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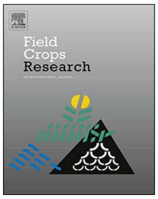

Breeding drought tolerant rice for shallow rainfed ecosystem of eastern India

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ABSTRACT

In shallow rainfed rice agro-ecosystems, drought stress can occur at any growth stage and can cause a significant yield reduction. During recent years, some rice varieties possessing tolerance of reproductive-stage drought stress have recently been developed. Tolerance of vegetative-stage drought stress is also required to improve rice productivity in drought-prone regions. In this study, we evaluated a set of rice breeding lines for their response to a range of different types of vegetative-stage drought stress in order to propose standardized phenotyping protocols for conducting vegetative-stage drought stress screening trials and also to identify genotypes combining tolerance of vegetative- and reproductive-stage drought stress. A soil water potential threshold of −20 kPa during the vegetative stage was identified as the target for effective selection under vegetative stage with grain yield reduction of about 50% compared to irrigated control trials. Genotypes identified as showing high yield under reproductive-stage drought stress were not necessarily the genotypes showing best performance under vegetative-stage drought stress. Genotypes IR72667-16-1-B-B-3, IR78908-126-B-2-B, and IR79970-B-47-1 showed tolerance of both vegetative-stage and reproductive-stage drought stress. For most, the genotypes that were best under vegetative stage drought or even vegetative stage + reproductive stage drought were different from the genotypes that were best under reproductive stage drought. Based on the cultivar superiority measure, IR69515-6-KKN-4-UBN-4-2-1-1-1 and IR78908-126-B-1-B were the stable genotypes (indicated by low P_i) under both irrigated control and severe vegetative stress conditions, genotypes IR83614-203-B and IR78908-80-B-3-B were stable under irrigated control conditions and moderate stress, whereas IR72667-16-1-B-B-3 was stable under both moderate and severe vegetative-stage stress conditions.

1. Introduction

Drought is the most important factor limiting rice productivity in the rainfed rice agro-ecosystem (Huke and Huke, 1997; Pandey and Bhandari, 2009). Climate change is predicted to increase the frequency and severity of drought, which will likely result in increasingly serious constraints to rice production worldwide (Wassmann et al., 2009). Drought can occur at any stage of the rice crop in any year in rainfed areas. Modern rice varieties are highly sensitive to drought stress at seedling, vegetative, and reproductive stages and even mild drought stress can result in a significant yield reduction in rice (O'Toole, 1982; Torres and Henry, 2016). At seedling stage, drought affects crop establishment and seedling survival rates. At vegetative stage, drought reduces leaf formation and tillering, which subsequently reduces the development of panicles per plant, thus causing a yield loss; whereas, at reproductive stage, drought causes a reduction in the number of grains per panicle, increases grain sterility, and reduces grain weight (Pantuwan et al., 2002).

The reproductive stage is recognized as the most critical stage at which drought stress can cause a high yield reduction (Hsiao, 1973), and drought at the vegetative stage was earlier predicted to have a relatively small effect on grain yield in rice (Boonjung and Fukai, 1996). However, it should be noted that these conclusions are based on the effects of drought stress on the rice plant, rather than on which type of drought stress is most frequently occurring in farmers' fields. Vegetative-stage drought has become a critical factor in reducing rice yield in shallow rainfed environments in recent years because of the late arrival of monsoon rains or long gaps between initial rains (Bunnag and Pongthai, 2013). In recent years, the frequency and intensity of vegetative-stage drought stress have increased in shallow rainfed areas of South and Southeast Asia, particularly in eastern India. Due to less initial rains, farmers fail to accumulate enough water in the field early in the season to prepare land and undertake transplanting. As a result, large areas in shallow rainfed ecosystem are left un-transplanted in years with less initial rainfall. Even when farmers are able to transplant, slow growth, less tillering, and in some cases death of early trans-

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Table 1
Trial-wise means and stress categorization of the 2008–2010 vegetative stage drought trials at Cuttack.

Trial	Year	Targeted treatment	Plot size	No. of lines tested	Trial mean yield (kg ha^{-1})	Heritability	% Yield reduction under stress	Assigned stress level
1	2008	Irrigated control	3.0 m^2	72	2634	0.77		Well-watered
2	2008	Moderate	3.0 m^2	72	773	0.85	71	Severe
3	2008	Severe	3.0 m^2	72	99.6	0.82	96	–
4	2009	Irrigated control	3.0 m^2	75	4554	0.55		Well-watered
5	2009	Moderate	3.0 m^2	75	2138	0.81	54	Moderate
6	2009	Severe	3.0 m^2	75	1035	0.80	77	Severe
7	2010	Irrigated control	3.0 m^2	63	3950	0.80		Well-watered
8	2010	Moderate	3.0 m^2	63	1630	0.86	59	Moderate

‘-‘ indicates that the trial was not considered for interpretation.

planted seedlings due to vegetative-stage drought stress cause heavy yield losses.

