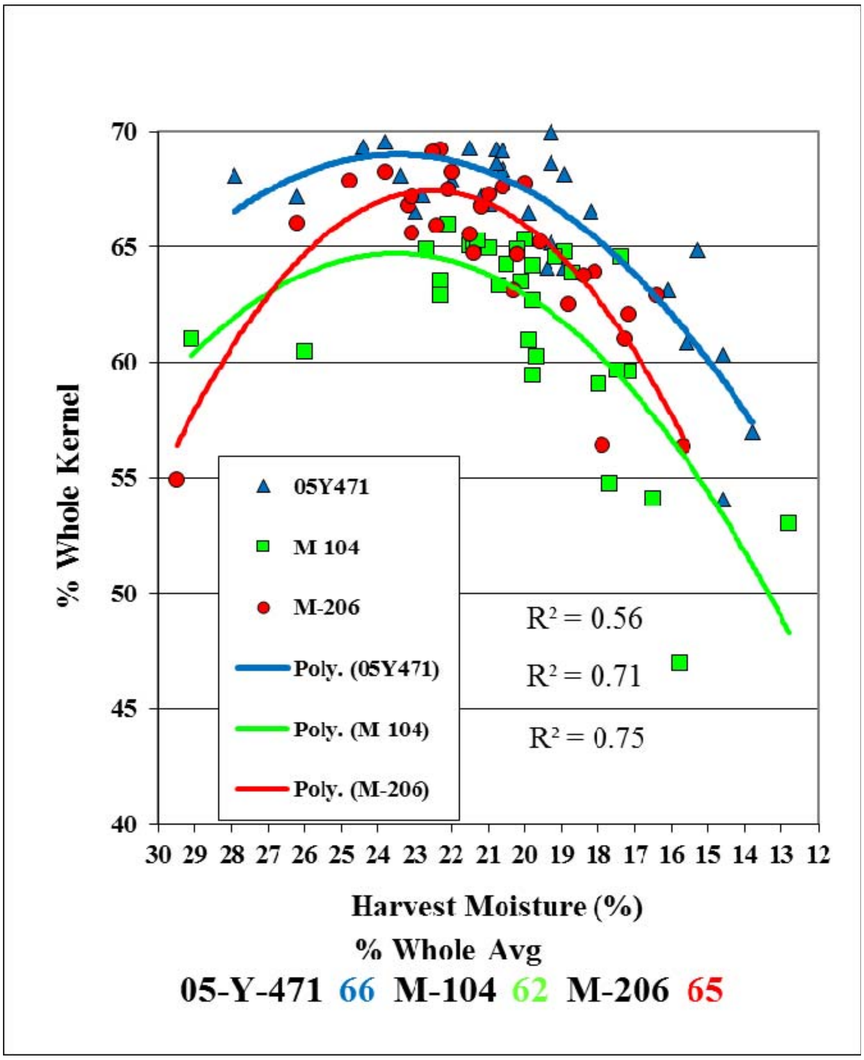

Figure 1. Harvest moisture and milling studies of medium grains 05Y471 (M-105), and its parents M-104 and M-206 at RES in 2009-2010.

lines in electric rice cookers (150 g), are done in house by the breeders. Samples are distributed to marketing organizations or outside experts when a line is under consideration for seed increase and possible future release.

