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Rice weed control: current technology and emerging issues in temperate rice

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Summary. Among temperate rice areas, the United States and Australia are most similar in climate and in the mechanisation of rice culture. Many weed problems, even weed species invading rice, are common to both countries; and the present technology for weed control as well as concern for the impact of these technologies to environmental quality, herbicide resistance, and other weed-related issues bear many similarities. Application of current, and any new, technologies to emerging issues in US rice weed control will therefore be directly relevant to rice production in Australia and all other temperate areas struggling with the same challenges. Weeds are a significant problem in temperate rice culture. In the United States, rice is mechanically direct-seeded, allowing weeds to germinate and establish with the crop. In the last 15 years weed growth and competition has been increased by the adoption of semi-dwarf cultivars, high N fertilisation, and, in water-seeded rice, shallow flooding. High rates, and often multiple applications, of herbicides have been necessary to maximise the yield potential of these cultural systems. Advances in cultural practices and herbicide technology have maintained, if not improved, weed control; but nearly 30 years of propanil use in the southern USA resulted in propanil-resistant barnyard grass *Echinochloa crus-galli* (L.) Beauv., and after 4 years of continuous use, bensulfuron resistance to 4 aquatic weed species was discovered in California. Although herbicides with different mechanisms of action are needed for alternation in resistance management strategies, fewer are likely to be available. Social and environmental concerns have slowed the development and registration of rice herbicides and increased the cost of controlling weeds. Water quality deterioration from ricefield tailwaters, drift to sensitive crops, the cost of renewing registration in aquatic systems, and weed resistance all forecast reduced herbicide use in rice. Neither cultural practices nor herbicides alone can solve weed problems in direct-seeded, mechanised rice culture. With fewer herbicides and a cultural system highly vulnerable to weed losses, integrated management strategies with better information on which to base weed control decisions will be needed to solve weed problems in temperate rice.

Introduction

All US rice is direct-seeded by drill or broadcast dry seeding, or by water seeding (Hill *et al.* 1991*a*; IRRI 1993). Unlike transplanted rice, direct-seeded rice has no competitive growth advantage over weeds. Weed seeds germinate simultaneously, or even before the rice is planted, and compete with the crop from the onset of stand establishment. Cultural practices to suppress weeds in direct-seeded rice are largely preplant or related to irrigation management. Hand weeding is limited to small infestations in rice grown for seed, and in-crop cultivation is almost nonexistent, if not impossible, even in drill-seeded rice (Smith *et al.* 1977).

Weeds surpass all other pest problems in US rice culture. From weed competition and weed control experiments, weed losses were estimated at 17% (Chandler 1981) compared with 8% for insects (James 1981) and 7% for diseases (Schwartz and Klassen 1981). In the major rice-growing states, weed losses ranged from 12% in California and Missouri to 34% in Texas (Table 1), with losses estimated to exceed $US250 million (Chandler *et al.* 1984). Complete crop losses on individual fields have occurred from weed interference.

All US rice is irrigated; therefore, weeds compete for light and nutrients but rarely for water. Dry-seeded fields are initially flush-irrigated and followed by permanent flooding within a few weeks of planting. Water is generally not limiting even under dry planting. The major impact of weeds is a lowering of rice yields, but they also interfere with other aspects of rice production. Weeds reduce rice quality, harbour insects and diseases, restrict the flow of irrigation water, slow harvest operations, increase grain drying costs, reduce land values, and increase energy consumption in their control (Smith *et al.* 1977; Smith and Hill 1990).

Table 1. Estimated average annual losses due to weeds in rice, 1975–79

Adapted from Chandler *et al.* (1984)

State	Reduction (%)	Quantity (t)
Missouri	12	6
Arkansas, Mississippi, Louisiana	17	650
Texas	34	573
California	12	160

No single weed management strategy will successfully control weeds in rice. US rice farmers combine preventative, cultural, and chemical practices including weed-free, certified seed; cropping systems to break weed cycles; precision land grading for irrigation management; seedbed preparation to cultivate weeds and prevent soil exposure after flooding; water management to ensure rapid flooding and uniform water depth;

Table 2. Weeds of economic importance to US rice production

Adapted from Smith (1983)

