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# Rice growth and yield respond to changes in water depth and salinity stress

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**Abstract**

Depth of standing water in rice paddy fields is an important agronomic parameter in the management of irrigation-related salinity problems. It was hypothesized that reductions in the yield of rice under salinity stress can be ameliorated by adjusting the water depth. This study was designed to determine the interactive effects of salinity and water depth on seedling establishment and grain yield in rice. Plants were grown in a greenhouse and irrigated with nutrient solutions amended with NaCl and $CaCl_2$ (5:1 molar concentrations). Treatments were three salt levels with electrical conductivities at 0.9, 3.3 and 6.0 dS $m^{-1}$ and six water depths at 4, 7, 10, 13, 16 and 20 cm. The effects of both salinity and water depth were significant on plant growth and yield. However, there was no interaction between the effects of salinity and water depth. Reductions in seedling establishment and grain yield with increases of salinity and water depth resulted from a simple combination of the two different stresses on plants. Highly significant negative correlations were identified between water depth and seedling establishment and also between water depth and grain yield when data were combined across salt levels. Generally, plants performed better with respect to seedling establishment and grain yield in shallow water (i.e. <10 cm) than in deep water (i.e. >10 cm). Under salt stress, the effect of water depth was significant for panicle number, but not significant for panicle weight. The loss of grain yield under salt stress with the increases of water depth was mainly due to reduction in fertile tiller number. We suggest that water depth be lowered during the initiation and growth of productive tillers. However, the practice by lowering water depth must be incorporated with appropriate field management such as the increase of irrigation frequency, precision leveling, and effective weed control methods.
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*Keywords:* Water depth; Salinity; Seedling establishment; Yield components; Rice

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## 1. Introduction

In recent years, salinity concerns are increasing in rice (*Oryza sativa* L.) producing areas of California, where direct water-seeded system is dominant. Salinity levels of standing water at rice fields in those regions have risen because of irrigation practices such as the use of recirculating water systems and the requirement of water holding after pesticide application during early growth stages (Scardaci et al., 1996). This has resulted in loss of plant stand and reduction of final seed yield in salt-affected rice fields (Scardaci et al., 1996; Shannon et al., 1998). The development of management options to ameliorate salinity problem requires analysis of agronomic parameters which affect the interaction between salinity and crop yield. For rice, the parameters such as planting density and timing of salinity stress have been analyzed and reported (Zeng and Shannon, 2000; Zeng et al., 2001). Water depth is another important agronomic parameter which may influence the effect of salinity on rice growth and yield.

Planting of presoaked (24–36 h) seeds on soil surface in water is a common practice in the direct water-seeded system (Hill et al., 1992). The subsequent processes of germination, growth and maturity occur under continuously flooded conditions. A certain depth of standing water is maintained throughout the growing season to facilitate irrigation practices and weed control (Hill et al., 1992; Tuong and Bhuiyan, 1999). Variations in water depth due to irregularity of leveling, especially in large size paddy fields, often affect rice growth and yield (Anbumozhi et al., 1998). Water depth is an important parameter for the prediction of rice growth. The simulation growth model without inclusion of water depth tends to overpredict rice shoot dry mass production (Caton et al., 1999). Excessive standing water tend to reduce photosynthetic leaf area (Yoshida, 1981), increase oxygen deficiency on soil surface (IRRI, 1964, 1979), inhibit tiller (Williams et al., 1990), and decrease water use efficiency (Tuong and Bhuiyan, 1999). The morphological cause of yield reductions in rice crop under partial submergence has been attributed to impaired tillering (Yoshida, 1981).

It has been well documented that salinity affects rice seedling growth and decreases seedling establishment (Pearson and Bernstein, 1959; Flowers and Yeo, 1981; Lutts et al., 1995; Shannon et al., 1998). Salinity also affects rice grain yield and yield components such as spikelet number and tiller number (Heenan et al., 1988; Khatun et al., 1995). However, how salinity affects rice growth and yield at different water depths is still unknown. We hypothesized that reductions in the yield of rice crop under salinity stress can be ameliorated by adjusting the water depth. The determination of the relationships between the effects of salinity and water depth will provide growers management option in dealing with salinity problems that occur in rice production. The objectives of this study were to determine the interactive effects of salinity and water depth on seedling establishment and seed yield in three rice cultivars, M-103, M-201 and M-202, and to identify the critical yield component(s) attributed to the yield loss of rice plants under the interactive effects of salinity and water depth.

