Paddy Water Environ (2006) 4: 13–19
DOI 10.1007/s10333-005-0026-2

REVIEW

J. E. Hill · J. F. Williams · R. G. Mutters · C. A. Greer

The California rice cropping system: agronomic and natural resource issues for long-term sustainability

Received: 22 August 2005 / Accepted: 3 December 2005 / Published online: 21 January 2006

Abstract California rice is produced on approximately 200,000 ha mostly in the Sacramento Valley. The crop is planted in April/May and harvested in September/October. The growing season is characterized by a Mediterranean climate with negligible rainfall, high solar radiation, and relatively cold nighttime temperatures, thus yields may exceed 9 t ha^{-1}, 20% above the US average. California is a highly urbanized State with an affluent population demanding agricultural practices to be environmentally benign and food products to be safe for human health. This has contributed to a rigorous regulatory climate for plant protection chemicals thus increasing the cost of production. Likewise, the resource base is being challenged. Increased demand for clean potable water for urban expansion and the demand for environmental water compete with rice for limited supplies while raising cost. Production problems, such as straw management for cleaner air, weed resistance to herbicides, and the introduction of exotic pests also contribute to higher costs. The California rice industry is challenged by the increasing complexity of the rice production system to meet both the off-farm public demands and the on-farm need for higher productivity.

Keywords Environmental quality · Alternative production systems · Pest management

Overview of California rice

The agronomic sustainability of rice farming in California is broadly related to the preservation of natural resources, efficiency of the production system, and maintaining and improving yields. Most US rice is produced in semihumid to humid environments in five contiguous southern states. California is unique among the US rice producing states in its geography and climate; and in its political, social, and environmental views. Because of its dry Mediterranean climate and northern latitude of 38–40° (Maclean et al. 2002), California varieties and many of the agronomic practices are quite different from those in the southern states. Additionally, California's urbanized population, largely unengaged in agriculture, demand, sometimes unreasonably, that rice (and other crops) be produced with environmentally benign methods with no off-farm impacts. Since agriculture represents much of the landscape in general, environmental and conservation organizations push hard for conjunctive use of farmland for habitat and other purposes. These groups have focused on rice, in particular, because it is representative of the vast wetlands that were once the major ecosystem of California's Central Valley. The industry has been highly successful in developing partnerships with urban and conservation groups, but these compromises have confounded agronomic practices from once relatively simple to complicated management-intensive crop production systems. About 96% of California rice is grown in the Sacramento Valley, and the balance in a few counties of the San Joaquin Valley (Fig. 1).

Climate, soils, and water

The rice growing season is relatively rainfree and characterized by high daytime temperature, high solar radiation, low humidity, and relatively cool nights. Cloud cover during the growing season is limited such that radiation remains high while cool nighttime temperatures minimize respiration losses. The soils on which rice is grown were formed from sediments carried by two major rivers and several tributaries to produce clay and silty-clay soils. Basin soils have clay content from 40 to 60% while the older terrace soils frequently are loam in the topsoil with dense clay in the subsoil overlying a cemented layer.

Seasonal infiltration rate of typical rice soils is 1–5 mm day^{-1}. Soil reaction ranges from very strongly acid to moderately alkaline, in the range of pH 4.5–8.0. About 300,000 ha of land in the Sacramento Valley are suited to rice production because of impeded drainage. Somewhat more than half of this land is only grown to rice. The

J. E. Hill (✉) · J. F. Williams · R. G. Mutters · C. A. Greer
University of California,
Davis, CA 95616
e-mail: jehill@ucdavis.edu

