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Modifications in development and growth of a dual-adapted tropical rice variety grown as either a flooded or an aerobic crop

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ABSTRACT

As the human population continues to grow and competition for natural resources increases, there is a consequent need to produce more food with fewer resources. Flooded rice crops use large quantities of water, which becomes scarcer for farmers. New methods of saving irrigation water have been tested and released but they often suffer from a yield trade-off. A comparative study was carried out with a recent dual-adapted variety cultivated as either a flooded transplanted crop or a direct-seeded and soil water-saturated crop, referred to as an aerobic crop, to dissect the crop physiological differences induced by crop management. Experiments were conducted at IRRI's experiment station in Los Baños, Philippines, in the dry seasons of 2011 and 2012. Grain yields were 2 tons/ha or 25% lower in the aerobic crop as a result of a complex series of modifications and adjustments in plant architecture and yield components. Four main changes — higher plant density, slower rate of leaf appearance, lower nitrogen content, and reduced size of all organs — induced by the aerobic crop environment were responsible for three chains of modifications that resulted in lower biomass accumulation and finally lower grain yield. Leaf appearance rates were bilinear in both environments, initially similar in both environments and slower after an inflection point that occurred at the appearance of the 8th leaf in aerobic crops instead of the 11th leaf in flooded crops. As a consequence, two fewer leaves were produced by main tillers in aerobic crops, whose individual leaf area thus was much lower. In 2012, plant nitrogen content was about 1% lower in the aerobic crop than in the flooded crop during the entire crop duration. Biomass accumulation of the variety used was biphasic in both environments, with high radiation use efficiency during the two phases of effective biomass accumulation in flooded crops, and the standard radiation use efficiency expected with C_3 species in aerobic crops during the same phases.

1. Introduction

The world population continues to increase annually by more than 1%, which meant roughly 75 million additional people in 2012 (United Nations, 2011). Food production must obviously increase at the same annual rate to avoid a major nutritional crisis; thus, more food must be produced in an environment where competition for natural resources increases. Water will be increasingly scarcer for agricultural purposes and the traditional flooded rice crop may not be feasible any more in many environments. Solutions to replace this highly efficient cropping system have been studied during the last decades: direct seeding in non-puddled soil to save both water and labor; saturated soil culture (SSC) in puddled fields; alternate wetting and drying (AWD) water management in puddled fields; and aerobic rice in non-puddled aerobic soil maintained close to water-saturation (Bouman et al., 2007). These methods save from 5% to 70% water but at the cost of a yield reduction from 5% to 50%. Nonetheless, these practices are increasingly being adopted in many Asian countries: dry direct seeding in India mainly because of the increasing cost and scarcity of labor and also the lack of availability of affordable Indian seeders (Pathak et al., 2011), or in Southeast Asia, together with AWD (Pandey and Velasco, 2002), while rice under drip irrigation is now being tested on a large scale in Xinjiang, China (A. Isoda, Chiba University, Japan, personal communication). Lastly, one recent paper reported no yield reduction or even higher yield in aerobic crops compared with flooded crops (Kato et al., 2009).

Yield penalties under aerobic conditions were associated with reduced height and harvest index, whereas biomass at anthesis was similar (Lafitte and Bennett, 2002). Yun et al. (1997) even reported higher biomass in aerobic crops until anthesis caused

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by delays of 7–14 days in both maximum tillering and anthesis dates.

It is thus a current scientific challenge to find agronomic systems and improved varieties that can obtain stable yields comparable with those in flooded conditions when using limited water resources. At IRRI, the Ecological Intensification (EI) platform has been designed as a futuristic advanced agronomic research pilot in which the efficiency of water use, land area, and other agronomic inputs is maximized. It aims to develop highly productive rice-based triple-cropping systems with sustainable ecological footprints, using water-saving irrigation and labor-saving technologies, in the humid tropics of Asia (Alberto et al., 2012). Rice is naturally one of the cereals studied in EI rotations and our team thus had a unique opportunity to collect data from a large area of rice crops grown under optimal current conditions.

This study aimed to precisely describe and understand the modifications induced by two contrasting cropping systems, both under optimal management, in the development and growth of rice plants. The flooded cropping system, in which young seedlings were transplanted into a puddled paddy field and flooded until 15 days before grain maturity, was compared with an innovative system in which rice was mechanically dry direct seeded and then sprinkler irrigated to always maintain soil at water saturation, above −10 kPa.

2. Materials and methods

2.1. Site description

The experiments were conducted at the International Rice Research Institute (IRRI) farm in Los Baños, Laguna, Philippines (14°11′N, 121°15′E, 21 m elevation). The soil under flooded cultivation was an Andaqueptic Haplaquoll with a topsoil of 58% clay, 33% silt, 9% sand, 1.71% organic carbon, 0.174% total nitrogen, and pH ($CaCl_2$) of 6.5. The soil in the aerobic system was a Lithic Haplustept as described by Alberto et al. (2012), with a texture range of loam to clay, a mean pH of 6.2 (1:1 soil/water), and an organic carbon content of 1.1%.

