In irrigated rice ecosystem in Asia, farmers mostly transplant seedlings into puddled and flooded soil, and keep the field flooded almost until harvest. However, increasing water and labor shortages now threaten the sustainability of Asian rice production. The culture of aerobic rice (direct-seeded rice grown in unsaturated soil) is a promising way to reduce irrigation requirements by more than half compared with conventional flooded culture (Humphreys et al., 2010). The attainable yield is 8 – 11 t ha\(^{-1}\) and equivalent to that in flooded culture (Kato et al., 2009), but a significant yield loss often occurs (Matsuo and Mochizuki, 2009).

Aerobic and flooded culture differs not only in water management, but also in crop establishment. In flooded culture, rice seedlings are transplanted, whereas in aerobic culture, seeds are drilled into unsaturated soil. To date, it remains unclear whether the variable performance of aerobic rice results from the crop establishment method (transplanting vs. direct seeding) or the water management method (flooded vs. aerobic). Although the yield of transplanted rice under aerobic conditions has been compared with that under flooded conditions (Peng et al., 2006; Matsunami et al., 2009), transplanting shock is inevitable in the absence of standing water. The grain yield of direct-seeded rice under aerobic conditions have also been compared with that under flooded conditions, but the planting density was not necessarily equivalent because of drilling or dibbling without thinning (Yun et al., 1997; Sudhir-Yadav et al., 2011). Although planting geometry is an important factor for plant growth, the yield of direct-seeded rice grown under various water management regimes with the same planting geometry has not been determined.

Our hypothesis was that even a slight water deficit due to the unsaturated soil may reduce rice leaf growth, biomass accumulation, and yield in aerobic culture, independent of sowing method and planting geometry. The objective of this study was to clarify the effects of water management regimes on the yield stability of direct-seeded rice.

**Materials and Methods**

1. **Experimental design**

   Details of the soil properties, crop management, and climatic data are as described by Kato and Okami (2011). In brief, the field experiments were conducted at the Institute for Sustainable Agro-ecosystem Services of The
University of Tokyo, Japan (35°43' N, 139°32' E), during the summer (May to October) of 2008 and 2009. The mean temperatures from May to October were 23.1°C in 2008 and 23.0°C in 2009. Rice plants were grown in lowland fields under three types of water management, viz. aerobic, near-saturated, and flooded. In each year, the trials were newly created from lowland fields that have been managed for conventional flooded rice culture for > 10 years. The experimental plots, each 20 m², were separated by 1-m bunds, and plastic boards were inserted to 50-cm depth into the soil to prevent lateral water movement above the rooting depth between the plots. The plots of aerobic soil with direct seeding (ARDS) and near-saturated soil with direct seeding (SADS) were not puddled. Flush irrigation in 2008 and sprinkler irrigation in 2009 usually kept the soil water potential at 20-cm depth above −30 kPa in ARDS and above −10 kPa in SADS. SADS received 10 − 15 mm of irrigation daily. The plots of flooded soil with transplanting (FLTP) and flooded soil with direct seeding (FLDS) were puddled, and a 5-cm water depth was maintained continuously after transplanting or seedling establishment. Treatments were arranged in a completely randomized design with three replicates each. A high-yielding cultivar, ‘Takanari’ (lowland-adapted indica), was grown in all four plots. The sowing dates were 12 May 2008 and 18 May 2009. In the direct-seeding plots, four or five seeds were directly sown at a depth of 1 cm in each hill. Plants were thinned to one per hill after seedling establishment. In the transplanting plots, one 4-leaf seedling was transplanted into each hill on 2 June 2008 (transplanting was not done in 2009). The hill spacing was 25 cm × 25 cm in 2008 and 20 cm × 20 cm in 2009. The planting density and geometry were identical among the treatments in each year. Manufactured fertilizer (N, P, K = 60, 39, 67 kg ha⁻¹) was applied before sowing, and ammonium sulfate was top-dressed every 2 to 4 wk (total N = 240 kg ha⁻¹ in 2008 and 160 kg ha⁻¹ in 2009) in all treatments. Weeds were controlled by hand and by

