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Spectral assessment of drought tolerance indices and grain yield in advanced spring wheat lines grown under full and limited water irrigation

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ABSTRACT

Because wheat varieties exhibit a high genotype × environment interaction, several drought tolerance indices (DTIs) have been developed to assist breeders in selecting genotypes with good performance under contrasting water conditions. We compared the relative yield of advanced breeding wheat lines under both well-watered and limited water irrigation conditions using different DTIs and evaluated how spectral reflectance indices (SRIs), as rapid and non-destructive tools, can effectively monitor DTIs and grain yield. Sixty-five recombinant inbred lines (RILs) developed from a cross between drought-tolerant (Sakha 93) and drought-sensitive (Sakha 61) genotypes were subjected to full irrigation (FI) and limited water irrigation (LWI) in the 2014 (F_6), 2015 (F_7), and 2016 (F_8) growing seasons. Eight vegetation- and water-SRIs calculated from canopy reflectance under FI and LWI, and taken at the heading and middle grain filling stages, were related to the DTIs and grain yield. We found that the yield performance of the RILs was not consistent across the two water regimes. Selection based on the DTIs, the stress susceptibility index and the tolerance index failed to identify RILs that had very low yields under both treatments. However, the mean productivity index (MPI) and the geometric mean productivity index (GMP) enabled us to identify RILs that produced desirable yields under both full and limited irrigation, and these drought tolerance indices further exhibited a high heritability. Across the three years of investigation and at the heading and middle grain filling stages, these DTIs were best described either by the vegetation-based dry matter content index (DMCI) or the water-based normalized multi-band drought index (NDMI), or a combination of both. In conclusion, our results demonstrate that a combination of near infrared (NIR) and shortwave infrared (SWIR)-based SRIs can be used as a fast and low-cost predictor for selecting wheat genotypes with superior yield under different water regimes.

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1. Introduction

Water shortages currently impair almost every country in the world's arid regions and they have become the norm rather than the exception in those regions. Most importantly, water shortages in arid regions will be further worsened due to abrupt climatic changes, continuous population growth, and rising incomes. According to Perry et al. (2009), as a consequence of climate change, most of the current water-scarce countries will become drier and warmer. Water shortage events have therefore gained increasing importance in both scientific and political contexts. Because the agriculture sector is the largest single user of fresh water, consuming about 75% of the available water supply (Prathapar, 2000), many governments in arid and semiarid regions have issued different regulations such as moratoriums on drilling new wells and mandates for the installation of water meters on pumping stations in order to restrict the irrigation water supply for this sector (Payero et al., 2008). These regulations will reduce the amount of

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water that can be allocated for each crop because the increase in yield under sufficient irrigation may not compensate for the costs of this extra irrigation water. Thus, different strategies are urgently needed to improve wheat production, especially since the production of major crops could be reduced by more than 50% under limited water irrigation (El-Hendawy and Schmidhalter, 2010; Nezhad et al., 2012; El-Hendawy et al., 2014; El-Hendawy et al., 2015a).

Although there are many strategies that can improve wheat production under limited water conditions, the development of new genotypes with higher yield potential and drought tolerance is still recognized as the most feasible strategy for addressing this challenge (Sinclair, 2011). Although many efforts have been made so far to improve the drought tolerance of wheat genotypes through molecular breeding, there have been very few successful examples of increasing the yields of wheat genotypes in farmers' fields. A major constraint on accelerating wheat breeding for drought tolerance is the lack of effective evaluation tools for precise phenotyping of drought-related traits in breeding programs (Tester and Langridge, 2010; Mir et al., 2012; Elazab et al., 2015; Barakat et al., 2016). Unfortunately, the majority of the current tools for phenotyping drought-tolerance traits are destructive, expensive, and unaffordable, especially when a large number of genotypes are being evaluated (El-Hendawy et al., 2015a,b). There is therefore an urgent need for non-destructive, easy, rapid, practical, and economical phenotyping tools that can evaluate large numbers of genotypes in a relatively short time.

One of the most promising techniques currently used to precisely monitoring traits related to drought tolerance for a large number of entries in a fast and nondestructive manner is the canopy reflectance sensing technique. The basic principle of this technique is based on the amount of light reflected from the canopy at a specific wavelength, which is a result of biochemical, physiological and structural properties of the canopy, providing several types of information that can be used to assess canopy chlorophyll content, canopy senescence, photosynthetic capacity, aboveground biomass, leaf area index, grain yield, and plant water status from a single spectrum (Aparicio et al., 2002; Babar et al., 2006; Prasad et al., 2007; Gutierrez et al., 2010; Weber et al., 2012; Erdle et al., 2013; Kipp et al., 2014; Lobos et al., 2014; El-Hendawy et al., 2015a; Elsayed et al., 2015). In cereals crop, the link between biomass and yield is established and well known. In the last decade, nondestructive devices based on chlorophyll fluorescence have been developed and tested for biomass and nitrogen assessment in several crops (Agati et al., 2013; Cerovic et al., 2015). Furthermore, the measurement of spectral reflectance with ground-based proximal sensing techniques has potentially be used as an easy, rapid, practical, and economical technique for assessing several phenotyping criteria related to drought tolerance.

