CROP ECOLOGY, PRODUCTION & MANAGEMENT

Assessment of Salt Tolerance in Rice Cultivars in Response to Salinity Problems in California

M. C. Shannon,* J. D. Rhoades, J. H. Draper, S. C. Scardaci, and M. D. Spyres

ABSTRACT

Stringent requirements for water holding for California rice producers who use pesticides have resulted in the loss of stand and visible symptoms of leaf damage for some growers. A field survey and subsequent series of experiments were conducted to determine the range of salt tolerance among 11 cultivars of rice (*Oryza sativa* L.) that are common to northern California rice-growing areas. A field assessment made on several farms led to the conclusion that growth reduction and stand loss were correlated with high salinity in soil mud and water. Plants from saline basins had significantly higher concentrations of leaf Na^+ and Cl^- than those from less saline basins. Greenhouse studies were conducted in sand cultures and flooded with saline waters having average electrical conductivities of approximately 1 (control), 3, 7, 11, 13, and 16 dS m^{-1}. Salinity decreased emergence rates and final stand and led to reductions in shoot and root fresh and dry weights. At the highest salinity, shoot weights were 20% of the control after 17 d. Leaf tissues of plants grown at 16 dS m^{-1} had five times as much Na^+ and three times as much Cl^- as controls. Leaf concentration of K^+ was decreased by about 40% by salinity, but tissue levels of Ca^{2+} and Mg^{2+} were unaffected. In a second experiment, salinity treatments were lowered to 0.8, 1.6, 3.2, 6, 8, and 10 dS m^{-1}. There were significant differences in growth rates related to cultivar, but relative salt tolerance differences were negligible, leading to the conclusion that genetic differences among the rice cultivars are limited.

Rice is an important grain crop worldwide and its acreage in the USA has fluctuated from about 400 000 ha in 1940 to over 2.4 million hectares in 1980 (Hill et al., 1992). Since that time, there has been a decrease in rice area, but renewed expansion is expected because of recent changes in trade policies with Japan (Nowlin, 1993). Rice culture requires soil with a high water-holding capacity and, therefore, provides value to land with little other agricultural use. On the other hand, rice culture requires large quantities of water, a resource which has become increasingly important because of issues concerning both quantity and quality. The amount of water used by rice through evapotranspiration is about 100 cm per growing season, similar to that used by alfalfa (*Medicago sativa* L.); however, losses due to percolation and outflow can increase the water requirement to as much as 235 cm (Learn, 1993). In northern California, the maximum water used is about 140 to 170 cm. In recent years, drought and environmental concerns have increased the use of recirculating water systems for rice production. These systems decrease the amounts of water used and the amounts of herbicides spilled to drains because they cycle the drainage from one basin into another by gravity. Since water is continually lost through evaporation, such systems also increase the salinity of the water on a crop that has very low salt tolerance (Maas and Hoffman, 1977). California growers first suspected damage due to salinity in 1990 when they noticed losses in stand and chlorosis of leaf blade tips. Moreover, rice has been described as a crop with limited genetic variability for salt tolerance (Yeo et al., 1990). This study was conducted to document the salinity problem in rice production areas of the northern Sacramento Valley, to determine the effects of salinity on rice grown in this area, and to investigate the potential for differences in salt tolerance among these local rice cultivars.

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MATERIALS AND METHODS

Field Survey

Observations made by growers and extension personnel in 1990 and subsequent years indicated that practices associated with water conservation and water holding required by herbicide regulations, i.e., the use of recirculating systems, could be causing reductions in stand and yield in rice fields. At several locations in the Sacramento Valley, visual symptoms of leaf burn were noticed in rice plants at various stages of maturity. In June 1993, three fields in the Sacramento Valley were located in which rice had been seeded on about the same day (14–17 May) with the same cultivar, M-202. Management practices in the fields were similar and included seeding of imbibed seed, flooding, and water holding with minimal flow. The field designations and soil types were Moore, Vann (both fine, montmorillonitic, thermic Typic Pelloxererts), and Charter (fine, montmorillonitic, Thermic Typic Chromoxererts). Replicate samples of young plants were taken from at least three random locations in each basin in these fields. Plants were in the early tillering stage of growth. Measurements were taken to determine the in situ salinity of the water, soil, and mud; water pH; and oxygen content. Mud was defined as the loose soil at the base of the plants, no more than 3 to 6 cm deep. Soil consisted of the compacted clayey layer, up to 30 cm. At each sample site, all plants were harvested from a 700-cm^2 area and counted to determine plant density. Samples of plants, water, mud, and soil were taken for subsequent analysis. Salinity of the water was determined by electrical conductivity (EC_w), whereas in situ mud and soil salinities were determined using a conductivity probe (Rhoades, 1979). Mud and saturated soil samples were vacuum extracted and the conductivity of the extracted water was measured. Plant samples were rinsed briefly in distilled water, dried, re-weighed, and ground. Calcium, magnesium, sodium, and potassium were determined on nitric-perchloric acid digests of the plant material by induc-