Table 1. Growth duration, the amount of water supply, grain yield and water productivity in 2008 and 2009.

|                | Growth duration (d) | Water supply (mm) | Grain yield (g m⁻²) | Water productivity (kg m⁻³) |
|----------------|---------------------|-------------------|--------------------|-----------------------------|
| 2008 FLTP      | 158                 | NA                | 990 NS             | NA                          |
| 2008 FLDS      | 158                 | 3199              | 1048               | 0.28 c                      |
| 2008 SADS      | 164                 | 2502              | 1049               | 0.36 b                      |
| 2008 ARDS      | 170                 | 1514              | 1055               | 0.60 a                      |
| 2009 FLDS      | 144                 | 3675              | 1205 a             | 0.28 c                      |
| 2009 SADS      | 156                 | 1940              | 1032 b             | 0.46 b                      |
| 2009 ARDS      | 158                 | 868               | 958 b              | 0.95 a                      |

Grain yield is expressed at 14% moisture content. Means followed by different letters are significantly different at the 5% level (n = 3). NS, not significant; NA, not available; FLTP, flooded soil with transplanting; FLDS, flooded soil with direct seeding; SADS, near-saturated soil with direct seeding; ARDS, aerobic soil with direct seeding.

Table 2. Biomass at maturity, harvest index and yield component in 2008 and 2009.

|                | Biomass (g m⁻²) | Harvest index | Panicles (m⁻²) | Spikelets (panicle⁻¹) | Spikelet number (× 10³ m⁻²) | Fertility | Grain weight (mg) |
|----------------|----------------|---------------|----------------|-----------------------|-----------------------------|-----------|-------------------|
| 2008 FLTP      | 1655 b         | 0.51 a        | 206 b          | 244 a                 | 50.2 NS                     | 0.80 c    | 21.2 a            |
| 2008 FLDS      | 1725 ab        | 0.52 a        | 227 b          | 219 b                 | 49.5                        | 0.86 b    | 21.2 a            |
| 2008 SADS      | 1703 ab        | 0.53 a        | 227 b          | 205 bc                | 46.1                        | 0.93 a    | 21.1 a            |
| 2008 ARDS      | 1846 a         | 0.49 b        | 271 a          | 186 c                 | 50.5                        | 0.89 ab   | 20.1 b            |
| 2009 FLDS      | 1923 NS        | 0.54 a        | 236 NS         | 219 a                 | 51.9 a                      | 0.88 a    | 22.6 a            |
| 2009 SADS      | 1730           | 0.51 b        | 232            | 193 b                 | 44.4 b                      | 0.89 a    | 22.5 a            |
| 2009 ARDS      | 1765           | 0.47 c        | 267            | 208 ab                | 55.6 a                      | 0.72 b    | 20.6 b            |

Means followed by different letters are significantly different at the 5% level (n = 3). NS, not significant.
herbicide application.

2. Measurements

At physiological maturity, 20 – 25 hills (1.0 – 1.25 m\(^2\)) in each plot were harvested. All panicles were counted and threshed by hand. The completely filled spikelets that sank in tap water were separated from unfilled spikelets. The filled and unfilled spikelets and the straw were oven-dried at 80°C for at least 72 hr to determine dry weights. Grain yield, harvest index, and the number of spikelets were then calculated. Water productivity was determined by dividing grain yield by the total amount of water supplied (irrigation plus rainfall) during the period of crop growth.

Dynamics of plant height, leaf area index (LAI), aboveground biomass, and aboveground N content were monitored in 2009. Thirty plants were harvested from each plot at 38 days after sowing, and 4 – 6 plants were harvested from each plot periodically during the growth stage. Green leaf area was measured with a leaf area meter (LI-3100, LI-COR, Lincoln, NE, USA). Samples were oven-dried at 80°C for at least 72 hr to determine dry weights. The dried samples were ground in an automated mill (Heiko Sample Mill TI-300, Fujiwara Seisakusyo Ltd., Tokyo, Japan), and the N concentration was analyzed with an NC analyzer (Sumigraph NC-90A, Sumika Chemical Analysis Service, Tokyo, Japan). The LAI and the N content of each organ were then calculated.