Taxon	Bayer Code[A]	Common name	Life cycle	Habitat[B]	Region[C]
		Grass			
Brachiaria platyphylla	BRAPP	Broadleaf signal grass	Annual	Aqu.	MD
Echinochloa colona	ECHCO	Jungle rice	Annual	Aqu.	All
E. crus-galli	ECWCG	Barnyard grass	Annual	Terr.	All
E. oryzicola	ECHOR	Late watergrass	Annual	Aqu.	WC
Glyceria spp.		Mannagrass	Perennial	Aqu.	GC
Leptochloa fascicularis	LEFFA	Bearded sprangletop	Annual	Aqu.	All
L. panicoides	LEFPA	Tighthead sprangletop	Annual	Aqu.	GC, MD
Oryza sativa	ORYSA	Red rice	Annual	Aqu., terr.	GC, MD
Panicum spp.		Panicum grasses	Annual/perennial	Aqu., terr.	GC, MD
Paspalum paspaloides	PASDS	Knotgrass	Perennial	Aqu.	All
Rhynchospora corniculata	RHCCN	Beakrush	Perennial	Aqu.	GC, MD
		Sedge			
Cyperus difformis	CYPDI	Smallflower umbrella sedge	Annual	Aqu.	WC
C. esculentus	CYPES	Yellow nutsedge	Perennial	Terr.	GC, MD
C. iria	CYPIR	Rice flatsedge	Annual	Aqu.	GC, MD
Eleocharis obtusa	ELEOB	Blunt spikerush	Annual	Aqu.	All
Fimbristylis miliaceae	FIMMI	Fimbristylis	Annual/perennial	Aqu.	GC, MD
Scirpus fluviatilis	SCPFV	River bulrush	Perennial	Aqu.	WC
S. mucronatus	SCPMU	Ricefield bulrush	Annual/perennial	Aqu.	WC
Typha spp.		Cattail	Perennial	Aqu.	All
		Broadleaf			
Aeschynomene virginica	AESVI	Northern jointvetch	Annual	Terr.	MD, WC
Ammannia auriculata	AMMAU	Redstem	Annual	Aqu.	All
A. coccinea	AMMCO	Purple ammannia	Annual	Aqu.	all
Alisma triviale	ALSPA	Common water plantain	Perennial	Aqu.	WC
Alternanthera philoxeroides	ALRPH	Alligator weed	Perennial	Aqu.	GC
Bacopa rotundifolia	BAORO	Water hyssop	Annual	Aqu.	All
Caperonia castaneaefolia	CNPCA	Mexican weed	Annual	Terr.	GC, MD
Commelina diffusa	COMDI	Dayflower	Annual	Aqu.	GC, MD
Echinodorus cordifolius	ECOCO	Burhead	Annual	Aqu.	WC
Eclipta alba	ECLAL	Eclipta	Annual	Aqu.	GC, MD
Heteranthera limosa	HETLI	Ducksalad	Annual	Aqu.	All
Ipomoea spp.		Morning glory	Annual	Terr.	GC, MD
Jussiae spp.		Water primrose	Annual/perennial	Aqu.	GC, MD
Lindernia spp.		False pimpernel	Annual	Aqu.	GC, MD
Najas spp.		Naiads	Annual	Aqu.	All
Polygonum spp.		Smartweed	Annual/perennial	Aqu., terr.	All
Potamogeton nodosus	PTMNO	American pondweed	Perennial	Aqu.	WC
Sagittaria longiloba	SAGLO	Gregg's arrowhead	Perennial	Aqu.	WC
S. montevidensis	SAGMO	California arrowhead	Annual	Aqu.	WC
Sesbania exaltata	SEBEX	Hemp sesbania	Annual	Terr.	GC, MD
Sphenoclea zeylanica	SPDZE	Gooseweed	Annual	Aqu.	GC, MD
Zannichellia palustris	ZAIPA	Horned pondweed	Perennial	Aqu.	WC
		Algae			
Chlorophyceae (green algae)		Filamentous	Annual	Aqu.	All
Cyanophyceae		Chara	Annual	Aqu.	All

[A] Bayer AG (1986). [B] Aquatic or terrestrial. [C] GC, Gulf Coast; MD, Mississippi Delta; WC, West Coast.

fertiliser management to enhance crop and minimise weed growth; and one or more treatments with a herbicide. With the exception of a relatively small area of organic rice (no synthetic chemical use) in California, nearly all US rice is treated at least once with a herbicide. Smith and Hill (1990) estimated that about 80% of the US rice hectarage was treated with multiple applications. Herbicide costs in drill-seeded rice range from $45/ha to as much as $168/ha (Chaney *et al.* 1989), and in water-seeded rice, from $61/ha to nearly $200/ha (Wick *et al.* 1992). Land leveling, seedbed preparation, and cultivation are all important for successful weed control. Few growers allocate the costs of cultural practices to weed control, but combined with herbicides, the total cost may exceed $200/ha in both dry- and water-seeded rice.

