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Evaluation of agronomic traits and spectral reflectance in Pacific Northwest winter wheat under rain-fed and irrigated conditions

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ABSTRACT

The US Pacific Northwest (PNW) is characterized by high latitude and Mediterranean climate where wheat production is predominantly rain-fed and often subject to low soil moisture. As a result, selection for drought-adaptive traits in modern cultivars has been an integral component of the regional breeding programs. The goal of this research was to evaluate phenotypic associations of morpho-physiological traits and their response to soil moisture variation in winter wheat germplasm adapted to the PNW. A panel of 402 winter wheat accessions (87 hard and 315 soft) was evaluated for spectral reflectance indices (SRIs), canopy temperature (CT), plant stature, phenology, grain yield, and yield components under rain-fed and irrigated conditions in 2012–2014. Variation in soil moisture and temperature cumulatively explained 86% of total yield variation across years and locations. The phenotypic associations of yield with phenology, plant height, and CT were environment dependent. Various SRIs related to biomass, stay green, pigment composition, and hydration status showed consistent patterns of response to drought and strong correlations with yield ($p < 0.001$). The compensatory interaction of grain number and weight was indicated in the negative correlation between thousand kernel weight and grain number per spike across moisture regimes. Area under vegetation index curve (AUVIC) explained 53–88% of the total variation in stay green estimated from visual score of flag leaf senescence ($p < 0.001$). Principal component analysis revealed three major clusters that explained more than 76% of interrelations among traits. The market classes within the study population showed differentiation with respect to these traits. This study highlights the potential use of spectral radiometry in field screening of winter wheat for grain yield and drought adaptation in Mediterranean-like environments.

1. Introduction

Winter wheat production in the US Pacific Northwest (PNW) is characterized by high latitude, relatively cool temperature, and a Mediterranean-like climate with most annual precipitation occurring in the winter (Mote, 2003). Annual precipitation ranges from less than 200 mm to more than 500 mm (Schillinger and Papendick, 2008). In addition to soil moisture deficits in semiarid areas, seasonal precipitation fluctuation between April and June is a major constraint of wheat production in the entire region (Lopez et al., 2003). Soil depth ranges from less than 1 m to over 7 m, causing spatial heterogeneity in water holding capacity and stress severity in the region (Shillinger and Papendick, 2008). Direct selection for grain yield has been successfully practiced for more than a century to improve yield across the precipitation zones. However, the genetic gain from this approach is generally low in the driest farms because of high genotype-environment interaction and unaccounted spatial heterogeneity (Blum, 2006).

Higher genetic progress in yield can be achieved by selecting secondary traits other than yield *per se*. Grain yield is determined by number of spikes per area, number of kernels per spike and kernel weight which are interrelated to each other and influenced by morpho-physiological traits such as early vigor, plant stature, flowering time, and physiological maturity (Alexander et al., 1984; McNeal et al., 1978; El-Mohsen et al., 2012; Mohammadi et al., 2012; Wu et al., 2012). The influence of environment on these secondary traits is relatively low and predictable resulting in higher genetic progress compared to yield based selection (Fischer et al., 2012; Wu et al., 2012). Recent reports suggest that some of the component traits are genetically independent suggesting the possibility

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of combining multiple traits in modern wheat cultivars (Dhungana et al., 2007).

The compensatory interactions and relative contributions of grain weight, grain number per spike, and spike number per area towards overall yield are affected by developmental characteristics and environmental factors (Cutforth et al., 1988; Duguid and Brule-Babel, 1994; Santra et al., 2009). Semi-dwarf stature (shorter and stiffer than standard height), early growth vigor, and early maturity are adaptive features for environments with terminal heat and drought stresses (Bai et al., 2004; van Ginkel et al., 1998; Morgan, 1995; Álvaro et al., 2008; Kirkegaard et al., 2001). On the other hand, dwarf stature and long grain-fill duration have yield advantage in optimum conditions (Bai et al., 2004; Blum, 1996; Gomez et al., 2014). As a result, indirect selection is an analytic approach that involves understanding interrelationships among various attributes, their yield advantages, and responses to environmental variation (McNeal et al., 1978; El-Mohsen et al., 2012).

Some physiological attributes contribute to grain yield and yield components like kernel weight by maintaining higher rate and duration of grain filling (Duguid and Brule-Babel, 1994). These physiological attributes include radiation use and photosynthetic efficiency, transpiration efficiency, water availability and retention capacity, biomass capacity, and assimilate translocation to the grain (El-Mohsen et al., 2012; Reynolds et al., 2012). However, direct measurements of these physiological attributes are labor and resource-intensive which limits their application to characterize large sets of germplasm.