Abbreviations: EC_w, electrical conductivity of water; dwt, dry weight.

tively-coupled plasma emission spectrophotometry. Chloride was determined on nitric-acetic extracts by coulometric-amperometric titration (Cotlove, 1963).

Greenhouse Studies

Experiments were conducted at the U.S. Salinity Laboratory in Riverside, CA. Eleven rice cultivars commonly grown in California were used in the study. The cultivars A-301, L-202, and L-203 are tropical japonica subspecies and Calmochi-101, M-103, M-201, M-202, M-203, M-401, S-201, and S-301 are temperate japonica subspecies (nomenclature indicates plant characters as follows: Calmochi = glutinous, A = aromatic, and L, M, S = long-, medium-, and short-grain types, respectively). Seeds of the 11 rice cultivars were surface sterilized by placing them in a 1 g L^{-1} $HgCl_2$ solution for 1 min, followed by soaking for 15 min in a solution of 16 mL L^{-1} formaldehyde + 4 mL methanol. Seeds were surface sterilized to remove fungi and other surface micro-organisms that would be detrimental to germination and seedling growth. Sterilized seeds were rinsed and imbibed overnight in tap water. Imbibed seeds were sown on 28 April 1991, in 25-seed rows in 1.2- by 0.8- by 0.5-m-deep sand tanks modified to allow flooding to a depth of 7 to 8 cm with half-strength Hoagland's nutrient solution (Hoagland and Arnon, 1938). The tanks were filled with Lytle Creek sand and irrigated from 800-L reservoirs. Irrigation solutions were returned by gravity to the reservoirs through a subsurface drainage system. The nonsalinized control solution was 1.05 dS m^{-1}. Additions of NaCl were made to appropriate reservoirs to achieve treatment electrical conductivities of 2.9, 7.0, 11.3, 12.6, and 15.6 dS m^{-1}. Approximately 640 mg L^{-1} NaCl is equivalent to 1 dS m^{-1} electrical conductivity. A randomized block design was used with 11 cultivar-rows per plot (plot = tank), six levels of salinity and three replications. Average daytime high and night low temperatures during the experiment were 30 and 18°C, respectively. Plants were harvested 14 d after seeding. Fresh and dry weights of roots and shoots were measured, and tissues were sampled for ion analysis.

A second greenhouse experiment was conducted similar to the first with the following exceptions: the seeding date was 2 May 1991; the cultivar A-301 was omitted; average electrical conductivities were 0.82, 1.67, 3.34, 5.74, 8.05, and 10.2 dS m^{-1}; and average day and night temperatures were 30 and 20°C, respectively; and plants were harvested after 25 d.

Table 1. Correlation coefficients between plant variables and salinity measurements in the soil, water, and mud at field locations in the Sacremento Valley (n = 42). All correlations were significant at probability of 0.0001.

Electrical conductivity	Shoot dry wt	Plant density	Biomass
	g $plant^{-1}$	plant m^{-2}	g dry wt m^{-2}
Ponded water	−0.800	−0.846†	−0.863†
Mud	−0.779	−0.797	−0.835
Soil	−0.766	−0.745	−0.763
Extracted mud	−0.803†	−0.827	−0.855
Extracted soil	−0.768	−0.802	−0.806

† Indicates highest correlation within column.

RESULTS AND DISCUSSION

Field Study

Plants from all fields were in the early tillering stage of growth at harvest. Plant response factors in rice fields were closely correlated to the electrical conductivity of the ponded water, mud, soil, and extracts of the mud and soil (Table 1). No correlations were noted with respect to pH and oxygen concentration. The conductivity of the ponded water gave the highest correlation coefficient with plant density and biomass, while plant dry weight was most significantly correlated with the conductivity of the mud extract.

