Looming water crises challenge sustainability in rice production systems, necessitating the development of suitable genotypes and crop management techniques that use less water compared with the traditional irrigated rice cultivation. Aerobic rice alleviates the adverse impacts created by a water stress environment. Tropical aerobic rice, unlike temperate aerobic rice in Brazil and China, is in a beginning phase of development. One of the major concerns is yield decline, and several biotic and abiotic factors have been identified as being responsible for the decline. However, no analytical information on water stress induced changes in the crop’s physical and biochemical root traits specific to tropical regions is available. In addition, responses of rice roots to soil moisture fluctuation upon aerobic adaptation with supplementary irrigation have not been studied.

It is evident in crops growing with water stress that formation of toxic reactive oxygen species (ROS) within roots often threatens the plant’s normal functions. Concurrent with the formation of ROS, the concentration of the major biochemical compounds hydrogen peroxide, total soluble protein (TSP), and proline in roots are likely to be greatly affected. Eventually, irreversible changes in these parameters may result in reduced grain yield as dynamic equilibrium of these biochemical compounds regulates a strong built-in mechanism for the functional root activities leading to better growth and adaptation. Understanding this mechanism, indicated water deficiency, particularly in between the maximum tillering and grain-filling stage, appears responsible for disruption of this equilibrium. Maintaining adequate soil water may be essential particularly at the critical stages in order to promote crop growth. It could imply the logic behind maintaining semi-aerobic conditions imposing marginal water deficiency, except at critical growth stages, that may not adversely impact crop vigor and grain yield significantly.

In the May–June 2012 issue of Agronomy Journal, researchers report on an experiment that was designed to address how water stress affects the biochemical and physical root traits in tropical aerobic rice and aid in the development of management techniques to alleviate the detrimental factors responsible for yield decline.

Materials and methods

Four rice genotypes, predominantly grown under different water stress conditions, were compared: two upland rice genotypes, ‘Annada’ and ‘Anjali’ and two aerobic rice genotypes, ‘Apo’ and ‘IR 4 74371-3-1-1’, plus one irrigated lowland rice genotype, IR 64. All genotypes were grown under two soil water conditions: (i) water stress aerobic condition (6 psi soil water potential) and (ii) partially aerobic (semi-aerobic) condition (3 and 6 psi soil water potential) with supplementary irrigation. These 6 and 3 psi soil water potentials were the indicators showing the maximum potential for scheduling irrigation in respective conditions. Thus, in the aerobic condition, irrigation water was applied as soon as root zone soil water potential reached 6 psi (as monitored by a tensiometer). In semi-aerobic conditions, similar schedules of irrigation were followed during entire growth stages except three critical growth stages: tiller initiation to maximum tillering stage (40 to 60 days of growth), panicle initiation to flowering stage (60 to 70 days of growth), and flowering to grain-filling stage (70 to 80 days of growth).

Crops at these three stages were treated with supplementary irrigation water when the root zone soil water potential reached 3 psi. A light irrigation after sowing, just flushing the field, was applied facilitating uniform seed germination. Seeds were drill-sown (using 3 to 4 seeds/hill) during the first week of January within the.
plots. Fertilizers were applied at the recommended rate along with farmyard manure. Farmyard manure was applied two weeks before final land preparation and the entire dose of P and K, and 50% of N was applied during sowing. The remaining 50% of N was applied in two equal splits at tillering and the panicle initiation stage.

The study was conducted under a controlled water environment at the research farm of the Central Rice Research Institute in India during two dry seasons in 2009 and 2010.

Measurement of ground water table and water potential at root zone depth

Portable electronic tensiometer units (SMS 2500S, no. 0660727, Eijkelkamp Agrisearch Equipment BV, the Netherlands) were installed to the root zone depth in each experimental plot and monitored soil water potential and irrigation as scheduled, maintaining appropriate soil water potential in the root zone. To quantify the amount of irrigation water applied, a “water flow meter” (CM/LO151526, 50 mm, Class-A, non-magnetic, DASMESH, India) was connected to the tail end of the PVC pipe delivering water to each plot. Piezometers were installed at the center of each plot monitoring daily fluctuations in the ground water table.

Plant (root) sampling for physical and biochemical study

Five plants were randomly selected in each plot at the “maximum tillering” stage of 65 days growth (degeneration of roots usually starts after 70 days of crop growth). Root volume was determined following the water displacement methods, and biomass of root and shoot was measured after drying. The biochemical compounds TSP, hydrogen peroxide, and proline were estimated following standard laboratory methods and empirical formula.