## 2. Materials and methods

The experiment was conducted in a greenhouse at Riverside, CA (33°58′24″N latitude, 117°19′12″W longitude) from July to November 1999. Three rice cultivars, M-103, M-201 and M-202, were provided by Kent McKenzie (California Cooperative Rice Research Foundation, Biggs, CA).

Plants were grown in Yoshida nutrient solutions (Yoshida et al., 1971) in large tanks (122 cm × 61 cm × 46 cm deep) filled with sand (#12, Cisco, Corona, CA).[1] Irrigation solutions were prepared in reservoirs of 1600 l each and pumped to provide irrigation to sand tanks. Each reservoir irrigated six sand tanks. Drainage from the sand tanks returned to the reservoirs through a subsurface system by gravity. Seeds were soaked in distilled water at 37 °C for 24 h before planting. Seeds were sown in four rows for each cultivar and 12 rows total for three cultivars in each sand tank. The rows were spaced 7 cm apart with 15 seeds per row. Sowing depth was 10 mm. Plants were irrigated with full strength Yoshida nutrient solutions (Yoshida et al., 1971). Air temperature was controlled at 24–33 °C during day and 19–25 °C during night. Relative humidity ranged from 40 to 90%. Daily accumulative light averaged 550 uE $m^{-2}$ $s^{-1}$ with a minimum 100 uE $m^{-2}$ $s^{-1}$ and a maximum 1300 uE $m^{-2}$ $s^{-1}$ during day.

The experiment design was a standard split–split plot with three replicates. The treatments were three salt levels (i.e. 0.9, 3.3 and 6.0 dS $m^{-1}$), six water depths (i.e. 4, 7, 10, 13, 16, 20 cm), and three cultivars (i.e. M-103, M-201 and M-202). The treatments of salt levels were assigned as main plot factor and the treatments of water depths and cultivars were assigned as sub-plot and sub-sub plot factors, respectively. All factors were considered as fixed effects. Salinity treatments were gradually imposed by addition of NaCl and $CaCl_2$ (5:1 molar concentration) to nutrient solutions on the first, third, and fifth days after planting (DAP). Electrical conductivity (EC) of irrigation water was measured twice each week and averaged 0.9 (non-saline control), 3.3 and 6.0 dS $m^{-1}$ over the course of the experiment. The water depths were created by removing different amounts of sand from each sand tank, and leveled using a straight-board leveler. Water depths were controlled by the distance between sand surface and the returning pipes for drainage.

Seedling survival rate was measured 29 DAP as the percentage of live seedlings from the germinated plants. Eight of surviving seedlings from each replicate of treatments were randomly sampled 30 DAP. Roots were removed. Shoots were dried in a forced-air oven (70 °C) for 1 week and weighed. A second harvest was conducted when the panicles on primary tillers matured. Eight plants were randomly sampled from each replicate and measured for yield and yield components. After drying at 70 °C for 1 week, all matured panicles were counted and weighed while immature ones were not. Main culms were not distinguished from tillers. Grain weight per plant was calculated as the product of grain weight per panicle and panicle number per plant. Finally, data were averaged over the eight sub-samples.

The significance of all experimental factors in the split–split plot design was calculated by deriving the mean squares in the analysis of variance using the GLM procedure of the Statistical Analysis System (SAS Institute, 1994). The significance of the main treatment (salt level) was tested by the first-order interaction, i.e. replicate × salt, as an experimental error. The significance of the subtreatment (water depth) and sub-subtreatment (i.e. cultivar) was also tested by the first-order interactions, replicate × water and replicate × cultivar, respectively, as the experimental errors. The second order interaction,

[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and dose not imply recommendation or endorsement by the US Department of Agriculture.

i.e. replicate × salt × water, was used as an experimental error to test the significance of the first-order interaction, i.e. salt × water. The other second-order interactions, i.e. replicate × salt × cultivar and replicate × water × cultivar, were used as experimental errors to test the significance of salt × cultivar and water × cultivar, respectively. The highest order interaction, replicate × salt × water × cultivar, was used as an experimental error to test the second-order interactions. *F*-tests for the significance followed the procedures described by Ott (1988). The mean values among treatments were grouped and compared using Tukey's Range Tests (Ott, 1988) if analysis of variance indicated the presence of differences among treatment means. In doing so, the first-order interactions, i.e. replicate × salt and replicate × water, were specified as experimental errors during the mean separations for the factors of salt and water, respectively.