United States rice weeds

Numerous annual and perennial flora infest US rice. These may be adapted to terrestrial and/or aquatic environments and include algae, grass, sedge, and broadleaf weeds (Smith *et al.* 1977; Barrett and Seaman 1980; Seaman 1983). Problem weeds may be common to all US rice-growing areas or found only in specific regions. The *Echinochloa* spp., for example, are found extensively in all areas and are regarded as the most serious competitors in rice. Red rice (*Oryza sativa* L.), a major weed of dry-seeded rice, northern jointvetch [*Aeschyomene virginica* (L.) B.S.P.], and hemp sesbania [*Sesbania exaltata* (Raf.) Rydb.], as well as other species are found only in southern US rice (Smith *et al.* 1977). Many of the aquatic species, although found in both the southern and western US, are primarily problems in water-seeded rice. Table 2 lists the major weed species of US rice.

The spectrum of weed species found in rice is largely dependent on the method of stand establishment. Dry-seeded, flush-irrigated rice in the southern US is infested mostly with terrestrial weeds early in the season, followed by aquatic weeds after the permanent flood. In water-seeded rice in California and southwest Louisiana, aquatic species dominate; however, *Leptochloa* spp. and, in California, large-seeded watergrass [*Echinochloa oryzoides* (Ard.) Fritsch] adapted to aquatic environments, may also cause severe problems.

Rice–weed competition

Weed species differ in their ability to compete with rice (Smith 1968). Relative yield losses from season-long interference were estimated for several weed species common to temperate rice (Table 3) using data from experiments on drill- and water-seeded rice (Smith 1988). Red rice and barnyard grass caused greater losses than bearded sprangletop [*Leptochloa fascicularis* (Lam.) Gray], or a number of broadleaf weeds. Fifty per cent yield losses were caused by 19, 57, and 148 plants/m^2 of red rice, barnyard grass, and bearded sprangletop, respectively. Densities as low as 1–3, 5–10, and 15–30 plants/m^2, respectively, were thresholds to implement control practices (Smith 1988). Red rice competition was generally midseason, whereas both barnyard grass and bearded sprangletop caused substantial yield losses after only 3–4 weeks. Even though red rice was a more serious competitor, early season control was more important for barnyard grass or sprangletop than for red rice (Smith 1988). Midseason control programs for red rice could still prevent serious yield losses. Red rice produced less biomass early than did bearded sprangletop or barnyard grass, accounting for the seasonal differences in interference due to the duration of competition.

Table 3. Yield losses in dry-seeded paddy rice due to season-long interference with different weed species

Rice densities were optimum (160–215 plants/m^2) and weed densities were high for each species

Adapted from Smith (1988)

Weed	Yield loss (%)
Red rice	82
Barnyard grass	70
Bearded sprangletop	36
Amazon sprangletop	35
Broadleaf signal grass	32
Ducksalad	21
Hemp sesbania	19
Spreading dayflower	18
Northern jointvetch	17
Eclipta	10

Cultural practice also influences weed competition in rice. Although direct comparison of different experiments was difficult, Smith (1988) estimated that losses from barnyard grass were greater in drill-seeded than in water-seeded rice. Fertiliser management may also affect competition. Nitrogen (N), for example, significantly increased watergrass competition (Hill *et al.* 1985). Nitrogen increased weed-free rice yields by 60%, but the benefit of added N decreased as N and watergrass levels increased. At watergrass densities of 172 plants/m^2, even the lowest rates of applied N decreased rice yields.

Most weed competition models in rice are based on regression analysis and are specific to the cultural system, weed species, and geographic area. These models have supported data on weed losses and the general rationale for good weed management programs in rice, but they have rarely served as a basis for the selection of weed management options in the field. It is unlikely that site-specific competition experiments can be generalised to all weeds and mixtures of weeds competing with rice. Mechanistic models, based on fundamental plant processes, will be needed to understand competitive interactions among multiple weed species and rice. These are being explored for their potential to improve weed management in rice and other crops (Kropff and Lotz 1992). Their importance is underscored by all of the factors limiting herbicide use in rice in the temperate zone.