Shoot dry weight and plant density (stand) decreased with increased salinity of the ponded water over a range of 0.01 to 4 dS m^{-1}, measured in different basins on three different farms (Moore, Vann, and Charter; Fig. 1). As salinity increased, plant density decreased to a proportionately greater extent than shoot dry weight. Thus, biomass (shoot dry weight $plant^{-1}$ × plant den-

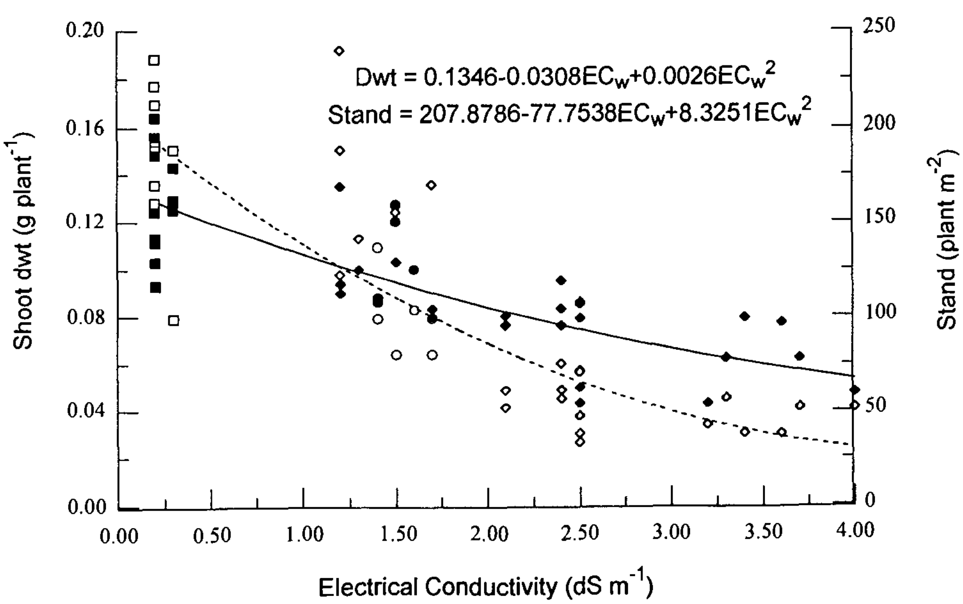

Fig. 1. The effects of salinity in the ponded irrigation water, as measured by electrical conductivity (EC_w), on shoot dry weight (closed symbols; F = 36.52*; df [2,39]) and plant density or stand (open symbols; F = 56.32***; df [2,39]) in field-grown rice (cv 'M-202'). Vann field (■, □); Moore field (◆, ◇); Charter field (■, □).**

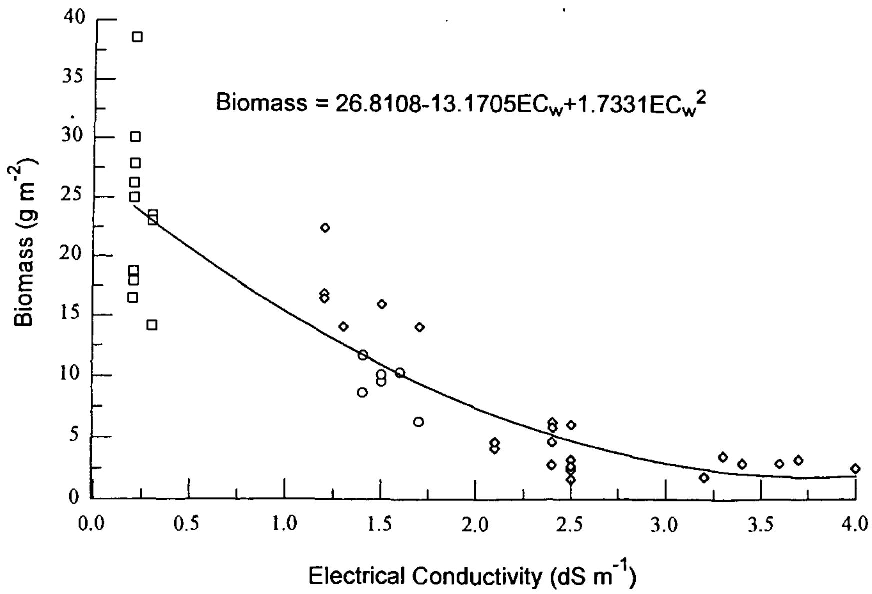

Fig. 2. Effects of salinity in the ponded irrigation water, as measured by electrical conductivity (EC_w), on plant biomass (shoot dry weight × stand; F = 78.24*; df [2,39]) in field-grown rice (cv 'M-202'). Vann field (□); Moore field (◇); Charter field (○).**

