Breeding improved rice cultivars for temperate regions: a case study

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Summary. An accelerated rice-breeding program was initiated in 1969 at the California Rice Experiment Station. The program is broad in scope, developing cultivars in all US market classes (long, medium, and short grains) and special purpose types (waxy and aromatics). This grower-funded rice-breeding program has released 27 new cultivars as well as improved germplasm lines. Statewide paddy rice yields have risen from 6.2 to 9.3 t/ha since 1978. The incorporation of semi-dwarfing genes, earlier maturity, and increased yield potential have contributed significantly to increases in grain yield. High experimental yields (>11 t/ha) are routine and achieving increased increments of yield will become more difficult. After the initial shift to semi-dwarf cultivars, increasing efforts were directed toward improving adaptation to environmental stresses and grain quality. Screening and selection for cold tolerance in the form of seedling vigour for water seeding and resistance to cool temperature induced sterility at the reproductive stage are integral parts of the rice-breeding program. Progress is being made on incorporation into California rice cultivars of resistance to stem rot (*Sclerotium oryzae* Cattaneo) and aggregate sheath spot [*Rhizoctonia oryzae-sativae* (Swada) Mordue] from wild species and tolerance to rice water weevil (*Lissorhoptus oryzophilus* Kuschel). New restrictions and regulations of agronomic management practices may negatively impact rice production, creating problems in stand establishment, soil fertility, and weed, disease, and insect control. Breeding efforts to help minimise the adverse effect of these restrictions on yield and quality will increase in the future. Increased emphasis is being placed on improving milling yield and cooking and processing characteristics, and new laboratory methods are being explored to aid in evaluation and selection for grain quality.

Introduction

A comprehensive rice improvement program was initiated in 1969 at the California Rice Experiment Station (RES). Its primary objective is to hasten the development of high yielding and quality rice cultivars in all US market classes (long, medium, and short grains) and special purpose types (waxy and aromatics) for California. This grower-funded rice-breeding program has enjoyed a productive and successful 25 years. The expanded RES rice-breeding program began with its major effort on increasing grain yield. As progress on grain yield was made, breeding for better adaptation and grain quality has been intensified. This article summarises the accomplishments, scope, activities, emphasis, challenges, and future directions of the RES rice-breeding program; the RES can serve as a case study of a successful temperate rice-breeding program.

Breeding program overview

Facilities and funding

The breeding nursery at RES annually occupies about 20 ha with an additional 8 ha in cold tolerance nurseries elsewhere. A winter nursery (5000 rows) is grown on Kauai, Hawaii, in cooperation with the University of Hawaii. Greenhouse facilities are used primarily for hybridisation, disease and cold tolerance screening, and plant quarantine introductions. Rice quality, genetic, breeding, and agronomic research is provided by cooperating scientists with the United States Department of Agriculture, Agricultural Research Service (USDA–ARS), and the University of California (UC), Davis. Advanced experimental lines from the RES program are tested for adaptation to California rice-growing regions by UC Cooperative Extension (UCCE).

The California Cooperative Rice Research Foundation (CCRRF) is a non-profit research foundation that owns and operates RES. CCRRF is owned by all California rice growers and its primary mission is development of improved rice cultivars and agronomic management practices for the benefit of the California rice industry. Its policies reflect those of public institutions and it cooperates with USDA–ARS and UC under a formal memorandum of understanding. Cultivars and germplasm are released cooperatively. The RES annual research budget is about $US1 million and is funded primarily by all California rice growers through grower assessments and seed sales. RES does not receive any government funds but does receive some grants from agribusiness and the Rice Research Trust.

Methodology

The pedigree method (including backcrossing) is the predominant breeding procedure used at RES. Induced mutation has been used successfully at RES and in California (McKenzie *et al.* 1987). An average of 800 new crosses are made each year in early spring and summer greenhouse nurseries. Parental material may include cultivars, advanced and early generation breeding lines, and plant introductions. Crosses are made by hand using vacuum emasculation and bagging with a male pollinator (approach crossing method). Transplanted F_1 nurseries are grown at RES and Kauai, Hawaii. Precision-planted drill-seeded F_2 nurseries (11 ha) are grown annually at RES and cold temperature screening sites. Progeny rows, preliminary and advanced yield test plots, headrows, and seed increases are all water seeded to mimic the predominant California rice cultural practices. Replicated yield testing begins in about the F_5. The most advanced and promising materials are included in replicated statewide on-farm yield tests conducted by UCCE. Outstanding experimental lines are proposed for release after several years of multi-location agronomic performance testing and grain quality evaluation including input from major California marketing organisations and users. A formal review and approval is received from CCRRF, UC, and USDA–ARS before foundation seed is released to California seed rice growers through the seed certification program.