Disease and insect resistance

In 1980, a rice pathologist was hired to support the breeding program and address problems with fungal diseases, particularly stem rot (*Sclerotium oryzae*). No effective fungicides were registered or available at that time. New semi dwarf cultivars were becoming popular and burning of rice straw for disease control and straw management was on its way out. Stem rot resistance, unfortunately, was only identified in an accession of the wild rice species *O. rufipogon* (Figoni *et al*, 1983). Screening efforts were developed (Oster, J.J. 1990). However, transfer of this resistance into adapted material has been a slow and arduous process. The first milestone was the recovery of the resistant long grain line 87Y550 (Tseng and Oster, 1994). Some tolerant short grain lines were recovered from crosses to the high yielding long grain lines derived from 87Y550 in the late 1990's, and these were used in the medium grain project. Efforts to recover this tolerance in to adapted medium grains have only recently been achieved. Materials recovered in the 3-grain types to date, do show improved resistance to stem rot and aggregate sheath spot *Rhizoctonia oryzae-sativae*. Unfortunately, lines suitable for release as cultivars have not been recovered due to weakness (i.e. low seedling vigor, grain quality weakness, and or blanking susceptibility). Studies are continuing on identifying markers for stem rot resistance that can be used for marker-aided selection to achieve this breeding objective.

Blast, *Pyricularia grisea* [race IG-1] was first found in California in 1996. California cultivars are very susceptible to blast and are used as susceptible spreaders in the rice breeding program in the southern US where blast is a major disease issue. Fortunately, the low humidity climate of California's rice growing regions is "permissive but not conducive" to this disease. M-208, released in 2005 contains a major blast resistance gene *Piz*, but recently has been observed to have blast at a low incidence in some fields, determined to be a second race IB-1. A backcrossing project was initiated by the RES pathologist in 2005, to incorporate the different blast resistance genes (Pi genes) into M-206 background. Breeding lines were selected and advanced using DNA markers linked to these genes, and the end-result were 10 near-isogenic lines (NILs) of M-206 containing individual Pi genes. Some of these lines are in the yield testing stage and are being used to pyramid genes into adapted germplasm.

The major insect pest of rice in California is the rice water weevil (*Lissorhoptrus oryzophilus* Kuschel). Root pruning by feeding larvae may be severe, resulting in stunted plants and decreased grain yield and quality. This pest has been controlled with registered insecticides. The breeding program began efforts to transfer tolerance to this insect pest from PI 162254 (WC 1403) identified by entomologists. Screening was done in a field that annually experienced high water weevil pressure with selection for lines with less yellowing and reduction in vegetative height. PI 506230 was released in 1987 as a water weevil tolerant germplasm (Tseng *et al*., 1987) and breeding efforts continued into the early 2000s. Materials continue to show improvement but could not match the yield and agronomic performance of the improved medium grains. With effective commercial insecticide availability, application and damage limited to the field margins, variable infestations, and the identification of other breeding priorities, the efforts in this area were discontinued.

Cultivar releases and pedigrees

Proposal for seed increase of a line is made by the breeder in his annual oral report to the Board of Directors in January. The merits, performance data for review, purity and uniformity, and market evaluation of the line is presented and with the Board approval, putative foundation seed is grown that is inspected, harvested and cleaned that season. The following year, the breeder will submit another proposal and data to the Board for review, approval and release. A cultivar name is proposed and the Board votes to release and determines intellectual property protection level (PVP and/or Utility Patent). The designated naming system uses the first letter to indicate grain type (M = medium, S = short, L = long, or specialty type e.g. A = aromatic); maturity group 100 s to 400 s for very early to late, respectively; and 1-99 the release number. All cultivars in commercial production in California are reviewed under California state law to determine commercial impact of any trait they might have (aroma, colored bran, or genetic engineered traits [none in the US]) and if production restrictions are required. A review by a California Crop Improvement Association (CCIA) technical committee approves the cultivar for certified seed production. Allocation of foundation seed is made to California rice seed growers by CCIA. The seed is sold in bulk from RES and used to produce registered seed that can be used to produce certified seed the following year. RES breeders are responsible for headrow planting, purity and storage of seeds for breeder seed production in their project's grain type. Cold storage is used to save seed, allowing headrows used for breeder seed planting to be done every 3 years.