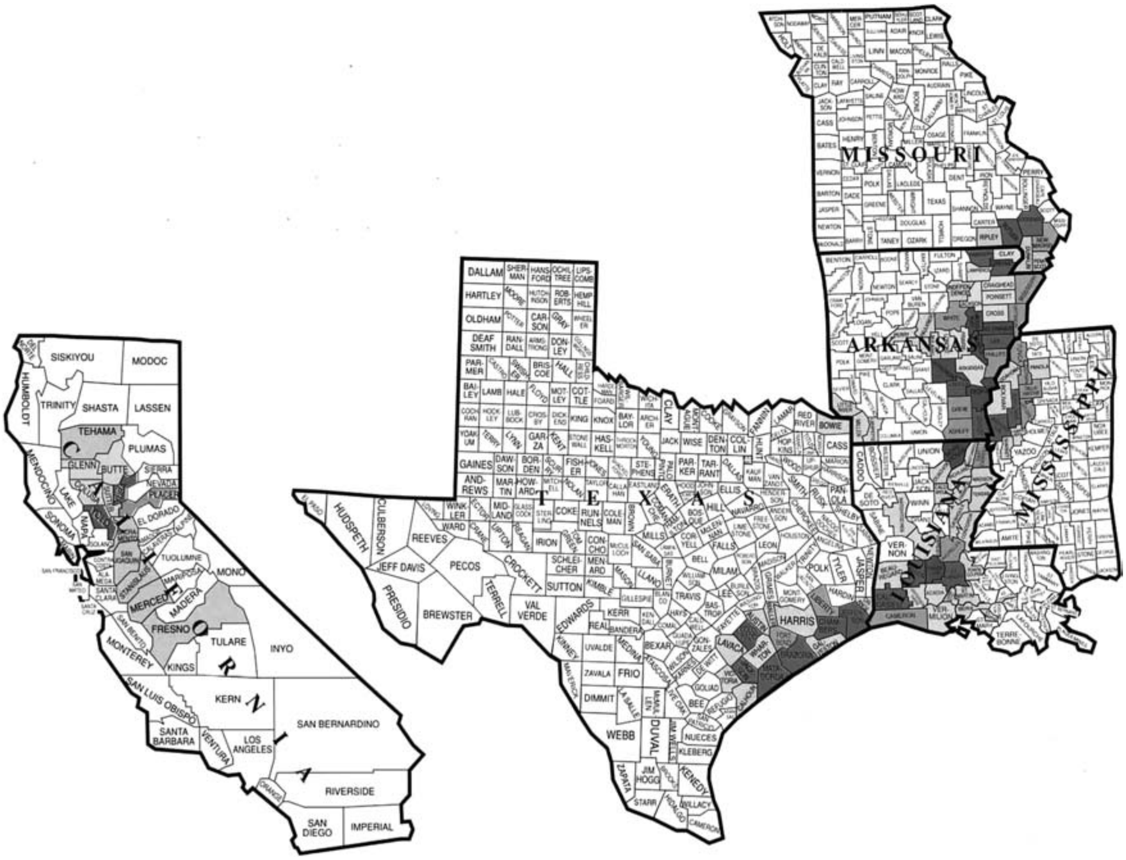

Fig. 1 Contiguous southern US rice producing states and California. *Darker shading* represents greater planted counties. Source: Specialized Agricultural Publications, Inc. Raleigh, NC, USA

remaining area varies in suitability for rotation crops (Carter et al. 1994). Approximately 80% of rice irrigation water is supplied from reservoirs captured as snowmelt from the Sierra Nevada Mountains to the east. Goundwater is also pumped from 15 to 50 m depth. Farmers who are some distance from primary water sources, often use drainage water as a primary source of irrigation. Water is distributed through water companies, irrigation districts, and drainage districts, although some growers have riparian rights and lift water directly from rivers and streams.

California cropping system

All California rice is direct seeded; most is pregerminated and aerially seeded into standing water under a continuous flood. Increasingly rice is drill-seeded or dry-seeded and permanently flooded after stand establishment. The water-seeded system was established to suppress barnyardgrass (*Echinochloa crus-galli*) and subsequent research proved that N could be used efficiently and that overall rice productivity was high. The California rice growing system is highly mechanized. A typical California rice farmer has an equipment investment of about US$ 1250 ha^{-1} of rice. Airplanes are typically contracted for seeding, fertilizer top-dressing, and the application of certain pesticides. Ground applicators are increasingly used for herbicide application to minimize drift to sensitive crops. Seeding rates average 150 kg ha^{-1}. Seed is pregerminated by soaking in water for 24 h and draining for 24 h. Over 90% of the area is planted to medium grain rice with limited sowing of short and long grain varieties. Seasonal length varies from 130 to 165 days, depending on variety, with the majority in early maturing varieties of 140 to 145 days duration. The irrigation season is about 120 days. Harvest takes place when grain moisture content is about 20–22% for short and medium grain and 16–18% for long grain. Postharvest activities include management of straw residue, primarily by soil incorporation, but with limited burning for disease control and minimal removal for use in straw-based products.