RES is not active in rice anther culture, tissue culture, or genetic engineering because it does not have the staff, facilities, or funding to conduct this research. Some molecular mapping work is in progress with the cooperating USDA–ARS rice geneticist at UC Davis. As new knowledge and technologies become available from this basic research they will be incorporated into the RES rice-breeding program.

Major accomplishments

The success of the California rice improvement program is well demonstrated by the 27 improved rice cultivars released and the 53% increase in state-wide average grain yield since the expanded research program began in 1969. From 1918 to 1970 California primarily grew only 3 tall cultivars (short and medium grains), and average paddy yields were about 6.2 t/ha (14% moisture). More than 95% of California's rice-growing area is now planted with 11 improved semi-dwarf RES cultivars with average yields of 9.3 t/ha (Fig. 1). These rice cultivars include very early to late maturing, short-, medium-, and long-grain types

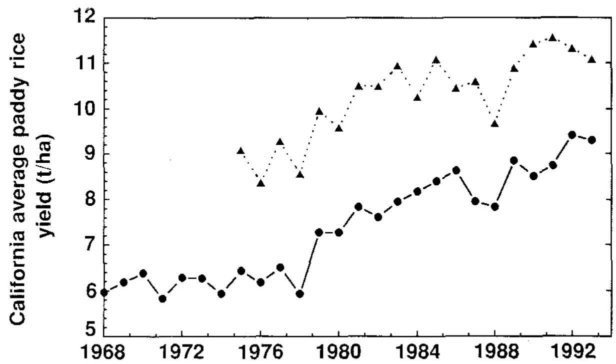

Figure 1. Average commercial paddy rice yield in California during the period of expanded rice cultivar improvement program (●), and average paddy yield of the top five RES experimental entries (▲) in University of California Cooperative Extension state-wide yield tests (1975–93).

(all major US market classes) and speciality types such as waxy and aromatic rice. The dramatic increase in yield is the result of improved cultivars being grown in conjunction with improved weed control, water management (laser leveling), and other technological advances. Carnahan *et al.* (1982*a*) estimated that 60% of the yield increase was due to improved cultivars.

Yield potential

High stable yield potential remains an important RES breeding objective. The rice-growing regions of California have climates and environments that are very conducive to high paddy rice yields (Rutger and Brandon 1981; Hill *et al.* 1992). Its Mediterranean climate is characterised by warm, dry, clear days, a long growing season favorable to high photosynthetic rate, and low relative humidities, which reduce the development, severity, and importance of rice diseases. Severe weather (thunderstorms, hail, hurricanes) experienced in other rice-growing areas are very rare. Soils are deep, relatively young, fertile clays, silty clays, and silty clay loams that are well suited to rice production. Most of the irrigation water for California comes from winter rain- and snow-fed mountain reservoirs and has been inexpensive, available, and of very good quality for rice irrigation.

When the accelerated rice-breeding program was initiated, a major goal was set to develop semi-dwarf cultivars in all grain types for California. Lodging of the old tall (120 cm) cultivars at high yield levels was a major production problem contributing to reduced grain yield and quality. The goal was accomplished through backcrossing using IR-8 (Carnahan *et al.* 1978) and TN-1 (Tseng *et al.* 1984), and by induced mutation in adapted germplasm (Rutger *et al.* 1977). Semi-dwarf cultivars were rapidly and successfully adopted, and commercial production shifted to semidwarf cultivars by 1980, resulting in a dramatic commercial yield increase (Fig. 1).

