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Radiation use efficiency, N accumulation and biomass production of high-yielding rice in aerobic culture

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ABSTRACT

The concept of aerobic culture is to save water resource while maintaining high productivity in irrigated rice ecosystem. This study compared nitrogen (N) accumulation and radiation use efficiency (RUE) in the biomass production of rice crops in aerobic and flooded cultures. The total water input was 800–1300 mm and 1500–3500 mm in aerobic culture and flooded culture, respectively, and four high-yielding rice cultivars were grown with a high rate of N application (180 kg N ha^{-1}) at two sites (Tokyo and Osaka) in Japan in 2007 and 2008. The aboveground biomass and N accumulation at maturity were significantly higher in aerobic culture (17.2–18.5 t ha^{-1} and 194–233 kg N ha^{-1}, respectively) than in flooded culture (14.7–15.8 t ha^{-1} and 142–173 kg N ha^{-1}) except in Tokyo in 2007, where the surface soil moisture content frequently declined. The crop maintained higher N uptake in aerobic culture than in flooded culture, because in aerobic culture there was a higher N accumulation rate in the reproductive stage. RUE in aerobic culture was comparable to, or higher than, that in flooded culture (1.27–1.50 g MJ^{-1} vs. 1.20–1.37 g MJ^{-1}), except in Tokyo in 2007 (1.30 g MJ^{-1} vs. 1.37 g MJ^{-1}). These results suggest that higher biomass production in aerobic culture was attributable to greater N accumulation, leading to higher N concentration (N%) than in flooded culture. Cultivar differences in response to water regimes were thought to reflect differences in mainly (1) early vigor and RUE under temporary declines in soil moisture in aerobic culture and (2) the ability to maintain high N% in flooded culture.

1. Introduction

The demand for rice in Asia will continue to increase as populations in the region grow in line with economic development. On the other hand, a worldwide water shortage is threatening the sustainability of rice production because of the crop's high water demand and sensitivity to water deficiency. The demand for more efficient water use in rice production is therefore increasing rapidly. Various water-saving technologies have been developed (Tabbal et al., 2002; Belder et al., 2004; Humphreys et al., 2005; Bouman et al., 2006a). Among them, aerobic rice culture has become a particular focus of attention (Tuong et al., 2005; Haryanto et al., 2008). In aerobic rice culture, high-yielding cultivars are grown on non-puddled aerobic soil.

Recent studies of aerobic rice culture have focused mainly on water use efficiency (Bouman et al., 2006b; Matsunami et al., 2009; Matsuo and Mochizuki, 2009). Maximum yields of 5–6 t ha^{-1} with water inputs of only 500–900 mm have been achieved in aerobic rice culture in northern China (Yang et al., 2005; Bouman et al., 2006b; Xue et al., 2008). We attained a grain yield of over 10 t ha^{-1} in aerobic rice culture in a previous study in Japan (Kato et al., 2009). In this study (Kato et al., 2009), a grain yield of 11.4 t ha^{-1} was achieved in aerobic culture by Takanari, a lowland-adapted high-yielding variety, and the average yield of four varieties under aerobic culture was similar to or even higher than that achieved with flooded culture. These results suggest that the productivity of aerobic rice culture is potentially comparable to, or even higher than, that of flooded rice culture. Unraveling the growth characteristics that resulted in the particularly high yield in aerobic culture in Japan might improve not only water use efficiency but also the yield potential of rice.

The concept of radiation use efficiency (RUE) has been widely used in crop growth analysis. Following the principles of Monteith (1977), aboveground total dry weight (TDW) is expressed as

$$TDW = RAD \cdot FRI \cdot RUE,$$

where RAD is the incident radiation and FRI is the fraction of radiation intercepted by the crop. N is a key nutrient limiting crop growth (Sinclair and Horie, 1989). Hence, the objective of this study was to quantitatively characterize crop growth in aerobic rice culture in Japan with respect to N accumulation and radiation use efficiency

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by the rice canopy. This is the follow-up study of our previous reports (Kato et al., 2009).

2. Materials and methods

2.1. Experimental design

The field experiments were conducted at the Field Production Science Center of The University of Tokyo (Tokyo), Japan (lat. 35°43′N, long. 139°32′E) and at the Experimental Farm, Kyoto University (Osaka), Japan (lat. 34°51′N, long. 135°37′E) during summer (May–October) in 2007 and 2008. The soils at the experimental sites are clay loam (Typic Melanudand) in Tokyo and sandy loam (Typic Fluvaquent) in Osaka. Hourly global solar radiation (incident radiation) was recorded by pyranometers at both experimental sites. The average incident radiation during the summer season was 14.9 and 13.8 MJ m^{-2} in 2007 and 2008, respectively, in Tokyo, and 17.7 and 16.9 MJ m^{-2} in 2007 and 2008, respectively, in Osaka. The average air temperature during the summer season was 23.6 and 23.1 °C in 2007 and 2008, respectively, in Tokyo, and 23.4 and 22.8 °C in 2007 and 2008, respectively, in Osaka. The total amount of water supplied (sprinkler irrigation plus rainfall) in the aerobic culture was 800–1300 mm, which was 21–74% less than the flood-irrigation plus rainfall in the flooded culture. In 2007, an especially limited irrigation supply resulted in chronically dry soil conditions during the vegetative stage in Tokyo and during later growth stages in Osaka.