Sustainablility of the natural resource base

The foundation of the California rice industry includes the availability of clean, abundant, and low cost water and land well suited to rice production. In California's urban environment, farmers must also be concerned about the off-site impacts of rice farming so as not to degrade air and water, to share water resources, and to maintain or improve environmental services. These complex issues are a challenge to the California rice industry and have dramatically changed the production system. These issues will be discussed in the following sections.

Water supply

Rapidly increasing demand for water by municipal and environmental users threatens the supply and cost of rice irrigation water. California's water supply varies geographically and seasonally. About 71% of the supply originates in the north of the State but 75% of the urban and agricultural demand is south of the Sacramento Valley. Since most of the runoff occurs from November to March, facilities to store and convey water from one area to another (California Department of Water Resources 1998) are required. No major new facilities have been developed since 1968, but the Central Valley is the fastest growing component of a rapidly growing California population, with the Valley population expected to triple by 2040 (American Farmland Trust 1995). Additional issues around competition for water are loss of substantial amounts of Colorado River water in Southern California and the need to flush the Sacramento-San Joaquin Delta of salt. In 1999, an additional 1 million megaliters was diverted from the Sacramento River for environmental services including maintenance of low temperature for migrating salmon and habitat for waterfowl. This change effectively reduced the supply for agriculture.

Among the irrigated California crops rice is a major water user, behind only alfalfa and pasture based on application rate ha^{-1}. It is similar to several crops based on evapotranspiration (California Department of Water Resources 1998). Seasonal water delivery for rice varies a great deal depending on soil type, management, and seasonal length (Table 1). The average delivered use is approximately 22.5–24.4 ML ha^{-1}, but varies from about 15.5 to 31.7 ML ha^{-1}, depending on the source, delivery system, and how it is calculated. Extensive laser leveling and conversion of fields from contour levees to parallel levees has improved water use efficiency (WUE) so that drainage has been considerably reduced. Additionally, regulations restricting drainage to keep rice herbicides from entering public waterways has improved WUE as well. Extensive recirculation of drain water and some use of a "static water irrigation system" in which water does not leave the field has also reduced total water requirements. Deep percolation is related to soil characteristics and few rice fields have high infiltration rates. Evapotranspiration has also been reduced by about 16% by planting shorter season varieties. Currently, about 88% of California rice has a seasonal length of 145 days or less, compared to the period prior to 1980 when over 50% had a season length of 165 days.

Water prices have risen quickly in response to greater demand. Water costs in 2001 were about US$ 133 ha^{-1} compared to US$ 111 ha^{-1} in 1998. Water transfers from the north to the south for agriculture and urban uses once unthinkable, is now more acceptable. Issues arising from water transfers include preservation of water rights, conserving local supplies, environmental affects, and third-party impacts on agricultural support infrastructure and tenant farmers who don't gain from the sale but may lose their water. Powerful urban political forces are gradually changing California water supply, cost and rights, and along with it water for rice will likely diminish in the future. Water promises to be a primary sustainability issue for the foreseeable future.

Table 1 Approximate seasonal water use by rice in California

Seasonal water use	ML ha^{-1}
Evapotraspiration (Et)	9.7–13.4
Percolation/seepage	1.8–7.6
Drainage	0–7.6
Delivery at field inlet	15.5–31.7

Water quality

California has strict laws governing agricultural pollution of surface and groundwater pertaining to sediment, nutrients, pesticides, and other "constituents of concern." Because flooded rice fields dominate the landscape of the Sacramento Valley, rice has always been under the microscope for its potential degradation of water quality. In the late 1970s, fish kills were attributed to the herbicide molinate and later a metabolite of thiobencarb was found to be the cause of off-tastes in the Municipal drinking water of the City of Sacramento. The industry responded with a highly successful program to reduce off-site water degradation and became a recognized leader long before most other commodities had to address the issue.