Improved lodging resistance is continuing as an important selection criterion at RES. Many semi-dwarf lines are quite susceptible to lodging, especially in short- and medium-grain germplasm, and vary in plant height (80–110 cm). Genotype x environment interactions for plant height and type are apparent in the different rice-growing regions of California. Lodging is often much more severe in the warmer rice-growing areas of the Sacramento Valley, and frequently, shorter, stronger straw lines excel. Taller, weaker straw lines typically give superior performance in cool locations. A new cultivar, M-204 (Johnson *et al.* 1994), was recently released in the continuing effort to address lodging. M-204 shows the good lodging resistance of M-201 (Carnahan *et al.* 1982*b*), in combination with better adaptation to cooler rice-growing areas where the popular, broadly adapted, but more lodging susceptible M-202 (Johnson *et al.* 1986) is preferred.

As the breeding and agronomic research continued beyond the first semi-dwarf cultivars, it became clear that increased yield potential of semidwarf lines resulted from factors other than just increased lodging resistance. Some positive pleiotropic effects of semidwarfing genes included increased tillering, which provides more panicles per m^2. Brandon *et al.* (1980) showed that the semidwarf cultivars produced significantly more panicles per m^2 than their tall counterparts. In a 10-year study by Roberts *et al.* (1993), semi-dwarf cultivars exhibited improved grain–straw partitioning [harvest index (HI)] and higher grain yield than older tall cultivars at all N rates. Studies demonstrated that semidwarf cultivars had fewer cold temperature induced sterile florets. The relative position of the reproductive apex in relation to the water surface of the semidwarf lines during the temperature-sensitive stage of pollen meiosis provided improved protection from low night air temperatures (Board *et al.* 1980).

Progressive incremental yield increases have continued in the RES semidwarf germplasm. Many factors have contributed to improvement in yield potential, although their contribution and relative importance have not been documented. RES breeders cite small improvements in yield components like tillering, panicle size, and the number of filled florets. Small improvements in quantitative traits were made, as well as the elimination of undesirable traits like late or delayed maturity in cold locations. The adaptation of the best experimental lines as measured by yield and yield stability over locations and planting dates at RES and the UCCE state-wide yield tests has been improved. Figure 1 shows the average-over-location yield of the top 5 experimental entries in the UCCE state-wide yield tests. Yields of the top entries have continued to increase after 1976 when essentially all experimental entries were semidwarf types. Large plot (13.94 m^2) tests characteristically produce coefficients of variation well below 10%, which has certainly contributed to effective selection for a quantitative character like yield.

Efforts continue to expand the germplasm base by using plant introductions in the crossing program to provide genetic variability for improvement. The founding semidwarf cultivars, Calrose 76 and M9, apparently provided a sizable amount of genetic variability for progress. M9 was developed through backcrossing from IR-8 (indica), in contrast to Calrose 76 which is an induced semidwarf mutant of Calrose (japonica). Intercrossing lines from the 2 germplasm pools allowed both opportunity to improve adaptation and genetic variability to make yield increases. These cultivars were extensively utilised in a recurrent crossing program and led to the development of second-generation semi-dwarf lines like M-202. L-202, a more recent release with TN-1 and long-grain parentage, represents an additional germplasm pool.

Progress continues to be made on increasing yield potential. Table 1 shows that very high-yielding experimental lines are being recovered that are superior to check cultivars. Incremental yield increases are smaller and are, not surprisingly, becoming more difficult to achieve. It is easy to envision problems in making further increases in yield potential, and yield improvements may be slowing (Fig. 1). Researchers speculate that further increases in grain yield can be accomplished by increasing total biological yield (Rahman 1984). Roberts *et al.* (1993) found that the biological yield did not differ significantly between tall and semidwarf cultivars across N rates, indicating that the photosynthetic capacity of the 2 types is similar. Thus, they suggest that future yield improvements will be made primarily as a result of stabilised or higher HI values at higher N rates and overall N responsiveness.

Table 1. Summary of average yields of preliminary yield test entries at the California Rice Experiment Station for 1989 to 1993

Grain type[A]	Number of entries	Average yield (t/ha) All	Highest	Top 5	Check[B]
Short	865	10.42	11.80	11.52	10.93
Medium	1292	10.21	11.75	11.55	10.88
Long	998	10.10	11.83	11.41	10.99
All types	3155	10.26	11.79	11.49	10.93

[A] A total of three yield tests per year per grain type (3 tests x 3 types x 5 years = 45 tests).
[B] Highest yielding commercial check cultivar in the test.