sity) also decreased with increased salinity (Fig. 2). The data support the conclusion that rice is sensitive to low salinities, but despite the fact that planting dates and cultivars were identical, the ranges of salinities found on each farm varied (Fig. 1). Other factors, such as basin design, soil type, soil fertility, and microclimate, may have contributed to differences in plant growth data taken at different locations. When basins were arranged in a simple retangular design and water flow was directed sequentially from the upper to the lower basins (Moore), the lowest salinities were found in the highest basin (EC_w = 1.35 ± 0.5, n = 6) and the highest salinities were found in the lowest basin (EC_w = 3.20 ± 0.5; n = 6). But when field shapes and sizes varied (Vann and Charter), correlations between salinity and sampling location were less clear.

Increased salinity had negative effects on plant growth and stand in young rice plants and these were closely correlated to the salinity of ponded water. Pearson and Ayers (1960) noted that salinity applied to 2-wk-old rice seedlings caused reductions in survival and reduced growth. It also was reported that the variety 'Kala-Rata' from India was more salt-tolerant than 'Agami Montakhab I' (Egypt), 'Asahi #1' (Japan), or 'Caloro' (USA). Thus, rice sensitivity is known to change noticeably during early development and to vary with variety. If additional information were known on the threshold salinity of California rice varieties and the interaction between threshold sensitivity and environmental factors, it is feasible that appropriate management strategies could be proposed based on monitoring water electrical conductivity.

Greenhouse Studies

In the first sand culture study, salinity decreased shoot dry weight of all cultivars. Even at the lowest salinity treatment, 2.9 dS m^{-1}, shoot dry weights after 14 d of saliniation were significantly reduced with respect to controls. Average plant dry weights among cultivars ranged from 17.3 to 38 mg plant^{-1} under nonsaline, control conditions (Table 2). These differences were

Table 2. Average shoot dry weights (dwt) of rice cultivars (CV) harvested under different salinity conditions in the first greenhouse experiment.

Salt 1 1.05 dS m^{-1}		Salt 2 2.9 dS m^{-1}		Salt 3 7.0 dS m^{-1}		Salt 4 11.3 dS m^{-1}		Salt 5 12.6 dS m^{-1}		Salt 6 15.6 dS m^{-1}	
CV†	dwt	CV	dwt	CV	dwt	CV	dwt	CV	dwt	CV	dwt
					mg plant^{-1}						
9	38.0 a‡	7	22.3 a	8	28.7 a	9	16.3 a	8	10.0 a	7	10.3 a
8	37.3 a	8	22.0 ab	9	27.3 ab	8	15.7 a	9	7.7 ab	8	10.3 a
7	35.7 a	9	19.7 abc	7	24.3 ab	10	13.7 ab	7	6.7 ab	9	9.7 ab
10	34.7 a	10	19.7 abc	6	22.7 ab	7	13.3 abc	6	6.0 bc	10	9.3 ab
6	30.7 a	11	16.7 bcd	10	22.3 ab	2	12.0 bc	11	5.0 bc	11	8.3 abcd
11	28.3 a	2	16.7 bcd	2	19.0 ab	11	11.7 bcd	2	5.0 bc	2	7.0 abcde
2	28.0 a	6	15.3 cde	11	15.0 ab	4	10.7 bcde	4	5.0 bc	6	6.7 cde
4	26.3 a	5	14.7 cdef	3	14.7 ab	6	10.3 cde	10	4.7 bc	4	6.3 de
3	20.7 a	4	12.3 def	5	14.3 ab	5	8.7 def	5	4.3 bc	3	5.7 de
5	20.3 a	3	11.0 ef	4	14.3 ab	3	8.0 ef	3	4.3 bc	5	5.3 de
1	17.3 a	1	9.7 f	1	8.7 b	1	6.3 f	1	2.3 c	1	4.0 e

† Cultivars: 1 = A-301; 2 = Calmochi-101; 3 = L-202; 4 = L203; 5 = M-103; 6 = M-201; 7 = M-202; 8 = M-203; 9 = M-401; 10 = S-201; 11 = S-301 mg plant^{-1}.
‡ Different letters after the means indicate Duncan's Multiple Range comparisons within columns at the 0.05 level of significance.