A combination of research, education, and regulation largely solved the water quality problem from rice field tailwaters. Through publications, meetings, and demonstration projects, growers adopted practices to mitigate water runoff. The field demonstrations compared conventional flow-through irrigation with a recirculation system and a novel static water irrigation system for utility in holding water and growing rice (Hill et al. 1991). From 1990 to 1993, 50 static systems and 41 recirculation systems were installed; several irrigation districts also began to operate as closed systems. Careful monitoring of these novel systems demonstrated they were effective in reducing pesticide residues in rice drain water. Most growers have now learned, however, to hold water in conventional flow through fields for up to 30 days without drainage. Regulation of drainage from treated rice fields was implemented by adopting "performance goals," residue levels considered safe for people and the environment. For example, the performance goal was set at 10 ppb for molinate and 1.5 ppb for thiobencarb. Holding periods were then determined to allow sufficient degradation to occur before drainage to meet the performance goals. Typical holding periods after application are 30 days for granular thiobencarb and 28 days for molinate. This program continues today and, together with adoption of improved irrigation practices, has reduced mass flow of pesticides in the Sacramento River by 97%.

However, the issue is not entirely resolved. The legal framework has changed and public resolve for zero degradation has increased. Currently, agriculture has a 2-year extension of a waiver from non point source pollution regulations. Within 2 years, each agricultural industry must file an irrigation management plan that addresses their particular water degradation issues. The rice industry is attempting to have its current pesticide program adopted as sufficient to meet the new regulations. If unsuccessful, the most severe consequence may be to require each grower to file a separate plan, including highly expensive water sampling to prove compliance. Increasing demands for clean water will likely add new water quality issues, for example from organic carbon as the result of the decay of straw, incorporated ironically to protect air quality from smoke.

Air quality

Alternative straw management practices to replace burning for residue disposal are creating fundamental changes in production practices, long-term yield potential, and production costs. Burning rice straw came to an end in 2001 after years of public debate about the contributions of smoke to air pollution and related human health problems. Regulations enacted in 1991 (Table 2) phased out burning while simultaneously promoting off field uses of rice straw. The net result is that 25% of planted acres may be burned for disease control and the balance must be disposed by soil incorporation or removal. Until 1991, nearly all the rice straw was burned after harvest. By 2000, 25% of the acreage was burned, 1.6% baled and 73.2% soil incorporated (Williams et al. 2002). However, it is likely that growers will be able to burn far less than permitted because of tightening burn regulations that are related to declining air quality. There are a decreasing number of "good" burn days in the confined air space of the Sacramento Valley. An inversion layer persists from July through December, during much of the burn season, greatly lowering the ventilating properties of the valley, trapping all forms of air pollutants. Hence, only 7% of the 2002 (10) and 13% of the 2003 straw residue had been burned before winter rains arrived.

Growers use two primary methods to incorporate rice straw including no winter flooding and winter flooding. Straw is usually chopped and/or disked directly into the soil after harvest. About 80% of soil-incorporated rice straw was winter flooded in 2000 (Williams et al. 2002). Winter flooding is a grower-developed practice which combines straw disposal benefits with creation of additional waterfowl habitat for winter migrations of ducks, geese, and swans. The rice industry has gained wide public recognition for this practice, although there has also been criticism regarding the additional use of water during migrations of anadromous fish that spawn in the Sacramento River and its tributaries, and potential organic carbon loading of streams from straw decomposition and subsequent drainage.