Heterosis may offer potential for further yield increases. Research on hybrid rice is being conducted by USDA–ARS rice geneticists and some private breeding programs. RES has yield-tested some of the Chinese hybrids provided by a private US company, Ring Around Products. Some of the indica hybrids yielded very well at RES in single-year tests, although they were not superior to the best experimental inbred lines. The last japonica hybrids tested yielded below the check cultivars. Grain quality of these materials was not suitable for California's rice markets. Potential for hybrid rice production in the United States was discussed by McKenzie *et al.* (1987) and they identified several obstacles including a narrow, non-indica genetic base, grain quality, high yielding inbred lines, and seed production. RES is not pursuing hybrid rice for California.

The RES program has expanded its emphasis on grain quality in all market types. The introduction of high rice quality donors into the crossing program is being accompanied by negative effects on yield potential. In addition to rearranging or replacing genes in well-adapted germplasm, some desirable quality characteristics may not be compatible with high yield potential. Large panicle size, large kernel size, or increased tillering would be expected to contribute to higher grain yield but may not be conducive to good kernel translucency and milling yield. Improving and even maintaining high yield potential may be very difficult in some grain quality types.

Adaptation

Efforts to improve adaptation of rice for production in California have been under way since the establishment of the Rice Experiment Station in 1912. Colusa (Johnston 1958), an early-maturing, short-grain selection from a Chinese variety introduced via Italy, was released in 1918 as the first improved cultivar for California. Caloro (Johnston 1958), which was selected from the Japanese introduction Early Wataribune and released in 1921, was the other predominant California short grain. A new, medium-grain type, Calrose (Johnston 1958), was released in 1948 and accounted for >50% of the California acreage by the 1970s. These 3 cultivars occupied most of the California rice acreage and remained in production into the 1970s.

Maturity

California has largely shifted toward earlier maturity (<100 days to heading) because of grower preference and successful breeding. This shift reduced the risks of problems related to cold or wet weather that may occur in the early spring or fall. Very early and early cultivars have improved production and reduced risk in the cooler locations. Shortening the growing season has reduced stand establishment problems, water requirements, and production costs, and early maturity permits more time for spring and fall tillage. The late-maturing Calrose heads in 110 days and the early-maturing M-202, which was grown on 65% of California rice acreage in 1993, heads in 92 days. Very early maturing cultivars M-103 (Johnson *et al.* 1990) and Calmochi-101 (Carnahan *et al.* 1986) are also in commercial production. The very early maturing materials when planted early are exposed to the detrimental effects of high temperatures at heading, grain-filling, and harvest stages. The very early and early maturing germplasm usually suffers more stem rot and aggregate sheath spot disease damage and often has problems with grain quality. Reduction in grain yields may become a problem in moving to even earlier maturity. Selection at RES is focused on the early and very early groups, although outstanding later maturing lines remain a part of the program.

Cold tolerance

Low temperatures are probably the major environmental stress of rice when grown in California, and adapted materials must show good levels of cold tolerance. Troublesome low temperature stresses in California occur primarily in the early spring at the seedling stage and again in the reproductive stage of rice plant development. Screening and selection for seedling cold tolerance (seedling vigour) and resistance to low temperature induced sterility (blanking resistance) constitute a major effort in the RES breeding program.