Grain yield and yield components

Height of the plants at maturity and salient yield parameters, such as total numbers of tillers and filled and unfilled panicles, were recorded at crop harvest. Plant height was averaged on 25 plants selected randomly within each treatment plot. Total number of panicles was recorded from the harvest sample of an area of 11 ft², and the mean weight of 25 panicles was taken. Grain yield was estimated from sample areas taken at the center of each plot, expressed at 14% moisture content. Water productivity was determined as the amount of grain produced per unit per quantity of water applied.

Experimental design and statistical analysis

The experiment was laid out in a split-plot design with soil water conditions in the main plot and rice genotypes in the subplots with five replications. The data on grain yield and other growth and yield components were collected during every year of experimentation. They were subjected to the analysis of variance using the “CropStat” statistical package (version 6.1). The treatment means of two years’ data were tested using a least significant difference (LSD) test and compared at the $P<0.05$ level of significance for a logical interpretation of the entire result.

Results and discussion

Structural development of root size is known to be affected due to soil water fluctuation across aerobic to semi-aerobic conditions. However, over the two years, no significant differences in those changes occurred. Mean results of two years’ study showed better root growth for both root biomass and volume of all genotypes. This was attributed to the favorable soil-water environment promoting root growth because of additional water availability. Greater vigor of roots encourages root penetration to the deeper zone, which could accelerate extraction of subsurface soil water effectively. Additionally, increased nutrient uptake and greater nitrogen use efficiency was associated with better root development. Average root biomass across the genotypes varied under the semi-aerobic condition with a 21% increase in root biomass compared with that under the aerobic condition. Root volume of these genotypes also increased by 8.3% in the semi-aerobic condition over that under the aerobic condition. Concurrently, the root and shoot ratio was higher under
semi-aerobic conditions, providing a 10.4% increase compared with aerobic conditions. Under aerobic conditions, the growth of shoots in some genotypes was inhibited significantly, leading to a decline in the root/shoot ratio. This implies greater root growth of those genotypes occurred at the expense of shoot growth.

Biochemical root traits

Soil water content varying from the water stress aerobic situation to the semi-aerobic situation with supplementary irrigation caused significant changes in the concentration of all biochemical compounds in both the years. The concentration of proline varied significantly with changing soil water conditions across the 31 genotypes. Unlike changing trends in the concentration of hydrogen peroxide and proline with varying soil water content, a reverse trend prevailed in the case of TSP. Its concentration declined under water stress aerobic conditions while its concentration increased with higher water availability at semi-aerobic conditions.

The study revealed significant variations in the concentration of all biochemical compounds with the depletion in soil water content from semi-aerobic to a water stress aerobic situation. An increase in the concentration of hydrogen peroxide of about 24% due to water stress under 15 aerobic conditions caused detrimental effects on plant growth; however, a 19% increase in its concentration occurred under the semi-aerobic condition. Hydrogen peroxide, the most stable form of ROS, is a product of peroxisomal and chloroplast oxidative reactions. Formation of some toxic ROS on account of molecular oxygen is known to be detrimental to the plants under an aerobic environment. This higher concentration of hydrogen peroxide results in disruption of the metabolic function and loss of cellular integrity causing several functional disorders within the plant. Better performance of genotypes ‘Apo’ and ‘IR 74371-24 3-1-1’ was likely due to their lower rate of increase (15%) in hydrogen peroxide, which was less than the average concentration of 24.6% as estimated across all genotypes.

Higher hydrogen peroxide concentration was associated with a 25% increase in proline concentration, which further deteriorated the plants' ability to thrive under aerobic adaptation. Applying supplementary irrigation at the semi-aerobic condition resulted in a 20% decline in its concentration, which helped boost growth and grain yield.

The reverse phenomenon occurred in the concentration of TSP while changing soil water content. Its concentration under the aerobic condition was 27% less than that in semi-aerobic conditions. This was also ascribed to the accumulation of hydrogen peroxide, which causes protein degradation. Applying irrigation at critical stages resulted in a 36% increase in its concentration under semi-aerobic conditions.