Table 2 Rice straw burning phasedown schedule

Year	Actual schedule	Original schedule
1992	90%	90%
1993	80%	80%
1994	70%	70%
1995	60%	60%
1996	50%	50%
1997	38%	38%
1998	200,000 ac	25%
1999	200,000 ac	25%
2000	200,000 ac	Conditional burn
2001	Conditional burn	

Amending legislation in 1998 changed the original schedule

Transition from burning has brought a mix of benefits and problems. Burning provided a measure of disease control and easy disposal at low cost, less than US\$ 7 ha^{-1}. Many studies have demonstrated an increase of stem diseases when straw is incorporated. But in a recent multiyear California study (Webster and Cintas 2001), winter flooding rice straw tended to suppress stemrot disease and increase yield compared to incorporation without winter flooding and may be a viable management strategy for stem rot. Disease levels appear to have increased slightly as sclerotia levels rose to the point where their number was no longer limiting to disease incidence or severity. The weed seed bank also increased when practices included burial of the straw (Hair 2001). Compared to burning or removing, soil incorporation has beneficial impacts on soil fertility (particularly N and K), allowing a reduction of fertilizer inputs after several years of incorporation, and on carbon sequestration that may reduce greenhouse gas emissions. For example, applied N can be reduced 28 kg ha^{-1} after 5 years of incorporation. However, yield potential of incorporated fields may be limited compared to burned fields because of increases in disease and weed pressure, and possibly unidentified causes. Nitrogen rate experiments comparing incorporated vs. burned straw showed that incorporated yields were higher at zero N and peaked at lower N than burned yields. However, maximum yield was consistently higher in burned plots suggesting there are non-N mechanisms affected. Reduced weed control and higher disease levels are suggested as the primary causes of lower yield in incorporated plots (Bird et al. 2002).

Fall straw management has also increased the post harvest workload, and greatly increased cost of rice production without tangible increase in returns. In a study reported in 1998 (Williams and Goldman-Smith 1998) average cost of soil incorporation, across all methods, was US\$ 89.72 ha^{-1}. A 2001 update of this study (Najita 2001) increased the cost to US\$ 106.25 ha^{-1}.

Rice straw utilization has developed very slowly because of economic and technical constraints, yet a commercial market could relieve the financial burden and agronomic problems associated with soil incorporation. Many products including paper pulp, livestock feed and bedding, compressed panels for interior walls, medium density fiber board (MDF), straw bale houses, erosion and sediment control devices, ethanol, methane, electricity, etc. have been successfully manufactured, but each product has its own set of constraints. The cost of acquiring and delivering rice straw is often the primary deterrent. Straw baling, storage, and transportation costs range from US\$ 27 t^{-1} to over US\$ 100 t^{-1}, depending on the method of baling, storage conditions, and distance transported (Jenkins et al. 2001). Today, rice straw usage remains very low and growers are dependent on soil incorporation of straw. While the industry continues to work diligently toward economic straw uses, the long-term prospects for significant use is not clear.

Land

Land is a limited resource and its availability for rice is challenged by rice farming economics, competing agricultural and urban uses, and potential degradation issues. Most California rice land has impeded drainage and over half is poorly suited to most upland crops. Many efforts have been made to grow summer and winter crops on "rice-only" land, and have failed due to poor yields and high input cost. For this reason, many rice fields, in addition to having poor internal drainage, are designed to optimize rice production, frequently with permanent levees and zero-grade slopes, further restricting their utility for rotation crops. While rice yields remain reasonably strong in a rice only production system, rotation to alternative crops would help improve weed and disease management, and improve soil fertility. Research on rotation crops for heavy rice lands is needed as expenses rise and the need for cropping diversity increases.

Rice fields close to urban areas are subject to conversion to commercial or residential uses, thus reducing the total supply of suitable rice land. Urban sprawl is estimated to consume over 400,000 ha of farmland in California by 2040 at the present growth rate coupled to low-density housing developments (American Farmland Trust 1995). Substantial development is underway on the north side of the city of Sacramento and south of Marysville consuming former rice fields. Many conflicts with agricultural operations exist at the interface between town and country, including dust, noise, pesticide drift, mosquitoes, drainage, aircraft operations, etc. As population increases, this loss of agricultural land will continue and these problems will increase. These problems can only be solved by policy to reduce the rate of urban expansion through land use designations, tax incentives, and purchase of development rights. Problems at the interface must be addressed with effective buffers and logical land use planning.