California rice is grown in a direct-seeded system in which presoaked germinating seed is sown into the flooded paddy and allowed to emerge through a shallow flood (14 cm). Low ambient air and water temperatures cause delayed and uneven emergence and subject seedlings to seedling diseases, insects, other invertebrate pests, and increased herbicide injury. To mimic the California production system and select for seedling vigour, all breeding lines from F_3 are water-seeded and visually rated for seedling vigour. California germplasm is well adapted to this system and shows very good levels of seedling vigour. Concern over the low levels of seedling vigour in early semidwarf germplasm was addressed in both breeding and agronomic research (Jones and Peterson 1976; Brandon *et al.* 1980; Li and Rutger 1980; McKenzie *et al.* 1980). Improved water management provided by laser-levelled fields with uniform shallow water depths has also made a major contribution to uniform rice stand establishment in California. Current medium- and short-grain semidwarf cultivars show seedling vigour levels that are comparable to, or better than, the older tall cultivars. Long-grain germplasm from RES shows good levels of seedling vigour and has been widely used as a source of seedling vigour in long-grain breeding programs in the southern United States. In addition to the difficulties of achieving good seedling vigour in a long-grain background, some long-grain material was very susceptible to damage by thiocarbamate herbicides. Screening methods were developed and used to eliminate susceptible lines (Tseng and Seaman 1982). Seedling vigour continues to receive emphasis at RES to maintain the current levels as well as to incorporate improved levels. Increasing restrictions on herbicide use, no tail water spillage from treated paddies, and deep water weed suppression are cited as reasons for further improving seedling vigour. Sources with very high levels of seedling vigour have been identified (Jones and Peterson 1976). One source, Italica livorno, has been used as a donor parent several times at RES but has many undesirable linkages with poor straw strength, very early maturity, susceptibility to disease, and poor kernel characteristics. Incubator screening of seedlings of backcross populations beginning in the F_3 is being used together with field evaluations to promote further progress.

Although the Sacramento Valley experiences high daytime temperatures in July and August, night temperatures may fall below 15°C, causing floret sterility in cool locations and even in warmer locations in some years. Visual screening for resistance to blanking is practised at RES and in the cold tolerance nurseries at UC Davis, San Joaquin County, and Kauai, Hawaii. UC Davis and San Joaquin nurseries are used to screen F_2 populations as well as preliminary and advanced breeding lines for blanking resistance. Refrigerated greenhouses are used to screen for blanking in preliminary and advanced breeding lines. The Hawaii winter nursery is usually exposed to low temperatures and provides useful cold tolerance information. This screening process combined over years and generations is used to select and develop all RES cultivars. Evaluating material in these different environments will frequently identify inferior or superior selections. Calmochi-101 and M-103 are 2 cultivars identified through this process that show excellent blanking resistance, target levels for future cultivars. New cold-tolerant germplasm and plant introductions are being used in crosses to continue progress.

Disease and insect resistance

The low humidity of California's rice-producing area is unfavorable for development of severe foliar diseases characteristic of humid subtropical and tropical areas. In cool periods during stand establishment, water mold fungi (*Pythium* spp. and *Achyla klebsiana*) can reduce seedling survival and rice stands. Chemical seed treatment is no longer used due to loss of registration and to government environmental regulations. Improved seedling vigour, moderate water depth, later planting dates, and increased seeding rate are used to help minimise damage from seedling diseases and pests and to insure an adequate plant population (Hill *et al.* 1992). Developing cultivars with good seedling vigour helps to minimise the impact of seedling diseases.

Stem rot (*Sclerotium oryzae* Cattaneo), primarily, and aggregate sheath spot [*Rhizoctonia oryzae-sativae* (Swada) Mordue], to a lesser extent, are the most serious diseases of rice in California. Stem rot is widespread in California (Webster *et al.* 1971) and yield reductions of 12–22% under inoculated conditions and 6–23% under natural infestations have been reported (Krause and Webster 1973; Jackson *et al.* 1977). Management of stem rot has been through a program of straw management (field burning), proper fertilisation, and cultivar selection (Webster 1992). Chemical control methods for foliar diseases are not registered for rice in California and rice field burning is being eliminated as a management practice by government mandate. Current cultivars show varying degrees of susceptibility to stem rot disease which is quantitatively inherited (Ferreira and Webster 1975). Resistance to this disease in California was found in *Oryza rufipogon* (Figoni *et al.* 1983; Rutger *et al.* 1987). Intensive screening for stem rot resistance (Oster 1990) is continuing at RES to transfer resistance into adapted cultivars. Recovering resistant lines with good seedling vigour, tillering, and yield potential has proven very difficult, especially in the short- and medium-grain germplasm. Recently, good levels of resistance to stem rot and aggregated sheath spot have been recovered from *O. rufipogon* in long-grain germplasm (Oster 1992; Tseng and Oster 1994). Molecular genetic techniques are being used in a cooperative project with the USDA–ARS geneticist at UC Davis to identify and map stem rot resistance genes to improve identification and selection of resistant lines. Cooperative research with pathologists at the International Rice Research Institute (The Philippines) is underway to transfer high levels of resistance from *O. officinalis*. Aggregate sheath spot is currently considered a minor disease commercially (Gunnell 1992). An adjunct crossing and screening program for resistance to this disease is underway at RES. Wild species (*O. officinalis* and *O. fatua*), and a rice x grass hybrid line from China, have been identified as sources of resistance in screening tests at RES. As with stem rot, we anticipate that transfer of resistance from wild species to high-yielding cultivars will be difficult.

