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Grain yield, adaptation and progress in breeding for early-maturing and heat-tolerant wheat lines in South Asia

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ABSTRACT

Maintaining wheat productivity under the increasing temperatures in South Asia is a challenge. We focused on developing early maturing wheat lines as an adaptive mechanism in regions suffering from terminal heat stress and those areas that require wheat adapted to shorter cycles under continual high temperature stress. We evaluated the grain yield performance of early-maturing heat-tolerant germplasm developed by CIMMYT, Mexico at diverse locations in South Asia from 2009 to 2014 and estimated the breeding progress for high-yielding and early-maturing heat-tolerant germplasm in South Asia. Each year the trial comprised of 28 new entries, one CIMMYT check (Baj) and a local check variety. Locations were classified by mega environment (ME); ME1 being the temperate irrigated locations with terminal high temperature stress, and ME5 as hot, sub-tropical, irrigated locations. Grain yield (GY), days to heading (DTH) and plant height (PH) were recorded at each location. Effect of temperature on GY was observed in both ME1 and ME5. Across years, mean minimum temperatures in ME1 and mean maximum temperatures in ME5 during grain filling had significant negative association with GY. The ME1 locations were cooler that those in ME5 in the 5 years of evaluations and had a 1–2 t/ha higher GY. A mean reduction of 20 days for DTH and 20 cm in PH was observed in ME5. Negative genetic correlations of −0.43 to −0.79 were observed between GY and DTH in South Asia during 2009–2014. Each year, we identified early-maturing germplasm with higher grain yield than the local checks. A positive trend was observed while estimating the breeding progress across five years for high-yielding early-maturing heat tolerant wheat compared to the local checks in South Asia. The results suggests the potential of the high-yielding early-maturing wheat lines developed at CIMMYT in improving wheat production and maintaining genetic gains in South Asia.

1. Introduction

Wheat, an important source of calories and proteins is a key cereal crop that impacts the global economy and food security. Continuous development of agronomically superior wheat varieties with high grain yield (GY), good nutrition and processing quality and tolerance to biotic and abiotic stresses is critical for ensuring food security. South Asia (comprised of India, Nepal, Pakistan and Bangladesh) is one of the most important wheat producing and consuming regions in the world. Though wheat production in South Asia has increased dramatically since the Green Revolution, multiple challenges such as high temperature stress and reduced water availability are major concerns. Rao et al. (2014) reported a rise of 0.32 °C and 0.28 °C per decade in the minimum and maximum temperatures over wheat growing areas in India. Warmer temperatures have already been determined to be one of the major factors in slowing the wheat productivity growth in South Asia and globally (Gourdji et al., 2013; Pask et al., 2014; Lobell et al., 2012; Sharma et al., 2007; Joshi et al., 2007a). Estimated GY losses in South Asia can range from 6 to 10% per °C rise in temperature during the grain-filling period (Lobell et al., 2008; Mondal et al., 2013; Asseng et al., 2015). Further, the current estimates by the World Bank indicate a population of 1.6 billion in South Asia, which is nearly 24%

Abbreviations: GY, grain yield; DTH, days to heading; DTM, days to maturity; PH, plant height; ME, mega environments.

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of the world population, adds to the urgency of increasing wheat production and maintaining food security.

Though a cool season crop, wheat is widely grown in temperate, tropical and subtropical areas of South Asia. The subtropical western Indo-Gangetic Plain of South Asia has a cool climate during the crop growing season and late incidence of high temperatures (>30 °C) during advanced grain filling. In contrast, the eastern, central and southern regions of South Asia are warmer throughout the crop season with maximum temperature ranges of 27–30 °C during the vegetative stages that gradually rises above 30 °C during grain filling. Thus, there is demand for prioritization of developing new wheat varieties with improved heat tolerance in South Asia.

The Cereal Systems Initiative in South Asia (CSISA), a collaborative effort between CGIAR centers (CIMMYT, IRRI, IFPRI, and ILRI) and national programs was established in 2009 to improve cereal productivity in South Asia (http://csisa.org). The CIMMYT bread wheat breeding program focused on developing early-maturing and heat tolerant wheat lines. Early maturity to escape high temperature stress has been suggested is an excellent crop adaptation approach in regions suffering from terminal and continual high temperature stress (Joshi et al., 2007b; Mondal et al., 2013). The new approach in breeding for early maturity has led to distribution and evaluation of trials in diverse locations in South Asia since 2009. CIMMYT wheat germplasm has shown excellent adaption to a wide range of climates and has been either directly released or been an ancestor of wheat varieties globally (Singh et al., 2007) and genetic gains have been reported in both optimal and stressed environments (Singh et al., 2007; Gourdji et al., 2012; Manes et al., 2012).