Weed management

The general principles of weed management in US rice production remain similar to those described by Smith *et al.* (1977). However, changes in cultural practices, including the adoption of semi-dwarf cultivars, higher applied N and the likelihood of fewer herbicides will require better integration of these principles to manage weeds in the future.

Prevention

Problems with the introduction and dissemination of weeds occur most often by planting contaminated rice seed, but also by weed seed movement in irrigation water and animals and on farm equipment. Many US weeds, including red rice, hemp sesbania, northern jointvetch, mexicanweed [*Caperonia castaniifolia* (L.) St. Hil.] and others are difficult to remove from rice seed (Smith *et al.* 1977). Red rice is a particularly troublesome weed in the drill-seeded culture of the southern US where it is often spread in planting seed. Red rice was at one time found in California, but water-seeding and the uncompromising requirement for red rice free certified seed eliminated it as a problem on the West Coast. More recently, northern jointvetch was discovered in a single Californian rice field (Barb 1990), probably introduced as a seed contaminate. In Louisiana, mannagrass [(*Glyceria fluitans* (L.) R. Br.]) was introduced in ryegrass seed used to stabilise rice field levees from winter rainfall (Dearl Saunders pers. comm.). The discovery of resistant weeds in temperate rice raises concern about seed movement in irrigation water.

Rice rotation and cropping systems

Crop or fallow rotations aid in breaking weed cycles and in using cultural practices or herbicides in the alternate crop. Rotation to other crops is practised extensively in the southern US, principally to control red rice. In Arkansas, Texas, and Lousiana, rotations to corn, sorghum, soybeans, or cotton for 1 or 2 years, combined with herbicides such as alachlor, metolachlor or trifluralin, are used to reduce red rice in subsequent rice crops (Louisiana State University 1987; Smith 1989; University of Arkansas 1990; Miller 1991; Texas Agricultural Extension Service 1993). Rotation to other crops is limited to about half of the rice area in California by heavy clay soils and poor drainage. Summer fallow on these soils is especially helpful to dry out the tubers, rhizomes, or large rootstocks of perennial weeds in rice such as river bulrush, cattail, and Gregg's arrowhead (Bayer and Hill 1993). The annual aquatic weeds are effectively controlled in summer fallow only by flooding to initiate germination, field drainage, drying, and tillage, followed by several repetitions of this cycle. Rotation to safflower, processing tomatoes, corn, and other crops on about half of the area helps to control barnyard grass, bearded sprangletop, and a few other weeds, but generally is not effective on the annual aquatic weed species.

Land formation and leveling

Over the past 15 years land formation and precision levelling with laser-directed equipment has greatly contributed to weed management in rice production (Bayer and Hill 1993). Uniformity of slope within basins, fewer levees, and, in some cases, reduced field size have facilitated irrigation management, essential for weed control. Poorly levelled fields have become infested with grass weeds where the soil is exposed after flooding, and with aquatic weeds where water is deep and rice growth is slow.

Large basins and fewer levees per field reduce the sites for weeds such as barnyard grass, bearded sprangletop, hemp sesbania, northern jointvetch, knotgrass, *Paspalum* spp., mexicanweed, and others that may grow on levees and subsequently infest rice. Basins that are too large, however, may lose water under heavy wind and wave action and become infested with weeds that germinate in the shallow areas. Large fields flood slowly and often have weeds that vary widely in growth and are difficult to control. Advances in land levelling and precision grading have allowed US rice farmers to match field size and irrigation capability. Hence, complete field drainage for herbicide contact when weeds are small, herbicide timing at proper growth stages, and reflooding to suppress weeds have all been remarkably improved.

Seedbed preparation

Field preparation contributes to weed management by tillage, drying of the soil, and forming a seedbed to establish a competitive crop stand. The elimination of weed growth up to planting is important in drill- and water-seeded rice. Rainfall during seedbed preparation is common in the southern US and occurs occasionally in California. US farmers often must delay planting on already prepared seedbeds to dry the soil and retill weeds that have been germinated by rainfall. Many rice weeds, including most of the grass species, will establish under nonflooded conditions and can be controlled by tillage. Tillage does not, however, control the obligate aquatic species such as algae, smallflower umbrella sedge (*Cyperus difformis* L.), redstem (*Ammannia* spp.), or ducksalad [*Heteranthera limosa* (Sw.) Willd.] unless alternated with flooding. In arid regions of the temperate zone, such as California, repeated tillage and drying of the soil is an effective method of controlling the propagules of perennial weeds by desiccation (Smith *et al.* 1977).