## 3. Results

The variances of plant growth and yield parameters were analyzed and the results are summarized in Table 1. The overall effects of salt level and water depth were highly

Table 1
Mean squares for growth and yield parameters at different water depths and salt levels

| Source | d.f. | Shoot weight ($\times 10^{-2}$) | Survival ($\times 10^{2}$) | Seed weight (per plant) | Panicles (per plant) | Seed weight (per panicle) |
|---|---|---|---|---|---|---|
| Salt (S) | 2 | 74.8*** | 81** | 48.9*** | 12.1*** | 2.91*** |
| Water (W) | 5 | 27.7*** | 57*** | 7.4** | 4.77*** | 0.07 |
| S × W | 10 | 2.88*** | 2.4 | 0.6 | 0.14 | 0.11 |
| Genotype (G) | 2 | 11.0*** | 34*** | 3.5** | 0.05 | 0.66** |
| S × G | 4 | 0.69 | 1.0 | 1.7 | 0.14 | 0.17 |
| W × G | 10 | 1.5* | 0.6 | 0.4 | 0.12 | 0.04 |
| S × W × G | 20 | 0.01* | 0.6 | 0.3 | 0.08 | 0.04 |

* Significant at 0.05 significance level in *F*-tests.
** Significant at 0.01 significance level in *F*-tests.
*** Significant at 0.001 significance level in *F*-tests.

Table 2
Effect of salinity on growth and yield with mean values averaged across water depth levels and genotypes

| Parameters | Salt levels (dS $m^{-1}$) | | |
|---|---|---|---|
| | 0.9 | 3.3 | 6.0 |
| Shoot weight (g per plant) | 0.44 a | 0.28 b | 0.21 b |
| Survival (%) | 83.7 a | 70.2 b | 58.9 b |
| Seed weight per plant (g per plant) | 3.77 a | 2.40 b | 1.91 c |
| Panicles (no. per plant) | 2.68 a | 1.79 b | 1.96 b |
| Seed weight per panicle (g) | 1.44 a | 1.36 b | 0.99 c |

Within rows, means followed by the same letter are not significantly different at 0.05 probability level based on Tukey's Studentized Range Tests.

Table 3
Effect of water depth on growth and yield with mean values averaged across salt levels and genotypes

| Parameters | Water depth (cm) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 7 | 10 | 13 | 16 | 20 |
| Shoot weight (g per plant) | 0.47 a | 0.37 ab | 0.32 bc | 0.29 bc | 0.23 cd | 0.18 d |
| Survival (%) | 86.8 a | 83.8 a | 78.9 ab | 70.8 bc | 59.5 cd | 48.5 d |
| Seed weight per plant (g) | 3.47 a | 2.99 ab | 2.75 abc | 2.48 bc | 2.49 bc | 1.93 c |
| Panicles (no. per plant) | 2.72 a | 2.46 ab | 2.22 bc | 2.07 bc | 1.82 cd | 1.52 d |
| Seed weight per panicle (g) | 1.31 a | 1.21 a | 1.23 a | 1.23 a | 1.35 a | 1.27 a |

Within rows, means followed by the same letter are not significantly different at 0.05 probability level based on Tukey's Studentized Range Tests.

significant $(P < 0.01)$ for most parameters investigated. The only exception was that the overall effect of water depth was not significant $(P \leq 0.05)$ for seed weight per panicle. The interactions between water depth and salt level were not significant $(P \leq 0.05)$ for most parameters except seedling shoot weight. Although the overall effect of genotypes was highly significant $(P < 0.001)$, the interactions between genotype and salt level and between genotype and water depth were not significant $(P \leq 0.05)$.

Since the interactions among water depth, salt level, and genotype were not significant, the main effects of the growth and yield parameters have been summarized by

Table 4
The mean values of the growth and yield parameters in rice cultivar, M-202, at different salt and water levels