Two in-field land degradation issues require discussion. First, salinity is a current problem for some growers on the west side of the Sacramento Valley particularly for those farmers who depend on drain water, but also for some areas when water is held without spillage. Salinity is also a problem with some well water on the east side of the Sacramento Valley. Recent salinity studies have shown that rice is highly salt sensitive in the seedling and flowering stages of growth. Threshold values of average seasonal salinity for no yield loss have been lowered from 3.0 to >1.9 dS m^{-1} (Grattan et al. 2002). Long-term holding periods mandated for pesticide residue degradation, and tightening water supplies will increase salinity problems. Second, approximately 1 million kg of copper sulfate is applied annually to California rice fields for tadpole shrimp and algae control. Very little copper in organically bound forms leaves the field. Nearly all remains behind as low solubility salts. While no copper toxicity problem in rice or rice rotation crops has been identified, continued use of copper eventually will cause toxicity problems. Research is needed to provide effective alternatives to copper use.

Sustainability of the production system

Herbicide resistance

Resistance to sulfonylurea herbicides among four broadleaf and sedge species, and multiple and cross-resistance to several grass herbicides has increased the complexity and cost of rice weed control. Beginning in 1989, the use of bensulfuron (Londax) an extremely effective, broad-spectrum broadleaf herbicide, rapidly increased to almost 100% of the acreage. In 1992, after only 3 years of use, resistance was confirmed, traced to a single gene difference in susceptible populations of four weed species. The number of fields with bensulfuron-resistant weeds increased rapidly from four in 1999 to most fields in 1995. Growers substituted less effective and more injurious alternatives, primarily the phenoxy herbicides. As a result, there was a marked increase in the average number of spray applications, greater cost, less effective weed control, greater incidence of crop injury, and more drift damage to neighboring crops, primarily cotton.

In 1996, 30 years after its introduction, the first confirmed resistance to molinate was found in watergrass (*Echinochloa phyllopogon*). By 2001, approximately 400 fields had confirmed resistance, including three species of *Echinochloa* and several herbicides. Cross resistance (resistance to the same mode of action in different herbicides) and multiple resistance (resistant to multiple modes of action) have been identified. A typical weed control program in 1991 included molinate or thiobencarb as the primary grass material, usually without additional grass herbicide application. By 2001, the program consisted of a thiocarbamate herbicide followed by propanil, and more recently, cyhalofop and clomazone have become major players. In difficult cases, mixtures of two or three products, or up to three applications of grass herbicides may be used. From 1996 to 2000, the number of grass herbicide applications rose from 1.03 to 1.59 per field (California Department of Pesticide Regulation 1996–2000).

Agronomic research has focused on the evaluation of candidate herbicides with new modes of action, characterization, and confirmation of resistance, and programs to manage resistance. Herbicides can be degraded by metabolic activity, for example oxidation by cytochrome P_{450} enzymes or conjugation to sugars, amino acids, or peptides. A primary issue is understanding whether our observation of multiple resistance is resistance to more than one site of action or is metabolic resistance Metabolic resistance would suggest that some weed populations have the ability to detoxify a broad range of herbicides, including those not currently in use. Of the confirmed resistance, the greatest number is in *E. phyllopogon*, and it appears that much of it arises from a preexisting mutant population in the Sacramento Valley, based on morphological traits and AFLP fingerprints. This implies that control of resistant seed dispersal and elimination of survivors after herbicide treatment are required for integrated management of resistance (Ryouichirou et al. 2003) which means an increase rather than a decrease in herbicide use.

Alternative systems

Increasingly, growers with severe weed resistance problems are seeking innovative methods to grow rice. These provide opportunities to use new mode-of-action chemistry. For example, a primary reason some growers drill seed is for access to glyphosate and pendimethalin as both are unsafe in water-seeded rice. Other innovative methods are also under evaluation, including "false" drill seeding which employs dry broadcast seed lightly covered and irrigated. "Stale seedbed" systems encourage weed growth in the unseeded, prepared seedbed either with winter rain or spring irrigation, which are then sprayed with nonselective herbicides. The seedbed is not disturbed and either drill seeded or flooded and water seeded. Research is just beginning to evaluate the utility of these novel systems.