Weed management programs are contingent on healthy rice stands of 100–200 plants/m^2 to compete with weeds. Thus, rice seedling establishment is the principal focus of seedbed preparation. However, seedbeds may directly influence weed germination and abundance. In water-seeded rice, large clods not covered by water allow establishment of weeds that would otherwise be drowned. Large clods may also melt down slowly, exposing previously encapsulated weed seed to conditions favorable for germination. Thus, seedbeds with large clods have uneven weed growth. In California, and increasingly in other water-seeded areas in the US, heavy rollers modified with corrugations on about 18–20-cm centres have been used to groove the soil (Hill *et al.* 1992). This practice provides anchorage for water-seeded rice seedlings otherwise provided by a cloddy seedbed, but the corrugated seedbed surface remains smooth. Weeds germinate and grow more synchronously, enhancing the opportunity for timing of control measures.

Conservation tillage. Non-selective herbicides such as glyphosate allow the production of rice in conservation tillage systems. In 1993, rice was produced in reduced and no-till systems, including stale seedbed culture, on about 5–10% of the Arkansas rice area. In a 4-year study where reduced and no-till cultures were compared with a conventional culture, weeds were controlled effectively, grain yields were increased slightly (50–330 kg/ha), production costs were significantly decreased ($25–50/ha), and net returns were significantly increased ($100–140/ha) (Smith *et al.* 1993). Weed infestations in conservation tillage systems are frequently different from a conventional tillage culture; hence, herbicides used in conservation-tilled rice require adjustments of application times and rates to control the weed species present. Scouting rice fields to identify weed species and to estimate their densities across the fields is especially important in conservation-tilled rice. Crop production practices in conservation tillage systems frequently require adjustments of inputs compared with conventionally tilled rice. Production practices that may require special attention include weed control programs, crop rotations, soil conditions, seeding equipment (especially no-till grain drills), cultivar selection, water management, N fertilisation, seed treatments with plant growth regulators, disease control programs, and, perhaps, others.

Water management

Of all cultural factors, the management of water has the most pronounced effect on weed control in rice. The presence or absence of water during rice stand establishment determines, in large part, the mixture of weed flora. The speed of flooding in water-seeded rice, and, to a lesser extent, in drill-seeded rice, determines the weed species present as well as the uniformity and rate of weed germination and growth. Intermittent draining and drying may successfully control algae and some aquatic species. Water depth impacts the species mixture by suppressing such weeds as *Echinochloa* and *Leptochloa* spp. while having less effect on others (Williams *et al.* 1990).

Seeding. Stands are established in drill-seeded rice by flush irrigation followed by a permanent flood. Hence drill-seeded rice is infested with many weed species well adapted to upland conditions. These include red rice, barnyard grass, bearded sprangletop, hemp sesbania, northern jointvetch, mannagrass, broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash], and others (Smith *et al.* 1977). Drill seeding delays infestations of aquatic species that occur after the permanent flood and compete less against already established rice stands. In contrast, water seeding suppresses many upland weeds but encourages the development of algae, sedge, and broadleaf aquatic species. The permanent flood in drill-seeded rice is timed to suppress weeds without weakening stands.

Time to flood. In water-seeded rice in California and southwest Louisiana, fields are flooded as rapidly as possible and rice is planted without delay. Slow flooding causes early and uneven weed growth before seeding, allowing weeds to out-compete rice.

Field drainage. Prolonged drainage during stand establishment encourages the germination of new weeds, and most US farmers avoid this practice. In California, and especially in southwest Louisiana where the oxygen concentration in water is low, farmers often establish rice stands by draining the floodwater for short periods after planting to improve rice growth, sometimes termed 'pinpoint flooding'. Short drain periods, if done carefully to avoid weed seed germination, have proven effective for promoting rice, but not weed, growth.