| Parameters | Salt levels ($dS\ m^{-1}$) | Water depths (cm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 4 | 7 | 10 | 13 | 16 | 20 |
| Shoot weight (g per plant) | 0.9 | 0.82 a | 0.67 ab | 0.47 abc | 0.42 abc | 0.33 bc | 0.16 c |
| | 3.3 | 0.45 a | 0.31 a | 0.25 ab | 0.31 a | 0.19 b | 0.24 ab |
| | 6.0 | 0.40 a | 0.23 ab | 0.15 b | 0.21 ab | 0.17 b | 0.15 b |
| Survival (%) | 0.9 | 92.7 a | 89.5 a | 80.9 ab | 66.8 ab | 60.5 b | 65.2 ab |
| | 3.3 | 85.7 a | 78.6 ab | 71.8 ab | 68.7 ab | 55.4 bc | 41.0 c |
| | 6.0 | 73.9 a | 75.7 a | 56.6 b | 59.3 b | 44.2 b | 29.6 c |
| Seed weight (g per plant) | 0.9 | 4.82 a | 4.02 a | 4.47 a | 3.25 ab | 4.72 a | 2.75 b |
| | 3.3 | 3.92 a | 2.98 ab | 2.53 ab | 2.99 ab | 2.24 b | 1.78 b |
| | 6.0 | 2.95 a | 2.34 ab | 1.90 bc | 1.41 c | 1.37 c | 1.44 c |
| Panicle number (no. per plant) | 0.9 | 3.03 a | 2.74 a | 2.63 ab | 2.44 ab | 2.53 ab | 2.00 b |
| | 3.3 | 2.32 a | 2.24 a | 1.78 ab | 1.56 ab | 1.47 b | 1.23 b |
| | 6.0 | 2.64 a | 2.41 ab | 2.06 abc | 1.79 bc | 1.60 c | 1.29 c |
| Seed weight (g per panicle) | 0.9 | 1.64 a | 1.41 a | 1.67 a | 1.46 a | 1.78 a | 1.45 a |
| | 3.3 | 1.68 a | 1.35 a | 1.31 a | 1.86 a | 1.48 a | 1.32 a |
| | 6.0 | 1.09 a | 0.94 a | 0.83 a | 0.82 a | 0.90 a | 1.15 a |

Within rows, means followed by the same letter are not significantly different at 0.05 probability level based on Tukey's Studentized Range Tests.

averaging data across the factors. The reductions in all parameters investigated were significant ($P < 0.05$) with the increases of salinity compared with the controls (Table 2). Generally, with the increases of water depths, reductions were observed in most parameters except grain weight per panicle (Table 3). Reductions in seedling survival and grain weight per plant at shallow water depths between 4 and 10 cm were not significant (Table 3). The means of the growth and yield parameters in cultivar, M-202, were also separated at different water depths and salt levels (Table 4). Reductions in growth and yield parameters with the increases of water depths occurred at each salt level including the control. The performance of most parameters at shallow water depths, i.e. 4–13 cm at 3.3 dS $m^{-1}$ and 4–7 cm at 6.0 dS $m^{-1}$, was better than those at deeper water depths.

The effects of water depth were regressed to plant growth and grain yield in cultivar, M-202, using linear regressions (Fig. 1). Water depth was negatively correlated to seedling survival (Fig. 1A), grain weight per plant (Fig. 1B), and panicle number (Fig. 1C), and, but not significantly correlated to grain weight per panicle (Fig. 1D).

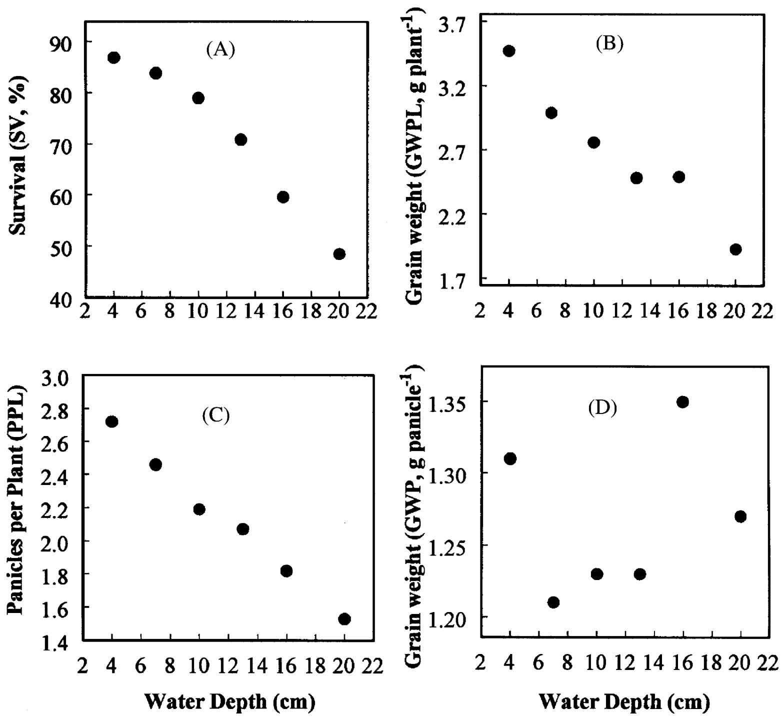


Fig. 1. Relationships between water depth and plant growth and grain yield in rice cultivar, M-202, with data averaged across salt levels. Linear regression was analyzed between water depth and different agronomic parameters: (A) seedling survival, $SV = 94 - 1.9$ water, $R^2 = 0.98$; (B) grain weight per plant, $GWPL = 4.3 - 0.15$ water, $R^2 = 0.87$; (C) panicles per plant, $PPL = 2.98 - 0.08$ water, $R^2 = 0.98$; (D) grain weight per panicle, $GWP = 1.5 - 0.02$ water, $R^2 = 0.11$.