Rice water weevil (*Lissorhoptus oryzophilus* Kuschel) is the major rice insect pest in California. Damage is done by larvae which hatch and feed on the roots. Rice water weevil is currently controlled by preplant incorporation of carbofuran insecticide, which is scheduled for phaseout as an approved rice pesticide. Plant tolerance to rice water weevil has been identified (Gifford *et al.* 1974; Grigarick 1974) and an agronomically improved germplasm line, PI 506230, has been developed at RES (Tseng *et al.* 1987). Selection for tolerance is effective and breeding lines with good levels of tolerance are being recovered, but yield potential and adaptation are still significantly below current cultivars (Grigarick and Way 1982; McKenzie 1992).

Regulatory impact

Government environmental and chemical regulations and urban growth are restricting grower options and use of optimum management practices. The phasing out of rice field burning is creating straw disposal and management problems for California rice growers. Incidence and severity of stem rot and aggregate sheath spot diseases are expected to increase, and intensify the need to incorporate disease resistance into improved cultivars. The long-term impact of straw incorporation is not known but problems in stand establishment, soil fertility and weed, disease, and insect control are anticipated. Rice-breeding efforts to help minimise the adverse effect of these restrictions on yield and quality will increase.

Grain quality

Increasing emphasis on grain quality is occurring at RES as well as rice-breeding programs worldwide. Grower, consumer, and processor demands for improved grain quality are increasing and driving efforts for quality enhancement in future cultivars. Indications are that this trend will continue. The development of adapted high-yielding, long-grain cultivars was a major accomplishment in California, and much of the grain quality research at RES has been in long-grain rice. Research and breeding for medium- and short-grain quality have expanded considerably in the past 5 years. Screening and evaluating breeding material for grain quality have involved selection for physical characteristics (kernel size, shape, translucency, milling yield) and cooking and processing characteristics.

Physical characteristics

Kernel size, shape, breakage, and translucency are the physical characteristics that are used to screen about 350 000 panicles for advancement each winter at RES. The evaluation of brown rice samples is repeated each generation beginning in the F_2 and includes advancing breeding material. Brown rice samples from bulk harvested progeny rows and plots are examined. Current US market types have specific grain size and shape requirements and considerable selection is practiced to meet those requirements.

Milling yield largely determines the economic value of rough rice, and is therefore a very important rice quality characteristic. Whole kernel milled rice (head) sells for a much higher price than broken kernels. Milling yield is determined by both environmental and genetic factors and is very complex (McKenzie 1994). Studies by Geng *et al.* (1984) found that commercial head rice yields were lower in the new, earlier, higher yielding cultivars than in the old, late-maturing cultivars. Following the major increases in grain yield that have been achieved, improvement in milling yields is now receiving particular emphasis at RES. More recent releases including M-103 and S-301 (Johnson *et al.* 1991) have shown higher, more stable head rice yield, and efforts to maintain or improve milling yield will continue in the future.

Previous research and experience have demonstrated a high correlation between percentage whole kernel brown rice and head rice (McKenzie 1990). Thus, screening brown rice for resistance to breakage is used in early generation screening. As breeding lines advance, actual milling yields are determined on a small portion of the seed from harvested nursery rows. Lines in preliminary and advanced yield tests are evaluated for milling yield in nurseries where sample harvest moistures are taken. On the most advanced breeding material, milling samples are collected over a range of harvest moistures which provides information on the milling performance of lines including the optimum harvest moisture for head rice. Milling yield data are collected over several years and generations. The arid climate with low humidities, daily wetting and drying of grain, and strong dry winds experienced in California make achieving good head rice yield a difficult challenge.