To date, plant breeders around the world consider grain yield per se as the main selection criterion for improving grain production under different environmental conditions. However, because of the substantial interactions between genotype and environment for this trait (Golabadi et al., 2006), repetitive evaluations of genotypes in different locations and in successive years are necessary to produce sufficiently accurate results when seeking to identify superior genotypes with high grain yield. In the absence of such a strategy, there is an increased risk of accidentally discarding good lines or retaining inappropriate genotypes in breeding trials. Further, measuring grain yield by conventional methods for a large set of entries and treatments is not an easy task. Because final grain yield is a function of many morphological and physiological characteristics that show significant differences among germplasm at different growth stages, several researchers have suggested that spectral reflectance approaches could be used to early predict grain yield prior to harvest in a rapid and nondestructive manner (Prasad et al., 2007; Lin et al., 2012; Weber et al., 2012; Erdle et al., 2013; Hackl et al., 2014; Elsayed et al., 2015).

Based on simple mathematical operations such as ratios and differences between the reflectance of the canopy at visible (VIS, 400–700 nm), near-infrared (NIR, 700–1300 ;1300nm), and short-wave infrared (SWIR, 1300–2500 nm) wavelengths, different spectral reflectance indices (SRIs) have been developed to predict different agronomic and physiological traits. Several researchers have suggested that measuring these SRIs periodically during different growth stages can be an effective way to rapidly and nondestructively predict grain yield under diverse environmental conditions (Weber et al., 2012; Erdle et al., 2013; Araus and Cairns, 2014; Lobos et al., 2014; El-Hendawy et al., 2015a; Elsayed et al., 2015). For example, Ma et al. (2001) found that under irrigated conditions, the green normalized difference vegetation index (GNDVI) had the highest association with soybean yield and explained up to 80% of the variability found in grain yield. The GNDVI and the near-infrared radiation (NIR)-based indices were also highly correlated with maize grain yield and explained 70–92% of yield variability at the middle grain filling stage under normal growing conditions (Shanahan et al., 2001). The normalized difference vegetation indices (NDVIs) were also well correlated with wheat grain yield under rainfed and irrigated conditions (Aparicio et al., 2002). The spectral indices related to normalized water indices (NWI-1, NWI-2, NWI-3 and NWI-4) were highly correlated with bread-wheat grain yield and explained more than 70% of the variation in grain yield under normal and water stress conditions in diverse studies (Marti et al., 2007; Prasad et al., 2007; Lobos et al., 2014; El-Hendawy et al., 2015a). Weber et al. (2012) reported that the spectral indices of wavelengths from 495 to 680 nm, from 680 to 780 nm, and at 900, 970, and 1450 nm, which are related to photosynthetic capacity, plant biomass, and plant water status, respectively, had the highest levels of association with maize grain yield under different water regimes. Lobos et al. (2014) reported that an NIR-based SRI such as the normalized difference moisture index (NDMI: 2200; 1100) was well correlated with the final wheat grain yield under limited water irrigation. Elazab et al. (2015) also found that the normalized green-red difference index (NGRDI) at anthesis was the trait best correlated with wheat grain yield under contrasting water conditions. However, because the response of genotypes to water stress varies with growth stage and with environmental conditions, care must be taken to identify a proper and consistent growth stage, as well as SRIs that can most effectively discriminate among genotypes in specific conditions and breeding trials.

Generally, grain yield performance is not consistent for all genotypes across environments (Raman et al., 2012). When the grain yield of a large number of genotypes is evaluated under well-watered and limited water irrigation conditions, the performance of genotypes for grain yield may be good or weak in both conditions, or good only in well-watered conditions, or in limited water conditions (Fernandez, 1992). Therefore, several drought tolerance indices (DTIs) that are based on mathematical relationships between normal and stress conditions have been proposed to identify desirable genotypes that perform well under a wide range of water treatments (Mohammadi et al., 2010; Cabello et al., 2013). The stress tolerance index (STI), stress susceptibility index (SSI), yield index (YI), tolerance index (TOL), mean productivity index (MPI), and geometric mean productivity (GMP) are examples of these selection indices and they have been applied in studies of many crops (Fernandez, 1992; Jafari et al., 2009; Singh et al., 2011; Drikvand et al., 2012; Cabello et al., 2013). It was found that MPI has an upward bias when the differences in grain yield between well-watered and limited water irrigation treatments are large (Hossain et al., 1990). The GMP and STI are suitable indices when the performance of genotypes for grain yield is tested at both well-watered

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