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Use of spectral reflectance for indirect selection of yield potential and stability in Pacific Northwest winter wheat

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ABSTRACT

The use of canopy spectral reflectance as a high throughput selection method has been recommended to augment genetic gain from yield based selection in highly variable environments. The objectives of this study were to estimate genotypic correlations between grain yield and spectral reflectance indices (SRIs), and estimate heritability, expected response to selection, relative efficiency of indirect selection, and accuracy of yield predictive models in Pacific Northwest winter wheat (*Triticum aestivum* L.) under a range of moisture regimes. A diversity panel of 402 winter wheat genotypes (87 hard and 315 soft) was grown in rain-fed and irrigated conditions across the eastern Washington in 2012 and 2013. Canopy spectral reflectance measured at heading, milk, soft dough, and hard dough stages were used to derive several SRIs which generally had higher broad sense heritability (H^2) than yield *per se*. Grain yield and SRIs showed generally high genetic variability and response to selection in moist-cool rain-fed condition. Efficiency of indirect selection for yield using SRIs was high in drought environment and exceeded efficiency of yield-based selection in the soft winter subgroup. Normalized water band index (NWI) showed consistent response to selection across environments, higher genetic correlation with yield (0.51–0.80, $p < 0.001$), and highest indirect selection efficiency (up to 143%). A yield predictive model with one or more SRIs explained 41–82% of total variation in grain yield ($p < 0.001$). The repeatability of genotypic performance between years increased when selection was conducted based on both SRIs and grain yield compared to selection based on yield or SRI alone. The generally high heritability of SRIs and their significant genotypic correlation with grain yield highlight the possibility to improve yield and yield stability in winter wheat through remotely sensed phenotyping approaches.

1. Introduction

Drought stress is a major constraint in rain-fed wheat production across the US Pacific Northwest (PNW), including the states of Idaho, Oregon, and Washington. The eastern and south-central semiarid regions of the PNW often receive less than 350 mm precipitation. The wheat growing period in the region including the high precipitation zone of the Palouse (>450 mm annual precipitation) exhibits seasonal fluctuation in precipitation and temperature (Schillinger and Papendick, 2008). The variation in precipitation and thermal time cumulatively contribute to more than 70% of total yield variation in the region (Schillinger et al., 2012; Gizaw et al., 2016). Climate prediction models indicate that the region will likely experience more unprecedented warm winters with lack of snowpack ensuing water shortages similar to the 2015 drought (Mote, 2003; Miles et al., 2010).

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).

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Grain yield, which is a result of biological and environmental processes that occur during the complete cycle of the plant, exhibits a high level of genotype x environment interactions (GEI). Genetic progress from yield-based selection is generally low in environments that exhibit precipitation fluctuation and moisture deficit (Blum, 2006). The effect of GEI on crop yield depends on the severity, duration, and timing of the stress with respect to the affected developmental stages. In addition, factors such as variation in soil depth and ambient temperature across different croplands often confound the partitioning of variation into genotypic and environmental effects (Silvey, 1981). To address these challenges, plant breeders need to augment yield based selection with secondary traits that have inherent association with grain yield and higher heritability than yield *per se*.

Morph-physiological traits often have predictable norm of response to environmental variation and as a result, maintain high heritability across environments (Fischer et al., 2012). The study of these traits can help understand how yield potential changes in response to environmental variation, identify traits that stabilize genotypic performance, to conduct selection at early generations, and advance lines with desired characteristics for target environments (Lafitte et al., 2003). Indirect selection uses secondary traits that have inherent relationship with agronomic performance, selectable genetic variation, and predictable response to environmental variations (Passioura, 2012). This study is a part of broader research initiative to characterize the phenotypic and genetic basis of drought adaptation in Pacific Northwest winter wheat using emerging phenotyping platforms.