Increased incidence of vegetative-stage drought stress under climate change requires the development of rice varieties that combine tolerance of vegetative-stage and reproductive-stage drought stress in addition to having high yield potential under well-watered conditions. However, the responses to drought at the vegetative stage are different from the responses to drought at the reproductive stage (Kamoshita et al., 2008). Depending on the drought tolerance mechanism, traits that confer tolerance of reproductive-stage drought may not necessarily be effective under vegetative-stage drought stress. Recent research to improve rice yield under reproductive-stage drought stress while maintaining high yield potential (Verulkar et al., 2010; Mandal et al., 2010; Kumar et al., 2008; Kumar et al., 2014) has resulted in the identification of some QTLs that impart increased yield in the reproductive stage (Bernier et al., 2008; Dixit et al., 2015). These efforts have been successful through the development of standardized reproductive stage drought screening protocols that allowed for clear discrimination of drought-tolerant genotypes from drought-susceptible genotypes (Kumar et al., 2008). The timing and severity of drought (mild, moderate, or severe) in relation to the growth stage was appropriately determined so as to capture the genetic variation for reproductive-stage drought tolerance (Kumar et al., 2008).

However, for vegetative-stage drought stress screening, although some information is available on screening protocols (Verulkar and Verma, 2014), guidelines for the severity of drought stress to be imposed have not been very precisely defined. These guidelines are necessary to aid scientists in deciding on the appropriate timing of irrigation for vegetative-stage drought stress screening experiments. The lack of proper screening methods acts as a constraint and often delays the attainment of breeding objectives (De Datta and Seshu, 1982). Developing protocols for effective vegetative-stage drought stress screening in rice will facilitate the identification and development of varieties that are tolerant of vegetative-stage drought. Currently, very few varieties have been characterized to possess high yield potential as well as tolerance to drought at both stages. Selection for yield and yield-attributing traits at the vegetative and reproductive stages in standardized drought screens as well as high yield potential under well-watered conditions may allow breeders to select lines combining tolerance of vegetative- and reproductive-stage drought stress in high-yielding genetic backgrounds.

In the present study, a set of genotypes previously reported to be tolerant of drought at the reproductive stage (Verulkar et. al., 2010; Raman et al., 2012) and some additional genotypes identified to be tolerant to reproductive stage drought were evaluated for tolerance of vegetative-stage drought stress. The genotypes were developed by crossing high-yielding but drought-susceptible rice varieties with drought-tolerant donors and subjected to direct selection for grain yield under reproductive-stage drought and well-watered conditions. The lines were evaluated over three years under different levels of vegetative-stage drought stress with the aim of (i) devising a suitable dry-season vegetative-stage drought stress screening protocol by carefully monitoring soil moisture status over time, (ii) characterizing the degree of yield reduction under moderate and severe vegetative-stage drought stress, and (iii) identifying breeding lines that show tolerance of both vegetative- and reproductive-stage drought stress, in addition to having high yield potential under well-watered conditions.

2. Materials and methods

2.1. Field sites and experimental designs

2.1.1. Vegetative stress screening

Vegetative-stage stress screening trials at the National Rice Research Institute, Cuttack, Odisha, India (20°27′9″N, 85°56′25″E), were conducted during the dry season over three years, from 2008 to 2010. The experimental site had a sandy loam soil. The genotypes tested were advanced breeding lines of 100-120 days’ duration generated using crosses of popular high-yielding rice varieties with a diverse array of donors for drought tolerance developed at IRRI. A total of 210 lines were evaluated (72 in 2008, 75 in 2009, and 63 in 2010) along with popular-varieties IR64, IR36, and MTU1010 used as checks. An alpha-lattice design with three replications was used in all years for each trial. The vegetative stage was considered to begin following the seedling stage (1 month after direct seeding or 10 days after transplanting) and to end when panicle initiation was observed. Two separate vegetative-stage drought trials were planted in 2008 and 2009, which differed in severity due to differences in planting date, time of initiation of drought stress, and/or time of re-watering, and one vegetative-stage drought trial was planted in 2010. A separate irrigated control treatment was also planted in each year of the study in which the water level was maintained at a depth of ∼2 cm through flooding irrigation (Table 1).

In 2008 and 2009, the trials were manually dry direct seeded into dry soil at a depth of 2–3 cm and a seeding rate of 60 kg ha^{-1} with 4–5 seeds per hill. This method gave uniform seedling emergence for all plots within 6-8 days. The seeds were dibbled in three rows of 2.5 m each at 20 cm x 15 cm spacing in 4-m-length rows. In 2010, 17-21-day-old seedlings (3–4 plants per hill) were transplanted at a spacing of 20 cm × 15 cm (Cuttack) in 4-m-length rows in puddled bunded fields. Inorganic NPK fertilizer was applied at the rate of 40-20–20 kg ha^{-1}. P and K were applied as a single basal dose at the time of sowing, whereas N was applied in two equal splits, one at the 15-20-day-old seedling stage after the first weeding and the other at maximum tillering stage. Weeds were controlled by two hand weedings per season. Insect and pest control measures were applied when required.

2.1.2. Reproductive stress screening

A total of 215 of advanced breeding lines of 100–120 days’ maturity duration which included popular varieties as checks were tested from 2008 to 2010 at four sites chosen to represent a wide range of drought-prone shallow rainfed lowland rice production environments in India. At all sites, the trials were planted under irrigated control and reproductive-stage drought stress in alpha lattice designs with three replications. The general information on each trial is presented in