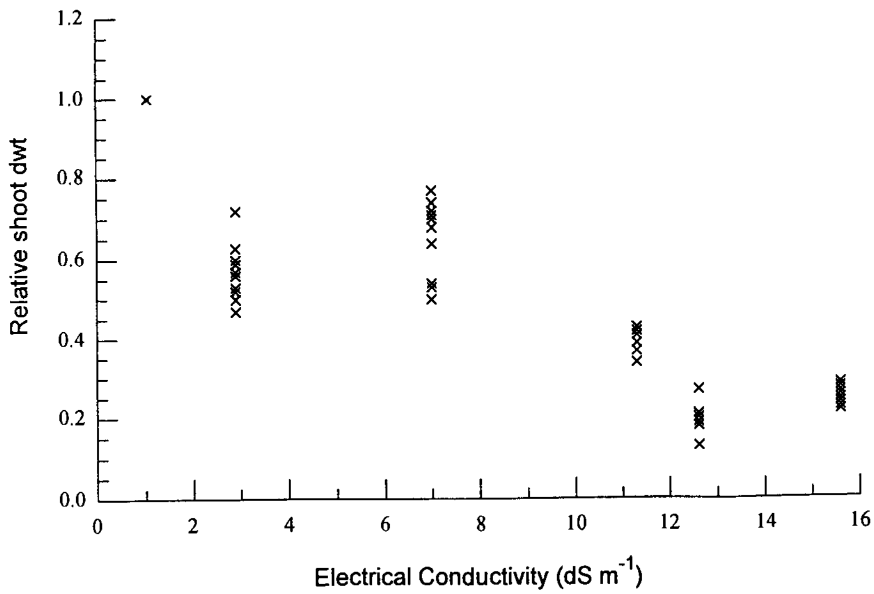

Fig. 3. Effects of NaCl salinity on relative shoot dry weights of 11 cultivars of rice grown in the first greenhouse sand culture experiment.

not statistically significant due to high within-cultivar variation. As salinity increased, variation due to cultivar decreased and significant salinity and cultivar differences were observed; however, because of the consistent ranking of the cultivars at each salt level, it was concluded that differences were not due to salt tolerance but to growth rate differences among cultivars. When decreases in shoot dry weight due to salinity were evaluated in proportion to growth of the respective cultivars grown under nonsaline conditions (i.e., relative salt tolerance), shoot dry weights of all cultivars were similarly reduced by salinity, and cultivar differences were statistically nonsignificant (Fig. 3). Thus, no significant genetic variability for salt tolerance was found during early seedling growth among the cultivars examined in this study.

In the second sand culture study, the relative shoot dry weight was not significantly reduced among cultivars at the two lowest salinities (Fig. 4). Only at 5.74 dS m^{-1} and greater did salinity levels reduce shoot dry weights with respect to controls. Whether these differences were due to the additional 11 d of growth or differences in environmental variables could not be determined. Although the recorded environmental variables were very similar in both studies, final dry weights of the controls were approximately ten times greater than those in the first study. Varietal differences with respect to seedling vigor were similar to those observed in the first greenhouse study, and again, cultivar differences in relative salt tolerance were not observed. In both greenhouse experiments, shoot dry weight decreases with increasing salinity were found to be more closely correlated to shoot Na^+ content than to any other single ion or ion pair (Table 3). Shoot tissue compositions of