Drift

Periodic episodes of rice herbicide drift triggered regulatory activity that has dramatically changed application procedures. Propanil drift to prune trees in 1968, phenoxy drift to cotton in the mid-1990s, carfentrazone drift to prunes in 2000, and cyhalofop drift on cling peaches in 2001 increased public scrutiny of rice production activities. Propanil was banned from use except in designated areas; most registrations were withdrawn for phenoxy products; carfethrazone was restricted to ground and specialized aerial application; and cyhalofop was confined to ground application in most areas. The primary method of managing products prone to drift is to limit their use to ground applicators equipped with low drift nozzles that produce spray droplet sizes above allowable limits. In addition, buffer zones near sensitive crops are created for each product. Typically, a ground buffer zone is 0.8 km, and an aerial buffer is 8 km. Given multiple products, methods of application, and numerous crops to protect, a complex network of no-spray zones has been created that requires significant management by regulatory officials and difficulty for growers. Many producers are denied access to effective chemicals and must use less effective substitutes. Resistance management is particularly impacted when growers can't use effective products. New granular products that can be applied directly into the water are urgently needed to reduce drift problems, lower the regulatory burden, and decrease the high water management requirements for the use of foliar applied herbicides.

Exotic pests

Exotic pest introductions jeopardize production and markets. To maintain California's position as a supplier of high quality rice and to develop specific market niches, germplasm and cultivars have been freely exchanged. But exotic pests and diseases on seed, processed rice, and equipment have been introduced where appropriate procedures were not followed. For example, rice blast (*Pyricularia grisea*) was first identified in California in 1996 and bakanae (*Gibberella fujikuroi*) in 1999. Both are thought to have entered the state on seed that did not go through quarantine procedures. Blast caused significant yield loss in 1996 and 1997 but has since been at a very low level. Bakanae rapidly spread in the seed and by 2002, an estimated 80% of fields had disease present. Yield loss associated with bakanae was as high as 30% although most fields experienced no yield loss. Existing laws governing importation of crop seeds are sufficient, but have been willingly violated. Interstate shipment of rice seed and equipment is another avenue of introduction. The Rice Certification Act of 2000 is a state law intended, in part, to supplement existing regulations by creating a program that approves research protocols to prevent introduction of exotic pests.

Yield

Rice yields before 1950 were a function of improvements in water management and use of certified seed. In 1947, 2,4-D was introduced followed by MCPA in 1952, and synthetic fertilizer nitrogen in 1945. Yields responded and received another boost in 1962 by introduction of propanil and molinate in 1966. The first semidwarf cultivar was introduced in 1976 and by 1982–1985 most acreage was in semidwarf cultivars. Yields rose dramatically in response to improved photosynthate partitioning and better agronomic characteristics that allowed higher application of fertilizer nitrogen. From 1976 to 2002, 33 semidwarf cultivars have been released from the public breeding program providing the industry with improved yields, higher quality, and better agronomic characteristics in a range of market types. Yields peaked in 1991, 1992, and 1994, among the highest in the world. Yield gains through plant breeding and production practices have been in small increments, and since 1994, have trended downward (Fig. 2).

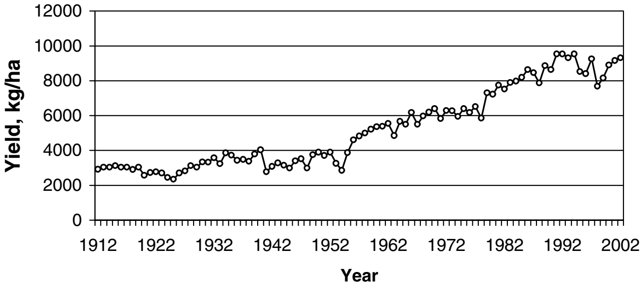

Fig. 2 California rice yield as a 3-year moving average

Inclement weather has played a role in perceived yield decline, and is probably the biggest cause. For example, heavy rain from El Nino in 1998 caused delayed planting and low temperature in 1999 caused widespread panicle sterility. Rain also played a role in 1995–1996. However, other factors are involved. For example, straw incorporation was widely used concurrent with declining yields in the 1990s, thus weed and disease interactions resulting from that new practice may be partly responsible. In addition, weed resistance became widespread during this same period and likely contributed to reduced yields. Yields for the past 3 years, however, have rebounded to near the 1991–1994 record. The cultivars in use do not appear to be limiting, with maximum yields in plots of 14.8 t ha^{-1} compared to a record average yield of 9.5 t ha^{-1}. Some producers routinely average over 11.2 t ha^{-1}. The component of yield decline not related to weather is most likely caused by weed and disease effects related to resistance and straw management, and research in these areas must be emphasized.