Forty-five new rice cultivars have been released by RES to California rice growers since the accelerated breeding program was initiated in 1970 (Table 5). These have included traditional California medium (Calrose market type), short and long grain, as well as specialty types including waxy, aromatics, and premium medium and short grains. RES rice cultivars constitute 90% of California's rice production. Reviews of US rice cultivars have been made by Mackill and McKenzie (2002) and Moldenhauer *et al*. (2004). Figure 2 shows the ancestry of RES cultivars. Selections from introductions from Japan and China were the founding cultivars. Breeding material from the southern US were used in crossing, followed by 'IR- 8' and induced mutations at the start of accelerated breeding effort. Long grains were developed later using long-grain breeding material from the southern US and plant introductions. The germplasm base is quite narrow (Dilday, 1990). Widening the germplasm base is difficult due to strict market and grain quality requirements, as well as adaption to the California rice production system and environment.

Table 5. Cultivars releases since the initiation and funding of an accelerated breeding program**.**

Name	Type	Year	Name	Type	Year	Name	Type	Year	Name	Type	Year
CS-M3	M	1970	S-201	S	1980	S-101	S	1988	M-402	P	1999
CS-S4	M	1972	M-302	M	1981	M-103	M	1989	M-104	M	2000
S6	S	1975	M-401	P	1981	S-301	S	1990	M-205	M	2000
M5	M	1975	Calmochi-202	W	1981	L-203	L	1991	M-206	M	2003
Calrose-76	M	1977	M-201	M	1982	M-204	M	1994	M-207	M	2005
M7	M	1978	L-202	L	1984	S-102	S	1996	M-208	M	2006
M9	M	1978	Calmochi-101	W	1985	A-201	A	1996	L-206	L	2006
L-201	L	1979	M-202	M	1985	L-204	L	1996	Calmati-202	A	2006
Calmochi-201	W	1979	A-301	A	1987	L-205	L	1999	Calamylow-201	W	2006
M-101	M	1979	M-102	M	1987	Calmati-201	A	1999	M-105	M	2011
M-301	M	1980	M-203	P	1988	Calhikari-201	P	1999	Calhikari-202	P	2012
									A-202	A	2014

*M=medium grain, S=short grain, L=long grain, A=aromatic, W=waxy, and P=premium quality.