Spectral radiometry and other indirect sensing methods became high-throughput phenotyping alternatives that enable evaluation of large germplasm collections over multiple target environments (Fiorani and Schurr, 2013). Spectral reflectance indices (SRIs) are calculated in the visible (VIS) and near infrared (NIR) ranges ($\lambda = 400–700$ and $\lambda > 700$ nm respectively). Three main categories of traits can be estimated using these indices: (1) biomass, pigment abundance, and area of photosynthetic canopy (Wiegand and Richardson, 1990; Haboudane et al., 2004; Naumann et al., 2009; Reynolds et al., 2012); (2) water availability and plant hydration status (Tucker and Sellers, 1986; Zarate-Valdez et al., 2012); and (3) composition of photo- and thermo-protectant molecules (Peñuelas et al., 1995; Ollinger, 2011).

A combination of both visible and infrared spectra are used to derive the vegetation indices of simple ratio (SR), normalized difference vegetation index (NDVI), and green normalized vegetation index (GNDVI) to discern minute differences in vegetative greenness, rate of senescence, and stay green duration (Gitelson et al., 1996; Stenberg et al., 2004; Babar et al., 2006; Edae et al., 2014; Lopez and Reynolds, 2012; Liu et al., 2015). The anthocyanin reflectance index (ARI) is derived from wavelengths in both the VIS and NIR regions as a surrogate for anthocyanin composition (Gitelson et al., 2002). Photochemical reflectance index (PRI), normalized chlorophyll-pigment ratio index (NCPI), and Xanthophyll pigment epoxidation state (XES) are derived from reflectance at the VIS light range to estimate the composition and abundance of plant pigments (Peñuelas et al., 1993; Peñuelas et al., 1995; Ollinger, 2011), whereas normalized water index (NWI) is derived from reflectance at NIR range to estimate plant hydration status (Babar et al., 2006).

Characterizing the interrelations of SRIs, developmental traits, and yield with respect to target environments is crucial to facilitate an integrated use of remotely-sensed and agronomic information in adaptation breeding (Edmeades et al., 1997; Farshadfar et al., 2013). Rigorous investigations have been carried out to fully account for the responses of SRIs in irrigated, warm, and low latitude spring wheat environments. Effects of environment and growth stages on SRIs were reported to be significant (Aparicio et al., 2002; Babar et al., 2006; Lopez and Reynolds, 2012). Aparicio et al. (2000) reported that association of SRIs with grain yield, biomass capacity, and leaf area index (LAI) was higher in rain-fed than irrigated condition. These reports suggest the need to carefully determine which growth stage and selection environment is most informative.

However, little or no previous assessment has been done on the properties and potential use of canopy spectral reflectance in the environments with a high latitude, cool to cold winter season, and strong photoperiod requirement. The main goal of this research was to evaluate various spectral reflectance indices associated with grain yield under dry, moist-cool, and irrigated conditions in winter wheat genotypes adapted to the PNW environment. Specific objectives were: (i) to evaluate phenotypic associations of SRIs with grain yield and morpho-physiological traits; (ii) to determine the interaction of these traits with environmental variables and developmental traits such as ear emergence, and (iii) to examine the trends of phenotypic associations across multiple growth stages in the crop's life cycle. Understanding the interrelationship and drought-responses of these developmental traits, morpho-physiological components, and agronomic performance will help in combining the yield advantage of multiple attributes through focused identification and introgression of traits that have synergetic effects on yield.

2. Materials and methods

2.1. Study population

The study was conducted on two PNW winter wheat subpopulations: hard winter (n = 87), and soft winter (n = 315). The winter wheat germplasm in the region has been continuously subjected to selection for yield, yield stability, end-use qualities, farming preferences, and disease resistance (Barrett and Kidwell, 1998; Chen, 2005; Schillinger and Papendick, 2008). Donaldson (1996) indicated that wheat cultivars adapted to the region contain significant variations for emergence, early canopy establishment, root growth and development, winter survival, osmotic adjustment, optimum maturity, and plant architecture. Barret and Kidwell (1998) attributed the broad and stratified genetic basis for these agronomic traits to the breeding effort in region that has been in place for more than a century. Similarly, the study population is known to have a genetic stratification that align with market class and breeding history. In particular, population structure analysis differentiated hard winter genotypes from club winter genotypes with only a slight overlap (Naruoka et al., 2015).

Genotypes were selected from mapping populations, advanced breeding lines, and cultivars from PNW breeding programs targeted to Oregon, Washington, and Idaho. The hard red winter wheat cultivar 'Norwest 553' (PI 655030) and the soft white winter cultivar 'Madsen' (PI 511673) were included as local checks. Madsen is known for its wide adaptation and disease resistance and has been grown in the PNW for over 20 years, whereas Norwest 553 has high yield potential, good disease resistance, and was the most commonly grown hard red cultivar in the PNW when the trial was initiated. Because both accessions have semi-dwarf plant height and photoperiod sensitivity, the variation across years and locations is expected to have low effect on their performance making them ideally suited to account for spatial variations within each trial.

2.2. Experimental conditions and field design

The study population was grown in three moisture regimes at the following Washington State University agronomy research farms: Central Ferry (46° 4′ N; 117° 8′ W), Pullman (46° 4′ N; 117° 5′ W), and Othello (46° 5′ N; 119° 2′ W) (Table 1). Central Ferry has a

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