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High-yielding, drought-tolerant, stable rice genotypes for the shallow rainfed lowland drought-prone ecosystem

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ABSTRACT

High and stable yield of rainfed lowland rice is important for sustainable rice production and food security. Many varieties grown on large holdings in rainfed areas provide good yield under normal water availability but suffer high losses in the event of drought. From a set of 129 genotypes tested in shallow rainfed drought-prone environments at three locations in eastern India from 2005 to 2007, a subset of 39 genotypes that were tested for two or more years under favorable irrigated, moderate reproductive-stage drought stress, and severe reproductive-stage drought stress situations in 16 environments was selected for a GGE biplot analysis to identify genotypes that provide stable yield across environments. IR74371-70-1-1 and IR74371-46-1-1 were identified as stable genotypes showing high yield under varied environments across different sites. IR36, IR64, and MTU1010, the three popular varieties grown on large holdings in rainfed areas but bred for irrigated ecosystem, as well as improved genotypes CB2-458, DGI237, R1027-2282-2-1, RR272-21, IR67469-R-1-1, and IR66873-R-11-1, and varieties PMK1 and PMK2 released for rainfed ecosystems performed well only in irrigated non-stress environments and were not found promising in drought environments. Improved genotypes ARB6, ARB2, ARB5, ARB7, ARB8, RF5329, CB0-15-24, IR72667-16-1-B-B-3, IR74371-78-1-1, and IR55419-04, and drought-tolerant released varieties Tripuradhan, Annada, and Poornima performed well only in drought-stress environments. The identification of improved genotypes with ability to provide stable high yield across variable environments and their release for cultivation by farmers will enable farmers to reap high yield and stable income.

1. Introduction

Rainfed rice accounts for around 45% of the world's rice area. Around 40 million ha of rainfed area is concentrated in South and Southeast Asia alone (Maclean et al., 2002). The rainfed rice ecosystem is highly fragile. It encounters environments more complex than other rainfed crops. Rainfed rice-growing areas are highly prone to abiotic stresses such as drought or submergence depending upon the amount and distribution of rainfall and toposequence of the region. Each rice-growing area targeted by any individual breeding program may still have a mixture of different types of water-stress environments in the same year or in different years.

Among the different stresses, drought is the single largest yield-reducing factor in rainfed areas of South and Southeast Asia, with production losses common on more than 23 million ha (Huke and Huke, 1997). In light of recent climate change, in the near future, water deficit is predicted to be a major challenge for sustainable rice production (Wassmann et al., 2009). The intensity and frequency of drought are expected to become aggravated (Bates et al., 2008), resulting in decreased food production and food security and increased vulnerability of the crop to drought (Bates et al., 2008). Among the different rainfed rice-growing areas, India and adjoining

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areas of Nepal occupy the largest drought-prone area in the world, followed by northeastern Thailand and Laos. In India, out of the total of 20.4 million ha of rainfed rice area, approximately 16.2 million ha lie in eastern India (Singh and Singh, 2000), of which 6.3 million ha of upland and 7.3 million ha of lowland area are drought-prone (Pandey and Bhandari, 2008). In India, from the beginning of the green revolution era in rice in 1965 till 2009, on 14 occasions, rice production failed to achieve the expected production level. Drought was the factor for lower production on 11 of these 14 occasions (DES, 2009). Severe drought witnessed in 2002 and 2009 caused a significant reduction in rice as well as total food production in India. In the eastern Indian states of Jharkhand, Orissa, and Chhattisgarh alone, rice production losses in severe drought years averaged about 40% of the total production, with an estimated value of US$ 888 million (Bhandari et al., 2007). Severe drought also has far-reaching effects on the production and productivity of subsequent-season crops grown after rice. Analysis of rice production in different years from 1950–1951 to 2009–2010 in India shows that severe to moderate drought stress not only reduced the production of rice but also of wheat and pulses. The absence of moisture in the soil caused by late-season drought resulted in a reduction in total food crop production (DES, 2009).

Despite the direct link with development issues, there has been little success in developing drought-tolerant rice cultivars. A cultivar with high mean yield but a low degree of fluctuations in yield in diverse environments is considered stable and desirable for the rainfed ecosystem. However, rice breeders have not been able to select for such stable varieties because of high genotype by environment (G × E) interactions for grain yield (Cooper et al., 1999a; Wade et al., 1999a). Earlier, a number of constraints such as difficulty in defining the target population of environments (TPE), choosing suitable test locations representative of the target population, and the absence of effective selection criteria from breeding populations were cited as reasons that hindered the development of stable varieties for the rainfed ecosystem (Mackill et al., 1996). The absence of resources and platforms for precise multilocation testing of a large number of varieties in a defined target population of environments is considered another hindrance to selecting stable varieties. In view of this, the emphasis of many rice breeding programs shifted from developing broadly adaptable varieties to developing varieties for specific target environments but this has met with very little success. Over the years, breeders have gained a better understanding of the target population of environments. In addition, in recent years, many national programs have developed systematic testing and evaluation systems for rainfed ecosystems. The development of stable varieties for rainfed ecosystems looks to be more feasible than the scenario a few years back.