Cooking and processing

US market types are associated with specific cooking and processing characteristics and end uses (Webb *et al.* 1985). Several physicochemical tests have been identified and are used by breeders in the United States to select for proper cooking and processing characteristics (Kohlwey 1994; McKenzie 1994; Webb *et al.* 1985). Amylose content and gelatinisation temperature have been used in selecting for the traditional long-grain market type in the southern United States. The experience in California long-grain breeding is that these 2 tests are not sufficient to recover adapted long grains with traditional long-grain cooking quality (Tseng *et al.* 1988). For this reason, micro-cooking tests are being used at RES to screen for cooking quality. Concurrently, the long-grain program is developing long grains with 'Newrex quality'. Newrex (Webb and Bollich 1980) has preferred long-grain processing characteristics that may be useful in quality enhancement of California long-grain cultivars.

California medium grains of the 'Calrose' market type are recognised for their cooking and processing quality characteristics. Reasons for these preferences are not clearly understood or available. Unidentified quality characteristics found in the California germplasm are probably major contributing factors, as is the California growing environment. Quality evaluation on promising advanced lines by industry users is being used to maintain or enhance medium-grain quality. Efforts to identify Calrose quality characteristics are in progress and will be helpful as new germplasm is used in the crossing program.

Short-grain production has fallen to <10% of California acreage due to a combination of loss of markets and the success of the medium grains. S-201 (Carnahan *et al.* 1980) is the predominant cultivar and has a large round kernel with a 'white belly'. Later releases with improved agronomic characteristics and smaller, more translucent kernels have not been adopted by the industry. Efforts to develop improved short grains with better adaptation and improved grain quality are continuing at RES to maintain short-grain production as an option for California growers.

California also produces premium quality medium-grain rice that is preferred by certain ethnic groups, especially consumers of Japanese and Korean descent. The appearance, texture, and taste of this rice are judged superior to other medium grains. Generally, this rice is very glossy after cooking, sticky with a smooth texture, and remains soft after cooling. Aroma and taste are also cited as important features. The predominant cultivar of this type is M-401 (Carnahan *et al.* 1981) and there are proprietary cultivars (Kokuhorose, KRM-2, SP-411). These types are similar to the high quality Japanese short-grain cultivars like Koshihikari and Akitakomachi. Interest and breeding efforts in premium quality medium and short grains have expanded in California recently due to increased domestic markets and the anticipated opening of the Japanese rice market to imported rice. Some of the problems being encountered in combining premium quality and adapted high yield potential have been discussed by McKenzie (1994).

As an adjunct to breeding for the major grain types, RES is continuing work on special purpose types. These rice cultivars have unique cooking and processing characteristics, constitute a small percentage of California's acreage, are often grown under contract, cannot be blended with traditional market classes, and may be sold in speciality markets and used in ethnic foods. Waxy (glutinous) rice is the most widely grown, with an estimated production area of about 4000 ha in 1993. RES-developed Calmochi-101 accounts for virtually all of the waxy rice production, although some new proprietary cultivars have recently come into production. RES is also breeding long-grain aromatic rice. A-301 (Tseng 1987) is an aromatic long grain grown on a small acreage in California and has the aroma of its parent Della (Jodon and Sonnier 1973). Breeding work is continuing to develop improved long-grain aromatics and basmati types for California. Some work is under way to develop large-seeded types like Arborio, and a large-seeded germplasm line was recently released (McKenzie *et al.* 1994). Sake, or special rice for processing or industrial use, are some of the other minor areas of interest.

Challenges

One of the major challenges to progress in rice quality is the identification, characterisation, development, and use of effective screening methods. This is a critical need for improvement of the long-grain, premium quality, and special purpose types and it is expected to grow in importance in the medium and short grains. New equipment and methods like near infrared spectroscopy are being explored and will be used by RES to help in breeding for rice quality. Kohlwey (1994) has reviewed new methods for the evaluation of rice quality and these tools will play an important role in breeding improved rice cultivars for California.

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