The drought stress intensity in the PNW, plant response to drought, and phenotypic association of secondary traits with grain yield were presented in the Gizaw et al. (2016). The major findings are summarized as follows: (i) more than 80% of total yield variation across the years and locations in the eastern Washington was explained by variation in precipitation and temperature; (ii) SRIs showed moderate to high phenotypic correlations with grain yield consistently across moisture regimes and subpopulations; (iii) variation in spike emergence and physiological maturity didn't have a net yield advantage under PNW drought conditions whereas longer vegetative period had a positive yield advantage under optimum conditions; (iv) SRIs showed strong association with stay green estimated from flag leaf senescence; and (v) the market classes of PNW winter wheat showed genotypic differentiation for agronomic and remotely sensed traits.

Similar results were reported in spring and winter wheat germplasm in low latitude environments (Aparicio et al., 2000; Babar et al., 2006a; Lopes and Reynolds, 2012). These reports altogether suggest the need to carefully determine which population, growth stage, and selection environment is most informative if SRIs are to be used efficiently in wheat breeding to augment selection for grain yield in diverse environments. Specific objectives of this particular research were the following: (i) Estimate genetic variability and heritability of SRIs, phenology, and grain yield across a range of precipitation zones in Washington. (ii) Evaluate genotypic correlations and relative efficiency of indirect selection. (iii) Develop predictive models for yield using selected in-season traits. (iv) Identify genotypes that have superior performance in optimum and stress environments.

2. Materials and method

2.1. Experimental population and field trial

The experimental design and phenotyping conditions were fully described in Gizaw et al., 2016. The study was conducted on two PNW winter wheat subpopulations: hard winter (n = 87), and soft winter (n = 315). 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 with in each trial.

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 well-drained and moderately permeable Chard silt loam soil with water holding capacity ranging from 220 to 280 mm. Othello has a well-drained and moderately permeable Shano silt loam soil with 170–220 mm water holding capacity. The Palouse silt loam soil in Pullman is the most fertile and highly cultivated soil with deep profile, moderate permeability, and high water holding capacity. Planting of winter wheat in the study area is usually between late September and mid-October. The annual rainfall is highest in Pullman followed by Central Ferry and Othello (S. Table 1).

The population was planted in two treatments in Central Ferry and Othello: a rain-fed planting representing the drought condition and irrigated treatment representing the water optimum condition. In Pullman, the population was planted only in a rain-fed condition representing the moist-cool condition. The irrigated trials were conducted using solid-set sprinkler systems for 4–8 h, one or two times a week depending on the weather. Overhead sprinkler irrigation system is recommended in the region to minimize runoff. This system delivered approximately 600 mm of water over the growing season. Irrigation started on booting (Feekes 9) before any sign of stress was detected and continued until the onset of physiological maturity. In all treatments, a modified augmented design was used with two checks, the cultivar 'Madsen' (PI 511673) and 'Norwest 553′ (PI 655030) each replicated in 16–20 percent of the trial design (Federer and Raghavarao, 1975; Lin and Poushinsky, 1983).

Details of data collection were described in Gizaw et al., 2016. Heading date was recorded as the number of days from sowing until full exposure of spikes in 50% of the plot. Canopy reflectance was measured at multiple growth stages using the CROPSCAN multispectral radiometer (CROPSCAN, Inc. Rochester, USA) and used to derive various SRIs. Grain yield (kg/ha) was calculated from the grain weight per plot obtained from a Wintersteiger NurseryMaster small plot combine (Wintersteiger AG, Austria).

2.2. Data analysis

2.2.1. Variance component analysis

Variance components were estimated for each trait within and across treatments with a mixed linear model using the PROC mixed procedure (SAS, Cary, NC). Genotype was considered to have a random effect whereas blocks within trial, environment, and check varieties were considered to have fixed effects.

$$y_{ij} = \mu + {}_{\beta j}X_{ij} + biZ_{ij} + \varepsilon_{ij}$$

where: y_i = the trait value for the i^{th} genotype in j^{th} trial; μ_j = mean value of the trait in the j^{th} trial; β_j = random-effect coefficient in j^{th} trial; X_{ij} = random-effect regressor for i^{th} genotype in j^{th} trial; b_j = fixed effect coefficient for block in j^{th} trial; Z_j = fixed effect