Investigations of G × E interactions in rainfed lowland rice have been conducted in many studies across Asian countries (Cooper and Somrith, 1997; Cooper et al., 1999a; Ouk et al., 2007). These estimated the variance components attributable to G × E interactions using restricted maximum likelihood (REML) and the best linear unbiased estimators (BLUPs) of genotype performances. If G × E interactions are significant, breeders need to know about stable genotypes with relatively consistent performance across a range of environments. Stability may be static (Lin et al., 1986; Becker and Leon, 1988) or dynamic. Stability is static if the genotype tends to maintain constant yield across environments and it is dynamic if a genotype's performance responds in a consistent fashion to changes in the environment. Several stability statistics have been proposed to investigate G × E. The traditional measures are the coefficient of variation (Francis and Kannenberg, 1978), environmental variance (Lin et al., 1986), Shukla's stability variance (Shukla, 1972), and regression-based parameters of the Finlay–Wilkinson model (Finlay and Wilkinson, 1963) and Eberhart–Russell model (Eberhart and Russell, 1966). Comprehensive reviews of these measures have been reported by Westcott (1987), Piepho (1998a), Piepho (1999), and Piepho and van Eeuwijk (2002). The assessment of the stability of grain yield under drought using the above-mentioned statistics has been reported by several workers (Seboska et al., 2001; Tollenaar and Lee, 2002; Okuyama et al., 2005).

Multivariate techniques are powerful tools in extracting patterns from interactions. The commonly used multivariate approaches for the analysis of G × E interactions are cluster analysis, principal component analysis, and pattern analysis. The major objective of the clustering procedure applied to G × E analysis is to cluster lines that have similar responses across environments, thereby reducing the number of comparisons (among lines). Wade et al. (1999b) used cluster analysis in addition to REML-based mixed model analysis to identify genotype groups that vary in yield and rainfed environment groups that were different in terms of their influence on genotypes. Pattern analysis is the combined use of classification and ordination methods to explore and explain the structure of G × E interactions inherent in the data under study (William, 1976). Pattern analysis has served as a useful tool to investigate patterns of G × E interactions of rice in rainfed environments (Wade et al., 1997, 1999b; Abamu and Alluri, 1998).

Biplots are an extensively used graphical technique to display interaction patterns and to visualize the interrelationships among genotypes, environments, and interactions between genotypes and environments and in identifying genotypes that are relatively stable across environments or suitable in particular environments. The biplots are obtained by subjecting the two-way G × E data to singular value decomposition (SVD) and displaying the result graphically. Two types of biplot models have been extensively used: (i) AMMI (the additive main effects and multiplicative interaction) biplots and (ii) GGE (genotype + genotype × environment) biplots. The AMMI model combines the analysis of variance of the genotype and environment main effects with the principal component analysis of the G × E interaction. The AMMI2 or the GE interaction biplot is based on the SVD of a double-centered genotype-by-environment table (Gauch, 1992). Since G and E are removed prior to SVD, it displays GE interaction only. The AMMI model has been shown to be effective in discriminating genotypes that performed well in irrigated and rainfed mega-environments and in identifying varieties that had stable performance across both conditions in wheat and maize trials (Ozberk et al., 2005; Farshadfar and Sutka, 2006; Kaya et al., 2006; Admassu et al., 2008).

The biplots based on singular value decomposition of environment-centered or within-environment standardized G × E data were referred to as "GGE biplots" by Yan et al. (2000). These biplots display both G (genotype) and GE (genotype–environment), which are the two sources of variation that are relevant to cultivar evaluation (Kang, 1993). The GGE biplot is based on the sites regression (SREG) linear–bilinear model (Cornelius et al., 1996; Crossa and Cornelius, 1997; Crossa et al., 2002). The sites regression model as a multiplicative model in the bilinear terms absorbs the main effects of cultivars plus the cultivar × environment interaction (GGE). Many studies have used GGE biplot analysis mainly for mega-environment evaluation, cultivar evaluation, and assessment of varietal stability (Navabi et al., 2006; Dehghani et al., 2006; Blanche et al., 2007; Otoo and Asiedu, 2008; Mohammadi et al., 2009, 2010).

In our study, a set of advanced breeding lines that were tested for two or more years under a diverse set of conditions that ranged from favorable irrigated conditions to conditions with moderate to severe reproductive-stage drought in the drought-prone eastern Indian region was analyzed using GGE biplots with the objective of identifying (i) genotypes with stable performance across different drought-stress levels and irrigated situations, and (ii) genotypes that performed well in a given situation or environment.