Water requirement and productivity

Water requirements caused by water stress imposed during the entire growth stages under the aerobic condition were provided through supplemental irrigation; to maintain the semi-aerobic condition, supplemental irrigation was increased 20%. This small increase in the quantity of applied water has far reaching consequences, resulting in a significant boost in productivity under the semi-aerobic condition. A 16.7% saving in water requirement under aerobic conditions was at the cost of

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Plant height</th>
<th>Panicles/plant</th>
<th>Panicle length</th>
<th>100-grain weight</th>
<th>Grain yield</th>
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<td>8</td>
<td>1.9</td>
<td>1.6</td>
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<tr>
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<td>7</td>
<td>1.9</td>
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<tr>
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<tr>
<td>IR 64</td>
<td>28</td>
<td>10</td>
<td>8</td>
<td>1.8</td>
<td>1.7</td>
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<tr>
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<td>41</td>
<td>11</td>
<td>7</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Anjali</td>
<td>40</td>
<td>10</td>
<td>8</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>IR 74371-24 3-1-1</td>
<td>33</td>
<td>9</td>
<td>8</td>
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<tr>
<td>Apo</td>
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a 17.4% yield decline; however higher water productivity under the aerobic condition was attributed to lowered yield reduction. On average, over two years, results indicated variable responses of rice genotypes to water stress. Even a small difference in root growth may result in large differences in water uptake. Water productivity under aerobic conditions was higher in ‘Apo’, which was reduced under the semi-aerobic condition. Higher water productivity under aerobic conditions was attributed to lower yield reduction than the amount of water saved.

**Grain yield and yield components**

Applying supplementary irrigation under the semi-aerobic condition resulted in significant development in yield components across the year. On average, over the two years, plant height was 4.5% taller than that under aerobic conditions (Table 1). Water stress adversely affected tillering and panicle emergence, accounting for a 22.6% reduction in panicle emergence.

Panicle numbers were reduced because of tiller mortality and drying up of non-emergent panicles at the booting stage. In contrast, the semi-aerobic condition encouraged growth of vegetative tillers, 64.5% of which emerged productive across the genotypes. Panicle numbers were reduced to 57.5% under aerobic conditions resulting in a 22.6% decline in panicle emergence compared with semi-aerobic conditions. Among genotypes, ‘Apo’ produced significantly higher numbers (14.5 panicles/plant) of panicles followed by IR ‘74371-3-1-1’. Length of the panicle decreased significantly to 23.5%. Unlike other yield parameters, water stress did not affect grain development, showing comparable test weight under both the conditions. ‘Apo’ developed significantly heavier grains under the aerobic condition.

Aerobic adaptation under a water stress environment caused a significant decline in overall grain yield, which was significantly enhanced under semi-aerobic conditions (Table 1). Earlier studies also reported yield declines on account of water stress in an aerobic rice system. There was significant interaction effect between soil conditions and genotypes on grain yield. Table 2 shows interaction effects between soil conditions and genotypes on grain yield. While analyzing the impact of individual soil condition on each genotype (comparing LSD values for the same genotypes or different soil conditions), it was noticed that interaction of the semi-aerobic condition with the genotype ‘Apo’ resulted in significantly higher grain yield compared with the aerobic conditions. It was noticed that interaction of all 19 genotypes with semi-aerobic conditions resulted in comparable grain yield. However, under aerobic conditions, a significant difference in grain yield was noticed on account of its interaction with genotypes, with ‘Apo’ producing significantly higher grain yield followed by ‘IR 74371-3-1-1’ and ‘Annada’. This implies that under aerobic conditions, higher grain yield could be achieved in ‘Apo’ followed by ‘IR 24 74371-3-1-1’ and ‘Annada’, while grain yield of these genotypes could be enhanced with supplementary irrigation under semi-aerobic conditions.

**Conclusion**

The present field study reported consequences of aerobic rice adaptation as manifested on root growth, particularly in its physical and biochemical traits across rice genotypes. Significant improvement in crop growth was achieved when supplementary irrigation was provided to the crops in their three most critical growth stages under semi-aerobic conditions. Overall results showed a 24.6% increase in the concentration of hydrogen peroxide and proline and a 20% decrease in TSP under aerobic conditions. As a result, aerobic rice grown with water stress experienced a 9.2 to 24.2% yield penalty across the genotypes, which was less pronounced in ‘Apo’. Despite requiring 20% more water following supplementary irrigation, water productivity remained similar at semi-aerobic conditions.