Aerobic and flooded cultures (one of each) were set up at each of the two sites. In the aerobic culture, fields were non-puddled and the rice seeds were directly sown into the soil. In the other trial, the fields were puddled and kept flooded after transplanting. In each trial, four high-yielding rice (*Oryza sativa* L.) cultivars were grown: Takanari (lowland-adapted indica, one of the highest yielding cultivars in Japan; Katsura et al., 2007, 2008), Akihikari (lowland-adapted japonica), Lemont (lowland-adapted japonica), and IRAT109 (upland-adapted japonica). The four cultivars were arranged in a randomized complete-block design with three replications. The area of each replicate was 50–70 m^2. Further details of the climate data, crop management are reported in Kato et al. (2009).

At both sites in both years, the sowing dates were early May. In aerobic culture, 4 or 5 seeds were sown into each hill at a density of 22.2 hills m^{-2} (30 cm × 15 cm), and plants were thinned to one plant per hill after seedling establishment. In flooded culture, one 25-day-old seedling was transplanted into each hill at the same density as in aerobic culture. A chemical fertilizer (N, P, K = 60, 39, 67 kg ha^{-1}, respectively) was applied before sowing, and ammonium sulfate (N = 30 kg ha^{-1}) was top-dressed at 6, 10, 13, and 16 weeks after sowing in all trials (total N = 180 kg ha^{-1}).

2.2. Measurements

For each cultivar, 30 plants from flooded culture and 50 plants from aerobic culture were harvested at 25–28 days after sowing (at transplanting for flooded culture) in both years. Eight plants were sampled from each plot periodically during the growth stage, and 24 plants were sampled at maturity from each plot. The total number of harvests during crop growth was 6 or 7 for each cultivar at both sites in both years. Plant samples were oven-dried at 80 °C for at least 72 h to determine aboveground biomass. For the determination of aboveground N content (total N), dried samples were ground, and the N concentration was analyzed with an NC analyzer (Sumigraph NC-90A, SCAS, Tokyo, Japan) at Tokyo and by the Kjeldahl method at Osaka. To ensure that the measurements from the different analytical methods were comparable between the two experimental sites, 10 of validation samples were run with both methods ($Y = 0.99X$, $R^2 = 0.975$).

The fraction of radiation intercepted (FRI) was measured about once a week during crop growth for each replication by linear photosynthetic active radiation ceptometer (AccuPAR, Decagon Devices Inc., Washington, USA). The number of times FRI was measured ranged from 12 to 17 for each cultivar at both sites in both years. The daily FRI values between two measurement dates were estimated by linear interpolation. The amount of radiation interception was calculated by multiplying daily FRI value and incident radiation. The cumulative total dry weight was plotted against cumulative intercepted radiation from the first harvesting time to a given harvesting time, and values of RUE were obtained from the slopes of the regression lines forced through the origin for each replication.

Greenwood et al. (1990) suggested that the critical N% in plants, which is defined as the minimum needed for maximum growth rate (Ulrich, 1952), can be expressed as a function of aboveground total dry weight (TDW):

$$\text{critical N\%} = a \cdot \text{TDW}^{-b} \quad (\text{TDW} \geq 1\ \text{t ha}^{-1}), \tag{1}$$

where *a* and *b* are parameters. Eq. (1) could be expressed as follows:

$$\log \text{critical N\%} = -b \cdot \log \text{TDW} + \log\ a \quad (\text{TDW} \geq 1\ \text{t ha}^{-1}).$$

In the present study, we estimated the parameters log *a* and *b* from intercept and slope of regression line between logarithm of N% in plants and that of TDW for each watering regime and experimental site (TDW ≥ 1 t ha^{-1}) so as to minimize the sum of square errors between the measured and estimated logarithm of N% in plants.

Data were analyzed by using the generalized linear model (GLM) procedure. Individual analyses of variance were conducted separately for each trial for each year according to a randomized-block design to assess cultivar differences. The effect of water regimes (aerobic culture vs. flooded culture) and the cultivar × water interaction were assessed by combined analysis of variance over trials. Differences were compared by least significant difference (LSD) tests at the 5% level.

3. Results

Aboveground biomass at maturity was greater in aerobic culture than in flooded culture for all cultivars and experimental sites and in both years, with the exceptions of Akihikari and Takanari at Tokyo in 2007, where the soil water potential fell to a particularly low level (sometimes below −60 kPa at 20 cm soil depth, Kato et al., 2009) during the early growth stage (Fig. 1). Takanari achieved aboveground biomass at maturity of over 20 t ha^{-1} in three out of the four experiments in aerobic culture. The highest aboveground biomass at maturity of all replicates, 23.6 t ha^{-1}, was recorded for Takanari in aerobic culture at Tokyo in 2008.

Total N at maturity in the rice plants was also greater in aerobic culture than in flooded culture in all cultivars, experimental sites and years, with the exception of Takanari at Tokyo in 2007 (Fig. 2). The highest total N of 315 kg ha^{-1} was recorded for Takanari grown in aerobic culture at Tokyo in 2008. In general, total N steadily increased during the early growth stage, but the N accumulation rate decreased in the ripening stage in both water regimes (Table 1). The N accumulation rate in the reproductive stage (from 9 weeks after sowing to heading) was generally larger in aerobic culture than in flooded culture, whereas in the ripening stage there was no significant difference in the N accumulation rate between the two water regimes in three out of four experiments (Table 1). Hence, the larger total N at maturity in aerobic culture relative to that in flooded culture was caused by the difference in accumu-