Our objectives were to evaluate the performance of early-maturing heat-tolerant germplasm developed in Mexico at diverse locations in South Asia from 2009 to 2014 and to estimate the breeding progress in developing high-yielding and early-maturing heat-tolerant germplasm for South Asia.

2. Materials and methods

2.1. Trial locations and climate data

Each year since 2009, high-yielding, early-maturing, heat-tolerant wheat genotypes were selected from advanced yield trials conducted at the Norman E. Borlaug Experiment Station (CENEB) in Ciudad (Cd.) Obregon, Sonora, Mexico (latitude 27.33, longitude −109.93, 40 msal). The CIMMYT advanced yield trials are tested across multiple environments in Cd. Obregon. As part of CSISA, the advanced lines with stable grain yields under irrigated normal and late sown (for high temperature stress) environments constituted the CSISA Heat Tolerant Early Maturity Yield Trial (CSISA-HT-EM). These trials were evaluated in collaboration with national program partners across several locations in major wheat producing regions of Bangladesh, India, Nepal, and Pakistan from 2009 to 2014 for GY performance and adaptation (Table 1). Each CSISA-HT-EM trial included 28 new entries, one CIMMYT check variety (Baj), and one local check, i.e., the best locally adapted variety at each location. Each trial had 3 replicates and was arranged in an alpha lattice design. Information on locations, sowing and harvest dates and plot sizes are presented in Table 1. Management practices were based on the established procedures followed at each individual location which are similar to those used for national yield trials conducted at that location. In South Asia, wheat is sown in November/December and harvested in March/May of the following year, depending on the location.

Locations in South Asia were also classified into mega environments (ME) based on the CIMMYT classification system described by Rajaram et al. (1995) and Braun et al. (2010), with ME1 and ME5 being most relevant to the studied region. This classification system defines ME1 as an optimally irrigated and highly productive environment where wheat grows in cool temperature but suffers from terminal heat stress and ME5 as hot, humid or non-humid, tropical, or subtropical regions, with continuous high temperatures during the crop season and the mean temperatures in the coolest month is >17.5 °C. These two MEs can be further differentiated based on the mean minimum temperature ranges of the coolest quarter, 3–11 °C for ME1 and 11–16 °C for ME5 (Ortiz et al., 2008).

Consistent weather data was not available for all locations across years. Thus mean temperature data during the crop season was extrapolated from NASA POWER Data (NASA, 2016) for the following locations during 2009–2014: Dinajpur and Jessore in Bangladesh, Karnal, Indore, Ludhiana, New Delhi, Ugar, Varanasi, Jabalpur in India, Bhairahawa in Nepal and Faisalabad in Pakistan. The maximum and minimum temperatures for the some of the same locations were either received from the collaborator or extracted from online archived weather data (www.wunderground.com).

2.2. Grain yield and agronomic traits

At the end of the crop season, collaborators provided data on GY (t/ha), days to heading (DTH), days to maturity (DTM), plant height (PH) and trial management practices. DTH was estimated as the number of days from sowing date/first irrigation till 50% of the spikes had emerged from the flag leaf. DTM was recorded as senescence in the peduncles of 50% of the spikes. At maturity, plots were harvested to determine GY.

2.3. Statistical analysis

Data for GY and agronomic traits for each trial were analyzed by using a mixed model for computing the least square means (LSMEANS) for each genotype at individual locations and across locations and MEs in each year using the program Multi Environment Trial Analysis with R for Windows (METAR, Alvarado et al., 2015). Genetic correlations between GY and DH were also estimated using METAR. The Dunnett's (one-tail) test and Fisher's LSD were estimated to compare the mean grain yield of the lines. The estimated LSMEANS of GY for each genotype was expressed as a percentage of the local check using the following formula:

$$\%GY = \left(\frac{GY_g}{GY_c}\right) \times 100$$

where, GY_g is the mean GY of a genotype and GY_c is the mean GY of the local check.

Broad sense heritability (H) was estimated for each trait in the multi environment trial planted in *e* environment using the following formula:

$$H = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_{ge}^2/e + \sigma_e^2/er}$$

where, σ_g^2 is the genetic variance, σ_e^2 is the residual variance, σ_{ge}^2 is genotype x environment (or location) interaction variance, *e* is the number of environments/locations and *r* is the number of replicates.

Regression analysis was performed to measure the rate of progress in breeding for early-maturing high-yielding heat tolerant wheat lines (Sayre et al., 1997; Sharma et al., 2012). The mean%GY of the five highest yielding lines (HYL) over the local checks was regressed over the 5 years of evaluations and the rate of progress was estimated from the slope of the regression line.