Data from all trials were analyzed by analysis of variance (SAS Institute, 2003). Fisher’s LSD (least significant difference) test was used for post hoc comparisons of treatment means.

Results

There was no significant difference in grain yield between FLTP and FLDS in 2008 (9.9 vs. 10.5 t ha\(^{-1}\); Table 1). The yields in SADS and ARDS were comparable to that in FLDS in 2008, but were 14% and 21%, respectively, lower than that in FLDS in 2009. The water supply in SADS was 22% and 47% less, respectively, in 2008 and 2009 than in FLDS, and that in ARDS was 53% and 76% less, respectively, in 2008 and 2009 than that in FLDS. Water productivity was highest in ARDS and lowest in FLDS in both years.

There was no significant difference in the aboveground biomass at maturity between FLTP and FLDS in 2008 (Table 2). The biomass in ARDS was larger than that in FLDS and SADS in 2008, but lighter than that in FLDS in 2009, but the difference was not significant. The effect of irrigation on harvest index was significant: The harvest index was lower in ARDS than in SADS and FLDS (Table 2). The panicle density in FLDS was slightly higher than that in FLTP (although not significantly). Interestingly, it tended to be higher in ARDS than in FLDS and SADS in both years. Spikelet number per panicle in SADS and ARDS tended to be lower than in FLTP and FLDS. Spikelet number per unit area in ARDS tended to be higher than in other treatments. Fertility and grain weight in ARDS were lower than in other treatments in both years.

Plant height and aboveground biomass were significantly lower in SADS and ARDS than in FLDS, and as were LAI and N content during the vegetative stage (Fig. 1a – d). There were no differences in LAI and biomass between SADS and ARDS during the vegetative stage. LAI and N content were higher in ARDS than in FLDS during the reproductive stage (Fig. 1b, d).
Discussion

In the same planting density and geometry, the grain yield and biomass in FLDS were comparable to those in FLTP in 2008 (Tables 1, 2), which was confirmed by the experiment without replicates in 2009 (10.4 t ha\(^{-1}\) in FLTP vs. 12.1 t ha\(^{-1}\) in FLDS). This result agrees with that in the previous study using the same cultivar: the brown rice yield of direct-seeded rice was not lower than that of transplanted rice (8.6 – 9.7 t ha\(^{-1}\); San-oh et al., 2004). However, grain yield was 14% – 21% lower in SADS and ARDS than in FLDS in 2009. The results suggest that rice yield is more sensitive to aerobic condition than to planting method. As seen in SADS, daily irrigation to avoid dry spells might increase oxidation and leaching or denitrification of soil N and reduce plant N uptake in aerobic culture (Fig. 1d).

Reduced leaf growth (Fig. 1b) was associated with low biomass accumulation in aerobic culture in 2009 (Fig. 1c) because the net assimilation rate did not vary with the treatment (data not shown). A low LAI would result from low uptake of N and water due to poor root growth in aerobic culture (Kato and Okami, 2011). Interestingly, water-saving irrigation slightly increased panicle number m\(^{-2}\) as direct seeding did compared with transplanting (Table 2), and reduced plant height (Fig. 1a). High-yielding rice cultivars in aerobic culture commonly show such a “bunchy” appearance with profuse tillering and dwarf stature (Okami et al., 2011), which our results show is due only to the aerobic condition, not to the sowing method. This plant architecture is not efficient for light interception and weed competitiveness when combined with a lower LAI. Even without any dry spells, rice could be vulnerable to aerobic conditions (Kato and Okami, 2011). The physiological mechanisms causing the above shoot response to aerobic conditions warrant further study.

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