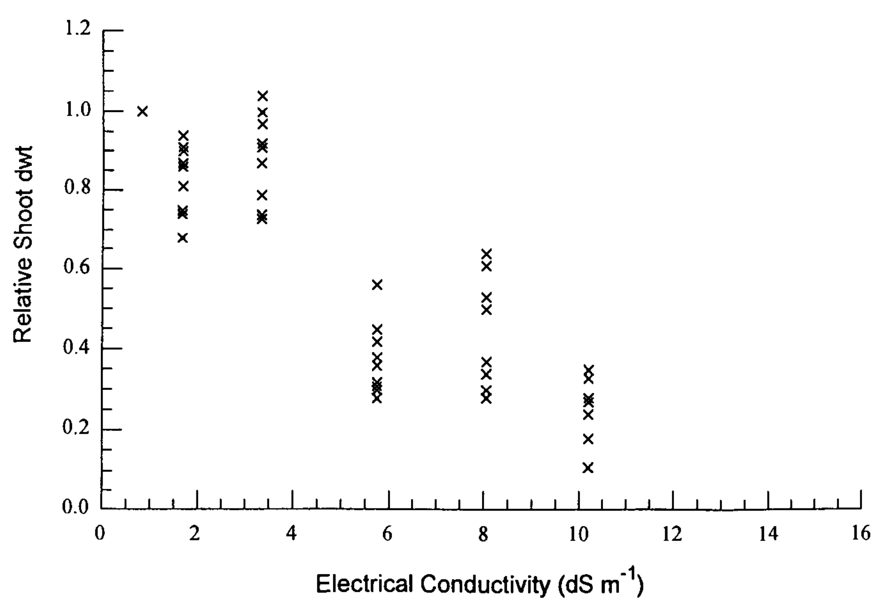

Fig. 4. Effects of NaCl salinity on relative shoot dry weights of 10 cultivars of rice grown in the second greenhouse sand culture experiment.

Table 3. Correlation coefficients between plant dry weights (all cultivars pooled) and tissue ion concentrations with increasing salinity in greenhouse salt tolerance trials (Exp. 1 and 2).

	Shoot dry wt		[Na] + [K]		[Na] + [Cl]	
Ions	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2
Na^+	−0.504***	−0.675***	0.838***	0.846***	0.933***	0.896***
Cl^-	−0.387***	−0.394***	0.552***	0.434***	0.899***	0.821***
K^+	−0.132	0.586***	0.478***	−0.024	−0.149*	−0.470***
Ca^{2+}	−0.404***	−0.474***	0.783***	0.714***	0.660***	0.651***
Mg^{2+}	0.008	0.487***	0.690***	0.128	0.339***	−0.219**
$[Na^+] + [K^+]$	−0.373***	−0.435***	1.000***	1.000***	0.765***	0.770***
$[Na^+] + [Cl^-]$	−0.500***	−0.637***	0.765***	0.770***	1.000***	1.000***

*,**,*** indicates significance at the 0.05, 0.01, and 0.001 levels, respectively.

Na^+, Ca^{2+}, Cl^-, $[Na^+ + K^+]$, and $[Na^+ + Cl^-]$ were consistently and negatively correlated with plant dry weight and positively correlated with irrigation water and salinity treatment. These findings were consistent with field studies, in which the correlation between leaf sodium and the electrical conductivity of the ponded water was high ($r^2 = 0.88$).

The results of these studies indicate that limited genetic variability exists for salt tolerance during early seedling growth among the most common rice cultivars grown in northern California rice-production areas. The most salt-sensitive growth stages in rice occur during emergence and growth of young seedlings, as measured by seedling death and reduced growth rates, and during flowering resulting in pollen sterility (Kaddah, 1963; Akbar et al., 1972). Water-holding restrictions without recirculating systems imposed at early growth stages can reduce early plant growth rates and decrease stand, potentially reducing yield. Additional studies are needed to determine optimum management practices necessary to minimize yield losses.

Previous studies support our conclusions that growth decreases are closely correlated with NaCl accumulation by individual plants (Flowers and Yeo, 1981). In field studies, Na^+ contents of shoots were highly correlated to the salinity of the ponded water ($r^2 = 0.885$; $F = 0.001$). Differences in the ability to restrict NaCl accumulation in shoots were noted among the cultivars studied in these experiments (data not shown), but these differences did not improve relative salt tolerance. Improved salt tolerance in rice has been found to be correlated with the ability of certain cultivars to restrict uptake of NaCl into the shoot, and a possible mechanism for Na^+ exclusion in rice roots has been identified (Tsuchiya et al., 1994). However, tissue ion compositions alone have not proved to be useful indicators of plant salt tolerance. Ion concentration changes need to be correlated to plant mass increases over time and eventually yield increases to derive a useful criterion for salt tolerance (Dalton and Poss, 1989).

It is possible that the salt tolerance of California rice cultivars can be improved through selective breeding with cultivars with higher salt tolerance. Other possibilities include the transfer of tolerance genes from more salt-tolerant wild relatives through wide hybridization or the improvement of salt tolerance through in vitro selection and regeneration of cell cultures (Jena, 1994; Winicov, 1996). Until solutions can be found to improve the genetic tolerance of California rice cultivars, growers will have to apply more careful management techniques to avoid yield losses due to high salinity during early growth stages.

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