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Predicting wheat maturity and stay–green parameters by modeling spectral reflectance measurements and their contribution to grain yield under rainfed conditions

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ABSTRACT

The normalized difference vegetation index (NDVI) continues to provide easy and fast methodologies to characterize wheat genetic resources in response to abiotic stresses. This study identifies ways to maximize green leaf area duration during grain filling and develops NDVI models to predict physiological maturity and different stay –green parameters to increase grain yield of rainfed winter wheat under terminal drought. Three wheat populations were evaluated: one containing 240 landraces from Afghanistan, the second with 250 modern lines and varieties, tested for two years under low rainfall conditions in Turkey, and the third with 291 landraces from Central and Western Asia (grown for one year in the same location). The onset of senescence, maximum “greenness”, rate of senescence and residual “greenness” at physiological maturity were estimated using sequential measurements of NDVI and have shown significant correlations with grain yield under low rainfall rainfed conditions. Trade-offs were identified among the different stay –green attributes, e.g. delayed onset of senescence and high maximum “greenness” resulted in accelerated rates of senescence and highest yields and were most evident in the landrace populations. It is concluded, that the use of rate of senescence to select for stay –green must be coupled with other stay –green components, e.g. onset of senescence or maximum “greenness” to avoid the effects of the trade-offs on final grain yield. The NDVI decay curves (using the last three NDVI measurements up to maturity) were used to estimate days to maturity using the NDVI decay during the senescence period and days to heading. A training and testing set (20 and 80% of each population, respectively) were used for calibrations allowing for correlations between predicted and observed maturity of up to r = +0.85 (P < 0.0001). This procedure will facilitate large –scale wheat phenotyping in the future.

1. Introduction

One of the most successful applications of physiology in breeding is the analytical exercise of defining traits at the genetic and phenotypic levels that maximize grain yield in different environments based on experimentation and phenotyping (Reynolds and Tuberosa, 2008; Pinto et al., 2010; Reynolds et al., 2011; Cossani and Reynolds, 2012). Trait dissection into maximizing grain yield leverages the ultimate adapted genotype for a specific type of environment, provides a holistic view required for field selection and has been shown to be less susceptible to environmental influences than selecting for grain yield alone (Hammer et al., 2005). Moreover, trait dissection requires new and upgraded methodologies to further automate and successfully apply these traits to better characterize breeding populations. One good example of automation is the use of spectral indexes like the normalized difference vegetation index (NDVI). NDVI has been particularly useful to predict grain yield, vegetation cover and senescence parameters like stay-green when measured at different stages of crop development

Abbreviations: DH, days to heading; DM, days to maturity; Eff, efficiency; GM2, grain number per square meter; GY, grain yield; MaxNDVI, theoretical maximum NDVI; NDVI, normalized difference vegetation index; POP, population; RS, rate of senescence; Stg, NDVI value at physiological maturity; SW, straw weight; TKW, thousand kernel weight; TTMaxNDVI, theoretical thermal time at MaxNDVI.

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(Lopes et al., 2014; Raun et al., 2001; Hammer and Schjoerring, 2003; Lopes and Reynolds, 2012). Specifically, stay-green refers to the heritable delayed foliar senescence character in a crop (Thomas and Ougham, 2014).

A stay-green phenotype may be induced by different phenomena: the onset of senescence is delayed, lower senescence rate, lesion of chlorophyll degradation whereas photosynthesis declines or "greenness" is retained due to rapid death at harvest (Thomas and Howarth, 2000). Stay −green in the past has been assessed visually (e.g. Joshi et al., 2007), with SPAD chlorophyll measurements (Harris et al., 2007), with NDVI (Lopes and Reynolds, 2012) and it has been continuously upgraded (Kipp et al., 2013; Christopher et al., 2014) allowing for a more complete view of the different components of stay −green. Previously, a simple model has been used to derive rate of senescence and residual "greenness" at maturity (Lopes and Reynolds, 2012) and this was further expanded to include the onset of senescence, crop or leaf spectral radiance variation after anthesis, and timing from anthesis to on-set (Vilmus et al., 2014). These developments in methodology have mainly contributed to a better understanding of how well the stay −green attributes contribute to grain yield and to grain protein concentration. However, these studies did not address the way these different stay −green components interact to influence final grain yield under low rainfall field conditions with terminal drought in winter wheat. Is there any compensation between different stay −green components working together for final grain yield? Specific objectives of this study were: 1) to define and estimate senescence parameters and their impact on crop performance in rainfed trials using proximal NDVI spectral radiance measurements in large germplasm collections; 2) to compare senescence parameters in wheat landraces and improved germplasm with basic physiological and agronomic traits; Finally, 3) this study tests NDVI decay curves of different maturing genotypes and tries to identify models to estimate difficult-to-measure traits like days to maturity.