## 4. Discussion

An understanding of plant response to the changes of water depths under salt stress is important for the water management, as a strategy in dealing with salinity problem, to improve the agronomic performance of rice crop in saline water irrigation. The relationships between water depth and crop yield under salt stress can be used to predict final yield under salt stress at different water regimes and increase water use efficiency. Under field conditions, it would be difficult to determine the critical parameters because the effects of salinity on plants are complex and easily affected by environmental conditions such as temperature and humidity (Shannon, 1997). The relationships between water depth and plant growth and yield under salt stress were successfully determined in this study under controlled conditions. The determined parameters can be used to predict yield combined with other environmental factors such as weed control in paddy fields.

The negative correlations between water depth and plant stand and between water depth and grain yield were identified under salt-stressed conditions. Generally, seedling establishment and grain yield were better in shallow (i.e. <10 cm) water than in deep (i.e. >10 cm) water. These findings are consistent with those of Anbumozhi et al. (1998) who found under non-saline conditions that plant growth and grain yield declined at water depths above 15 cm.

Yield of rice, in common with many other small-grain cereals, is highly dependent upon the number of fertile tillers per plant. Generally, productive tillers emerge and develop early in the life cycle of the crop. Hoshikawa (1989) refers this period as the "productive tiller number determining stage" in the morphological development of rice. Environmental conditions present at this growth stage affect the final number of fertile rice panicles. Our results indicate that deep ponding saline water reduces grain yield by inhibiting the formation of productive tillers. In this study, the effect of water depth was significant on panicle number, but not significant on panicle weight under salt stress. If grain yield is expressed by the equation:

$$\text{grain weight per plant} = \text{panicle number} \times \text{panicle weight},$$

the loss of grain yield under salinity with the increases of water depth was mainly due to reductions in tillers. This agrees with the observation that under non-saline conditions the loss of grain yield in rice under partial submergence was due to the impaired tillering (Yoshida, 1981).

There was no interaction between salt level and water depth identified in the experiment. This indicates that the effects of water depth on rice growth and yield in the cultivars investigated are similar at different salt levels or vice versa. Reductions in seedling establishment and grain yield with increases of salinity and water depth resulted from a simple combination of the two different stresses on plants. Therefore, a simple reduction in water depth should reduce the stress on rice plants and the same adjustment of water depth can be applied to different paddy fields with the variations of salinity.

A routine management practice in rice fields is to maintain a water depth that will suppress weed growth during the growing season. The relationships between water and weed management practices are complex. The effectiveness of weed control depends on water depth and other factors such as tillage, herbicide, and weed species, and also varies at different growth stages of rice crop (Bhagat et al., 1996). Generally, shallow water depth can effectively suppress weeds at first few weeks of seedling growth with the integration of herbicide application (Bhagat et al., 1996). In fields under continuous floods without herbicide treatment, rice yield was three times greater in deep (20 cm) water than in shallow (5 cm) water, but that difference between water depths disappeared when herbicide was applied (Williams et al., 1990). These observations were consistent with our contention that rice plants under salinity stress can perform better in shallow water than in deep water when weed control is efficient. In the regions where the application of herbicide is limited for reasons of either environmental concern or availability, weed control is more dependent on the depth of standing water. At those situations, the timing of adjusting water depth could be critical since a sufficient depth of water may be required for efficient weed control. Therefore, when saline water must be used for rice production, we suggest that water depth be lowered during the initiation and growth of productive tillers. Maintenance of a shallow water depth in fields could be difficult due to evapotranspiration. The reduction in total water volume because of evapotranspiration could be extreme in shallow water and further cause an increase of salinity level in standing water. Therefore, the practice by lowering water depth must be incorporated with appropriate field management such as increase of irrigation frequency, precision of leveling and effective weed control methods.

In conclusion, there was no interaction between the effects of salt level and water depth. The negatively linear correlations between water depth and rice seedling establishment and grain yield were identified under salt stress. Plants under salt stress performed better at shallow water depths (i.e. <10 cm) than at deep water depths (i.e. >10 cm). Inhibition of tillering ability was the morphological cause of the yield loss in deep water under salt stress.

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