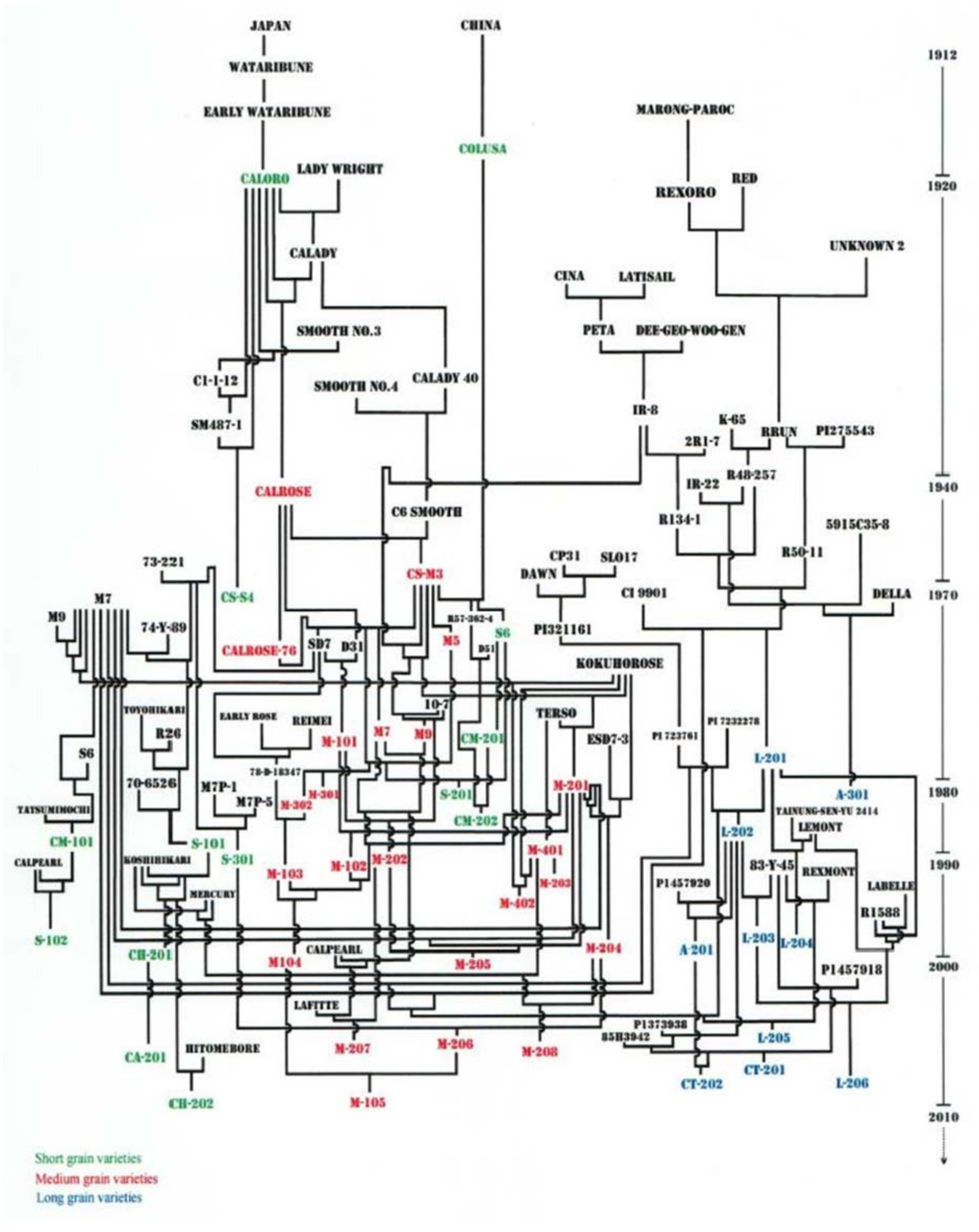

Figure 2. Pedigrees of RES cultivars.

Future outlook and challenges

Future prospect for US rice yield increases were recently discussed by McKenzie *et al*. (2014). Currently the RES breeding projects are producing lines that show incremental improvements in yield over existing cultivars. Capturing the agronomic and quality requirements for California rice in higher yielding lines is a formidable challenge. Considerable effort is being made in evaluating milling yield and grain quality in the selection process in all projects to address quality requirement for new cultivars. Culinary characteristics (aroma, texture, and taste) are critical evaluations that are especially important for the aromatic types and premium quality short and medium grain. Screening and selecting material in cooking tests are resource and time demanding, rely on subjective evaluations, and complicated by environmental effects including post-harvest processing. The pyramiding of resistance genes for rice blast is well underway in medium grains and can be expected to produce adapted cultivars with multiple blast resistance genes. Efforts at RES are being made in the hopes of developing non-transgenic herbicide tolerant mutants for weed control. The challenges in this area include selection of suitable herbicide, recovery of and acceptable mutant(s), weed control and production system verification, weed resistance stewardship program, herbicide registration and approval, and a commercial sponsor. In California, water is a premium commodity, and as in the case of the current drought, the planting acreage rice is reduced to ensure an adequate supply to produce the crop. UC research on water use at RES and the prospects for improving water use efficiency is not encouraging for commercially viable rice production in California. All these activities will need to be done under the prospect of climate change. Selecting in the nurseries environmental conditions for performance and adaptation are standard practice in the breeding process. And finally the RES Rice Breeding Program will need the continued support and funding of growers, the UC and USDA-ARS research, and an innovative and productive staff to continue forward in its 2nd century.