2. Materials and methods

2.1. Plant materials

Three wheat (*Triticum aestivum* L.) populations were used in this study: population 1 containing a group of 240 landraces from Afghanistan (Kihara collection collected in 1955, by courtesy of Dr. Tomohiro Ban, Kihara Institute for Biological Research, Yokohoma City University) (Manickavelu et al., 2014; Sohail et al., 2015); population 2 containing 250 modern wheat varieties and advanced lines from the International Winter Wheat Program (IWWIP); and population 3 containing 291 landraces from Central and Western Asia (Lopes et al., 2015) from the International Maize and Wheat Improvement Center (CIMMYT) Germplasm Bank.

2.2. Experimental design and environments

Field trials conducted for stay-green modeling were sown during two growth cycles at the Bahri Dagdas International Agricultural Research Institute in Konya, Turkey: in 2012–2013, on 1st October, 2012 (populations 1 and 2), and in 2013–2014, on 24th October, 2013 (populations 1, 2 and 3); additionally population 2 was grown in 2014–2015 in the same location for predictions of physiological maturity. Konya is located at 37.86472° N and 32.5603° E and 1000 m above sea level, this site has low-to-moderate precipitation and occasional high temperatures during grain-filling (Table 1). As a reference, the two growth seasons used in this study, showed terminal drought typically happening during the last month of grain filling up to maturity and overall both seasons were drier and warmer in the winter (January and February, particularly in 2013–2014) than long term meteorological data (Table 1). The experimental design was an alpha lattice design with two replicates in plots 1.5 m long with three rows (distance between rows was 25 cm apart and distance between plots was 50 cm) and approximately 200 seeds per m^{-2}. Soils had 1.1% of organic matter, 2.5 ppm nitrate and a pH of 8.3. Nitrogen fertilization was applied at sowing with 200 kg ha^{-1} of di-ammonium phosphate and in March with 40 kg ha^{-1} of ammonium nitrate. Daily weather and soil moisture data were obtained from an IMT 300 (iMETOS) meteorological station and a Watermark Sensor (Irrometer Co., Inc., Riverside, CA) located on site.

2.3. Phenotypic trait evaluation

Grain yield (GY), straw weight and yield components were determined by manually harvesting the middle row of each plot. At harvest, each middle row containing straw and grain was weighed and threshed. The difference between straw plus grain weight and grain weight was used to calculate straw weight. Straw weight was only determined in population 2 and 3 but not in population 1. Thousand-kernel weight (TKW) was determined in samples of 200 grains, and grains per unit area (GM2) were derived from TKW and GY. Days to heading (DH) was determined as the number of days from the sowing date until the point when more than 50% of plants were displaying heads (Zadoks Stage 59, Zadoks et al., 1974). Physiological maturity (DM) was measured as the time when 50% of the spikes in a plot showed a total loss of green color, corresponding to Zadoks stage 89 (Zadoks et al., 1974). Plant height was determined by measuring the distance from the base of the stem to the top of the spike, excluding awns in the field (after physiological maturity) with a ruler. NDVI measurements were taken with a GreenSeeker sensor (Optical Sensor Unit; 2002 Ntech Industries, Ukiah, CA, USA), which records the reflectance in one plot at a frequency of 30–50 times $plot^{-1}$. NDVI measurements started early March 2013 until the end of June (in the 2012–2013 cycle) and in April 2014 until the end of June (in the 2013–2014 cycle) up to maturity. Measurements continued every one or two weeks up to physiological maturity in 2013 and, in 2014, up to the complete senescence of all plots. NDVI data up to complete senescence was measured in populations 1 and 3 for the 2013–2014 cycle and in population 2 for the 2014–2015 cycle.

2.4. NDVI modeling

2.4.1. Estimating senescence parameters through individual genotype NDVI modeling

NDVI measurements were taken as explained above; in total, nine and ten measurements were taken during the 2013 and 2014 crop seasons, respectively. Daily weather data were used to convert NDVI measurement dates into degree days post heading using base temperature estimated as 5.5 °C as described in Saint-Pierre et al. (2012).

For each plot, we followed a modified procedure described in (Vilmus et al., 2014): specifically, the maximum measured NDVI value through time was identified and all NDVI measurements taken before that date were assumed to correspond to wheat vegetative growth stage. After this date, NDVI decayed and was considered to reflect the wheat senescence stage during grain-filling.

For both vegetative growth and senescence stages, a linear [Eq. (1)] modeling method was used:

$$NDVI = \beta_0 + \beta_1 t + \varepsilon \quad (1)$$

with *NDVI* as measured NDVI, t as time in °Cd, β_0 and β_1 as the two parameters of the linear model and ε as the residual term;