Water depth. In addition to the presence or absence of water due to seeding method or drainage, the depth of water after flooding may strongly influence weed establishment and growth. Williams *et al.* (1990) compared the growth of several weeds in water-seeded rice under shallow (5 cm), moderate (10 cm) and deeper (20 cm) continuous floods. Without herbicides, 20 cm water gave good, but not perfect, control of the *Echinochloa* spp. and smallflower umbrella sedge, compared with poor control in 5-cm-deep water. Deeper water had an intermediate effect on redstem and ricefield bulrush (*Scirpus mucronatus* L.). Ducksalad showed little overall effect from water depth. Even at 20 cm deep, water was unable to control weeds without herbicides. Weed control was improved at all water

Table 4. Herbicides currently used in temperate rice culture

Herbicide	Southern USA	California	Australia	Reference
Aciflourfen	+	—	—	Smith and Hill (1990)
Bensulfuron	+	+	+	Smith and Hill (1990); Bayer and Hill (1993); Clampett and Jones (1986)
Bentazon	+	—	—	Smith and Hill (1990)
Copper herbicide	+	+	—	Smith and Hill (1990); Bayer and Hill (1993)
Endothal	—	+	—	Bayer and Hill (1993)
Fenoxaprop-ethyl	+	+	—	Smith and Hill (1990); Bayer and Hill (1993)
Glyphosate	+	—	+	Smith *et al.* (1993); Clampett and Jones (1986)
MCPA and 2,4-D	+	+	—	Smith and Hill (1990); Bayer and Hill (1993)
Molinate	+	+	+	Smith and Hill (1990); Bayer and Hill (1993); Clampett and Jones (1986)
Pendimethalin	+	—	—	Smith and Hill (1990)
Propanil	+	+	—	Smith and Hill (1990); Bayer and Hill (1993)
Quinclorac	+	—	—	Smith and Hill (1990)
Thiobencarb	+	+	+	Smith and Hill (1990); Bayer and Hill (1993); Clampett and Jones (1986)
Triclopyr	+	+	+	Smith and Hill (1990); Street *et al.* (1992); Clampett and Jones (1986)

depths by herbicide treatments, but weeds were not controlled in shallow water, even with herbicides. Therefore, both water depth and herbicides were necessary for consistent weed control.

Biological control

In the southern US, northern jointvetch is controlled by an endemic anthracnose disease incited by the fungus *Colletotrichum gleosporioides* (Penz.) Sacc. f. sp. *aeschynomene* (C.g.a.) (Smith 1986). C.g.a. applied at 187 x 10^9 spores/ha post-emergence at midseason requires 5–10 days to show symptoms on weeds and 4–5 weeks to kill them. Herbicides including propanil, MCPA, and 2,4-D, as well as fungicides, injure C.g.a. when applied together in tank mixtures, but timely sequential applications of C.g.a. followed by these other pesticide treatments do not inhibit activity of the mycoherbicide. C.g.a. does not injure rice, nontarget crops, or other economical plants and has no soil residual activity. Unlike broadspectrum herbicides, C.g.a. controls only northern jointvetch and kills the weed more slowly. C.g.a. was the first microbial herbicide registered for weed control in a US agronomic crop.

Herbicides

Water-seeding rice into continuously flooded fields was developed as a cultural control for severe infestation of barnyard grass. Practices associated with water seeding continue to be important in today's integrated pest management programs for weeds. After World War II, the introduction of 2,4-D, followed successively by other herbicides, contributed to substantial gains in US rice yields through improved weed control. By the mid 1950s, 50 to 60% of the rice in Arkansas and 40% in Louisiana was treated with phenoxy herbicides (Smith 1956), the only herbicides used in US rice at that time. To achieve the full yield potential of high-yielding varieties introduced in the past decades, herbicides have become an integral component of the rice-cropping system (Table 4). Weed control has continued to improve with advances in herbicide technology, but only in conjunction with good management practices. Neither herbicides nor crop management practices alone adequately controls weeds. Each herbicide is effective for the control of a relatively limited number of weed species, and typically, 2 or more herbicides are required to provide satisfactory broadspectrum weed control. The critical consideration in using a herbicide is timing of application. Herbicide selectivity is rate-limited, and an excessive rate or an application made at an inappropriate stage of growth may be phytotoxic to the rice.

Current issues in US rice weed control

Rice herbicides have contributed greatly to improved weed control and to the efficiency of weed management but have also caused problems. As urban populations have increased social and environmental concerns have been raised about chemical use in rice production. Rice herbicide residues have been detected in well water, polluted agricultural drains, and rivers, and have caused off-tastes in potable waters in California (Cornachia *et al.* 1984). Damage to sensitive crops from herbicide drift has occurred in all US rice areas, particularly from the phenoxy herbicides (Smith *et al.* 1977). In California, propanil use was severely restricted because of long-range drift and excessive damage to deciduous orchards (Elmore *et al.* 1970). The continuous use of single, site-specific herbicides has led to the development of herbicide-resistant weeds. These problems, and increased regulatory costs, have sharply reduced the development of new herbicides for US rice-based cropping systems.