Additional information about the RES Rice Breeding Program including annual reports, field days, a centennial program, and other information are available online at http://www.crrf.org/. Information on California rice production from the University of California is available at the following website: http://ucanr.edu/sites/UCRiceProject/.

REFERENCES

Carnahan HL, Johnson CW, Tseng ST, Oster JJ, Hill JE (1986). Registration of ‘Calmochi-101’ rice. *Crop Sci*. 26 (1):197.

Dilday RH (1990). Contribution of ancestral lines in the development of new cultivars of rice. *Crop Sci*. 30:905-911.

Figoni, RA, Rutger JN, Webster RK (1983). Evaluation of wild *Oryza* species for stem rot (*Sclerotium oryzae*) resistance. *Plant Dis*. 67(9): 998-1000.

Jodari F (2008). Rice cultivar ‘L-206’. U.S. Patent 7,579,531. Date Issued 14 August.

Johnson CW (2002). Rice cultivar ‘M-104’. U.S. Patent 6,495,746 B2. Date Issued 17 December.

Johnson CW (2005). Rice cultivar ‘M-206’. U.S. Patent 6,911,589. Date Issued 28 June.

Johnston TH (1958). Registration of rice varieties. *Agron. J*. 50:694-700.

Johnson CW, McKenzie KS (2013). Rice cultivar ‘M-105’. U.S. Patent 8,426,708, issued on April 23.

Mackill, DJ, McKenzie KS (2002). Origin and characteristics of U.S. rice cultivars. p. 87-100. *In* C.W. Smith and R.H. Dilday (eds.) Rice: origin, history, technology, and production. John Wiley & Sons, New Jersey.

Moldenhauer KAK, Gibbons JH, McKenzie KS (2004). Rice Varieties p. 49-75. *In* E.T. Champagne (ed.) Rice Chemistry and Technology, 3rd ed. Am. Assoc. of Cereal Chem. St. Paul, Minnesota.

McKenzie KS (1992). Breeding for rice quality. p. 83-111. *In* W. Marshall and J. Wadsworth (eds.) Rice science and technology. Marcel-Decker Inc., New York.

McKenzie KS (1992b). Relation of whole kernel brown rice yields to head rice yields. *In* Proceedings of 23rd Rice Technical Working Group. Biloxi, MS. 26-28 Feb. 1990. Texas Agric. Exp. Sta., College Station. p.39.

McKenzie KS, Johnson CW, Tseng ST, Oster JJ, Brandon DM (1994). Breeding improved rice cultivars for temperate regions: A case study. *Aust. J. Exptl. Agric*. 34:897-905

McKenzie KS, Johnson CW, Tseng ST, Oster JJ, Hill JE, Brandon DM (1997). Registration of 'S-102' rice. *Crop Science* 37:1018-1019.

McKenzie KS, Rutger JN, Peterson ML (1980). Relation of seedling vigor to semidwarfism, early maturity, and pubescence in closely related rice lines. *Crop Sci.* 20:169-172.

McKenzie KS, Sha X, Moldenhauer KAK, Linscombe SD, Lyman NB, Nalley LL (2014). Rice Chapter 10 p. 267-292. *In* S. Smith, B. Diers, J. Specht, and B. Carver (eds.) Yield gains in major U.S. field crops. CSSA Special Publications 33, Madison, WI.

Oster JJ (1990). Screening techniques for stem rot resistance in rice in California. *Plant Dis*. 74:545-548.

Tseng ST, Johnson CW, Grigarick AA, Rutger JN, Carnahan HL (1987). Registration of short stature, early maturing, and water weevil tolerant germplasm lines of rice. *Crop Sci.* 27:1320-1321.

Tseng ST, Oster JJ (1994). Registration of 87-Y-550, rice germplasm line resistant to stem rot disease. *Crop Sci*. 34: 314.

Williams JF, Peterson ML (1973). Relations between alpha-amylase activity and growth of rice seedlings. *Crop Sci*. 13:613-615.