2.2. Crop management

Two dry-season experiments (2011 and 2012) were conducted under two contrasting soil conditions, flooded (anaerobic) and non-flooded (aerobic), using rice variety NSICRc222, a high-yielding inbred released in 2010 that was developed under flooded conditions, but that has shown good adaptation to rainfed environments.

For the flooded rice experiments, the seeds were soaked in water for 24 h before being incubated at room temperature for another 24 h. The pre-germinated seeds were sown in seedling trays on 5 January 2011 and 3 January 2012. Thirteen-day-old seedlings in the 2011 DS and 16-day-old seedlings in the 2012 DS with leaf stage from 3 to 4, including the immature leaf, were manually transplanted in the puddled field at a hill spacing of 20 cm × 20 cm, with one seedling per hill. Phosphorus (50 kg P ha^{-1} as single superphosphate), potassium (50 kg K ha^{-1} as muriate of potash), and zinc (5 kg Zn ha^{-1} as zinc sulfate heptahydrate) were applied and incorporated in all the plots a day before transplanting during both the 2011 and 2012 dry seasons. A total of 120 and 160 kg N ha^{-1} as urea were applied in three and four split applications during the 2011 and 2012 DS, respectively. The field was irrigated to saturation for a week, and then a 3–5-cm layer of water was maintained until 10 days before physiological maturity, at which point the field was drained. Weeds were manually controlled when required and pests were controlled using chemicals. In 2011, one plot of 70 m^2 (20 × 3.5 m) was used, from which two random samples of five consecutive plants were taken weekly. In 2012, one plot of 70 m^2 (20 × 3.5 m) and two plots of 21 m^2 (6 × 3.5 m) were used, from which one random sample of five consecutive plants was taken weekly.

For the aerobic experiments, after tillage and land leveling of four 1-ha fields as described by Alberto et al. (2012), a tyne planter at 20-cm row spacing was used to sow dry rice seed directly into the soil at 50–60 kg seed ha^{-1} on 29–30 January 2011 and 40–45 kg seed ha^{-1} on 25–27 January 2012. Basal fertilizer was applied at 40 kg ha^{-1} of N, P_2O_5, and K_2O in 2011 and 32 kg ha^{-1} of the same in 2012. A total of 150 kg N ha^{-1} in the form of urea was broadcast in four splits during the DS of 2011, whereas 150 kg N ha^{-1} as urea was applied in five splits via fertigation during 2012. Irrigation water was applied through overhead sprinklers using a Zimmatic® center pivot, 103 m in length. Irrigation was applied when the matric potential of the soil reached −10 kPa at a depth of 15 cm. Cumulative crop evapotranspiration and rainfall were used to calculate the amount of water applied at each irrigation, which ranged from 10 to 24 mm per event. Weeds were controlled by applying pre- and post-emergence herbicides as well as hand weeding when required. Insect pests and fungal pathogens were controlled using chemicals. In both years, two 25-m^2 areas were identified in three 1-ha fields in the pivot irrigation system, from which one random sample of five consecutive plants was taken weekly. However, in 2011, one of the three 1-ha plots had a poor plant stand from the beginning and was discarded, thus reducing the sampling areas from six to four.

2.3. Measurements

Incident global sun radiation (GS1 dome solarimeter, Delta-T Devices, Cambridge, UK, or LI-200 Pyranometer, Li-Cor, Lincoln, NE, USA), air temperature at 2 m above ground level (HMP35A, Vaisala, Helsinki, Finland), and soil temperature at 2-cm depth (T thermocouples, PyroControle, Vaulx en Velin, France) were measured at 1-mn intervals, averaged on an hourly basis, and stored in dataloggers (CR10X or CR1000, Campbell Scientific, Logan, UT, USA). Data on daily rainfall were acquired from the IRRI Climate Unit.

In the 2011 flooded experiment, panicle initiation was determined by weekly dissecting and observing the main tiller of two randomly selected plants from each plot under a binocular microscope (Leica MZ 95, Leica Microsystems Ltd., Heerburgg, Switzerland). Panicle initiation was considered to have occurred when the first row of floral primordia was visible on the shoot apex. In other experiments, panicle initiation was observed visually weekly as the white feathery cone stage when dissecting the sampled main tillers. Flowering was determined in each plot when an average of 50% of the spikelets per panicle of the main tiller of 50% of the observed plants had exerted their anthers. The crop reached maturity when 95% of the spikelets of the whole plot had turned from green to yellow.

Right after transplanting for the flooded crop and at about 2 weeks after seeding for the aerobic crop, 16 sampling areas were identified in each plant where ten consecutive plants were tagged with rings and blades of the main tiller were tagged with markers according to their rank of appearance. At transplanting, for the flooded crop, seedlings were randomly sampled as three sets of five seedlings, whereas, for the aerobic crop, five consecutive hills were sampled about 2 weeks after seeding and plants were placed in plastic bags and brought to the laboratory for processing. For each subsequent sampling in both fields, plants were sampled from five consecutive hills until harvest. The length occupied by the five plants under an aerobic crop was measured for each weekly sampling. From this sampling, the number of tillers was counted and the number of fully expanded leaves, appeared leaves, and senesced leaves, as well as the plant height (collar of last fully expanded