Water quality

In the late 1970s, fish kills in the agricultural drains of the Sacramento Valley, California, were attributed to the herbicide molinate. In 1981, a sulfoxide metabolite of thiobencarb was implicated as the cause of an off-taste in the municipal drinking water of the City of Sacramento (Cornacchia *et al.* 1984). The metabolite was never detected in potable water, but the herbicide was found in the Sacramento River at the intake of the drinking water treatment facility. The appearance of the herbicide with peak thiobencarb use in rice, the off-taste in potable water, and taste panel evaluation of metabolite-spiked water samples provided evidence that thiobencarb was responsible. A Rice Pesticide Working Group was formed by the California Department of Food and Agriculture and included several State agencies, the University of California, and rice grower organizations to establish voluntary and regulatory practices to reduce herbicide discharges from rice fields.

Conventional rice irrigation systems were designed to facilitate water depth management by allowing a continuous flow of water through a series of basins in the field. In-levee weirs (rice boxes) maintained water depth control by allowing excess water to flow out of the field. Herbicide registration labels were developed largely as a compromise between holding water static for efficacy and allowing water flow as soon as possible for convenience in managing irrigation water. The Working Group's principal strategy to mitigate against herbicides moving off-site was by increasing in-field water-holding beyond label requirements. The half-lives of molinate and thiobencarb in rice irrigation water are 4 and 8 days, respectively; therefore, longer holding periods allowed greater degradation. But longer holding periods were difficult to manage and risked damage to the crop. As an incentive to develop permanent solutions for water containment, earlier draining was allowed in fields, or groups of fields, where tailwater recovery systems were installed. Progressive growers installed recirculating systems and developed novel static or tailwater recapture systems (Hill *et al.* 1991*b*). Even fields with conventional irrigation, despite inherent problems with excess buildup of water in the lower basins, were better managed as growers increased their efforts to keep herbicide-treated floodwaters from escaping.

Over the past decade, water-holding periods following molinate application were increased from the label requirement of 4 to 19 days, and for thiobencarb to 30 days. From 1982 to 1992, rice herbicide mass discharge into public waters had been reduced by >98% (Fig. 1) as estimated by measured herbicide levels and river flow volumes. Challenges remain, including regulatory mandates to meet even more stringent residue performance goals; the need to accelerate conversion of the remaining rice cropping area under conventional irrigation to more controlled irrigation systems; and the development of agronomic practices to enhance stand establishment and to reduce herbicide use.

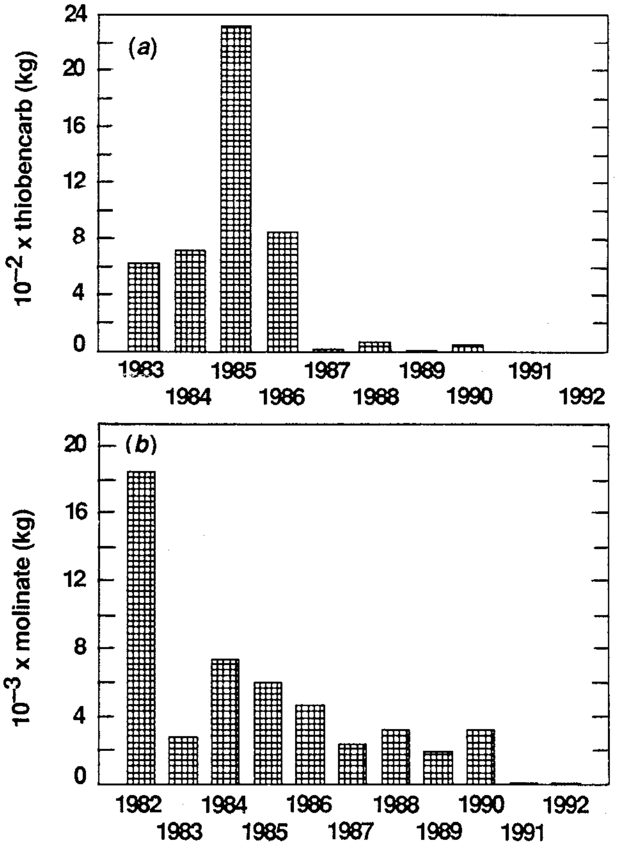

Figure 1. Mass transport in Sacramento River from 1982 to 1992: (*a*) thiobencarb and (*b*) molinate.