Conclusions

The current natural resource and production issues facing California rice farmers differ from those in the past in that they must be cast in a changing context of a rapidly growing population, tightening regulations, and an enhanced regard for environmental services. The industry is highly organized, willing, and able to fund research, promotion, and political activities. Furthermore, rice farmers have a high level of technical skills to increase the rapid adoption of practices as well as the political sophistication and understanding of issues to communicate with policy makers. And, through their various leadership organizations, usually speak with a united voice that is very powerful in gaining recognition and favorable policies. Competition for and degradation of the resource base and threats to the production system are real and substantial. The strength of the industry is in its talent for understanding and working to affect the outcome rather than "stone walling" their importance. How well they resolve these issues will depend on success of future research and conservation of resources as well as continued involvement in the policy process.

References

American Farmland Trust (1995) Alternatives for future growth in California's Central Valley. Washington, DC

Bird JA, Eagle AJ, Horwath WR, Hair MW, Zilbert EE, van Kessel C (2002) Long-term studies find benefits, challenges in alternative rice straw management. Calif Agric 56:69–75

California Department of Pesticide Regulation (1996–2000). Pesticide use reports. http://www.cdpr.ca.gov/

California Deptartment of Water Resources (1998) The California Water Plan Update Bulletin 160–198, Vol 1, November

Carter HO, Chappell G, Heffren D, Hill J, Jenkins B, Learn E, Moore C, Newman R, Roberts JR, Webster R, Williams J (1994) Maintaining the competitive edge in California's rice industry. University of California Agricultural Issues Center, 50 pp

Grattan SR, Zeng L, Shannon MC, Roberts SR (2002) Rice is more sensitive to salinity than previously thought. Calif Agric 56:189–195

Hair M (2001) Impact of straw management practices on rice weeds. Proc Rice Straw Management Update, UC-DANR Rice Workgroup, March 6, Yuba City, CA

Hill JE, Scardaci SC, Roberts SR, Tiedeman J, Williams JF (1991) Rice irrigation systems for tailwater management. Univ. of Calif. Div. Ag. & Nat. Res. Pub. 21490

Jenkins BM, Summers MD, Bakker RR, Yore MW (2001) Performance and economic issues in the utilization of rice straw. Proc Rice Straw Management Update, UC-DANR Rice Workgroup, March 6, Yuba City, CA

Maclean JL, Dawe DC, Hardy B, Hettel GP (2002) Rice in North America. In: Rice Almanac, 3rd edn. IRRI, pp 72–75

Najita T (2001) Report to the legislature: Progress report on the phase-down and the 1998–2000 pause in the phase-down of rice straw burning in the Sacramento Valley air basin. CA Air Res Board/CA Dept of Food and Agric, August, p 36

Ryouichirou T, Fischer AJ, Yoshino M, Roel A, Hill JE, Yamasue Y (2003) Herbicide-resistant late watergrass (*Echinochloa phyllopogon*): similarity in morphological and amplified fragment length polymorphism traits. Weed Sci 51:740–747

Webster RK, Cintas NA (2001) Effects of various methods of straw management on Sclerotium oryzae inoculum, stemrot severity, and yield of rice in California. Proc Rice Straw Management Update, UC-DANR Rice Workgroup, March 6, Yuba City, CA

Williams JF, Goldman-Smith S (1998) Rice straw incorporation costs in California. Proc 27th Rice Technical Working Group, Reno, NV, pp 103–104

Williams JF, Buttner P, Webster RK, Mutters RG (2002) Rice disease certification program for California. Proc 29th Rice Technical Working Group, Little Rock, AR, pp 150–151