Herbicide resistance

Propanil was introduced in the 1960s for barnyard grass control in US rice. For the past 30 years, weed control programs for rice in the southern US have been developed around propanil (Smith 1974; Smith and Hill 1990). In recent years, about 70% of Arkansas rice hectarage has been treated twice each year with 3.4 kg/ha. In 1990, observations that barnyard grass was surviving propanil treatments in Arkansas rice fields (Walton and Holmdal 1992), coupled with greenhouse assays, confirmed that populations from 6 sites were not controlled by rates as high as 11 kg/ha (Smith and Baltazar 1993; Carey *et al.* 1992). A 1991 survey indicated that barnyard grass samples from 60 Arkansas rice farms in 11 counties were highly tolerant to propanil (Smith and Baltazar 1993). The occurrence of propanil resistance was greater in continuous rice than in rice rotated with soybeans. Therefore, rotation to soybeans with alternative herbicides, or, in continuous drill-seeded rice, use of fenoxaprop, quinclorac, pendimethalin and thiobencarb with different mechanisms of action from propanil, can be used to control resistant barnyard grass in rice (Baltazar and Smith 1994).

Bensulfuron was introduced in California in 1989 and controlled nearly all annual aquatic broadleaf and sedge weeds (Hill *et al.* 1990). Regulatory restrictions on other herbicides and the effectiveness of bensulfuron resulted in annual use of bensulfuron on >90% of California rice hectarage (Hill *et al.* 1994). In only 5 years, 4 weeds (California arrowhead, smallflower umbrella sedge, ricefield bulrush, redstem) were found to be resistant to bensulfuron in 72 sites (Pappas-Fader *et al.* 1993; Pappas-Fader *et al.* 1994). Resistant California arrowhead was the predominant weed, followed by smallflower umbrella sedge, redstem, and ricefield bulrush. Resistant weeds are not widespread in total California hectarage, but they have been found in nearly all rice-growing counties. It appears likely that the mechanism for development of resistance is endemic to many, if not most, rice fields. As more fields develop resistance, dispersal from field to field by equipment, irrigation water, and animals may play a greater role. A grower education fact sheet, 'Londax Resistant Management Strategies' (University of California 1993), was developed and distributed to rice growers. Only the phenoxy herbicides, MCPA and 2,4-D, are available as alternative broadleaf herbicides, although thiobencarb may be used to control 1 resistant species, smallflower umbrella sedge. Thus, nearly all alternative practices are considerably less desirable than bensulfuron.

Herbicide drift

Temperate rice may be grown amid a diverse array of crops intolerant of many rice herbicides. In the southern USA, these crops are principally cotton and soybean. In California, crops range from deciduous orchards to vines, and field and row crops, including grapes, tomatoes, cucurbits, sugar beet, and corn. Spray drift from rice herbicides to non-target crops in all rice areas of the US is a major issue, and phenoxy herbicide spraying is highly regulated in all US rice-producing states. Regulatory agencies provide restrictions on aerial applications of phenoxys as related to spray volumes, drift control adjuvants, flying height, nozzle size and angle, boom adjustment, and distance from sensitive crops, as well as environmental conditions such as wind speed, wind direction in relation to sensitive crops, and temperature inversions. All of these factors may severely limit the amount of herbicide that may be applied each day. In some areas, these regulations have virtually eliminated phenoxy use because the presence of sensitive crops makes compliance impossible. In California, propanil drift in the 1960s and 1970s caused serious damage to deciduous tree crops (Miller *et al.* 1969; Elmore *et al.* 1970), especially the French prune, and its use was prohibited on all but about 10% of the rice area. Propanil drift continues to injure nontarget crops in the US, especially cotton, soybeans, and home gardens. Bensulfuron drift has occasionally damaged seedling tomatoes, sugarbeets, and sensitive broadleaf crops in California. Novel precision equipment was developed for aerial, direct dry application of bensulfuron to eliminate spray drift. Aerially applied quinclorac has caused drift problems by injuring cotton and tomatoes in the southern US and attention to controlling drift of quinclorac is an important regulatory issue in this area. Triclopyr drift has injured cotton. Advances in application technology are badly needed to solve problems of rice herbicide drift and injury to sensitive crops.

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