grain protein levels. Two studies conducted in bread wheat found that canopy reflectance was highly associated with leaf N and grain protein content (Wang *et al.*, 2004; Wright et al., 2004). Currently there are no reports on predicting crop yield and evaluating grain protein content in durum wheat using image processing and canopy reflectance indices in Arizona. This project investigated the potential of canopy reflectance and image processing for durum wheat yield and grain protein prediction.

Materials and Methods

Six common durum wheat varieties with low (cv. Duraking and Topper), medium (cv. Kronos and Havasu), and high protein content (cv. Orita and Ocotillo) were planted in December, 2009 at Maricopa Ag Center. Three nitrogen rates were used in this project: 90, 200, and 310 lbs/A (See table 1). N rate of 200 lbs N/A is considered the standard N rate for most growers.

Table 1. N application rate at different growth stage

	Nitrogen rate (lbs/A)		
Growth stage	Low	Medium	High
3-4 leaf	50	100	150
Jointing	20	40	60
Booting	20	40	60
Flowering	0	20	40
Total	**90**	**200**	**310**

Biomass was collected at jointing, booting, flowering, and maturity. Canopy reflectance indices were estimated using a spectroradiometer from 350 to 1050 nm (GER 1500, Spectra Vista Corp, New York). Fifteen canopy reflectance indices were estimated at each growth stage, including vegetative indices [i.e., normalized difference vegetative index, RNDVI = (R900-R680)/(R900+R680) and green normalized difference vegetative index, GNDVI = (R880-R590)/(R880+R590)], nitrogen indices [i.e. nitrogen reflectance index, NRI = (R810/R560) and normalized difference far red index, NDFR = (R790-R720)/(R790+R720)], chlorophyll indices [i.e. ratio analysis of reflectance spectra-chlorophyll a, RARSa = (R675/R700) and ratio analysis of reflectance spectra-chlorophyll b, RARSb = (R675/R650*R700)], and water indices [i.e., normalized water index 4, NWI-4 = (R970-R920)/(R970+R920)].

At flowering stage, spikes in 0.5 meter row were collected and images of spikes were taken using a black background. All images were analyzed using the program ENVI ver. 4.5 to obtain the pixel number (area of green spike) of each plot. The information was used to predict crop yield at flowering stage for late N management. Wheat was harvested at maturity and grain quality was analyzed.

Results and discussion

There were significant differences in grain yield, biomass, and grain protein among varieties under low, medium, and high N levels (Table 1). Variety Duraking produced the highest grain yield and biomass, while the Ocotillo the lowest. The low yield in Kronos and Ocotillo was due to lodging caused by a wind storm after irrigation during grain filling stage. The high N rates reduced yields in all varieties while the grain protein content showed an increase with higher N levels. Variety Orita had the highest protein content in grain across all three N treatments.

About 15 canopy reflectance indices were tested for their correlation with crop biomass and grain yield. Among them the normalized water index 4 (NWI-4 = (R970-R920)/(R970+R920)) showed consistent relationships with crop biomass and grain yield. The normalized water index 4 is related to the water transpired from plants. High-yielding varieties have high transpiration rates which are also associated with high gaseous exchange (CO_2 uptake). A variety with high biomass also transpired higher rates of water compared with a variety with low biomass production. The inverse relationship of the index with biomass and grain yield is caused by the inverse relationship between radiation absorbed at 970 nm and water transpired from plants.

The biomass measured during the growing seasons (jointing, booting, and anthesis) showed a linear relationship with NWI-4, indicating that NWI-4 could explain part of the biomass variations across the growing season (Fig. 1). We have also tested the relationship between lower stem nitrate measurements with canopy reflectance indices, but did not find consistent correlations. The relationship will be examined again in next year's study.

NWI-4 measured at anthesis showed the strongest relationships with grain yield and biomass at harvest among all the indices. This relationship was significantly improved without variety Havasu (Fig. 2). This association implies that the NWI-4 measured at anthesis can be used to predict grain yield and/or biomass at harvest. Spike size at anthesis measured as pixel number with image processing also had a significant relationship with grain yield and biomass at harvest, although it can be improved with reduced variation in measurements (Fig. 3).

Grain protein content was negatively correlated with grain yield and positively correlated with spike nitrate content at anthesis (Fig. 4). The multiple regression resulted in the following equation: Protein (%) = 15.32 + 0.022 * SpikeN – yield * 0.0003, where the unit for SpikeN and yield are ppm and lbs/A, respectively. If growers could obtain the crop yield estimation by canopy reflectance indices and the NO_3-N in the spike by laboratory analysis, they can predict grain protein at anthesis and apply N fertilizer accordingly. In the next growing season, we will employ additional N rates (lower N levels) to explore a wider yield range of crop yield to refine these relationships among grain protein content, canopy reflectance indices, and crop N status.

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Table 1. Grain yield, biomass, and grain protein content in six durum wheat cultivars grown under three nitrogen rates in the season 2009-2010.

Nitrogen rate (Lb/acre)	**Cultivar**	**Grain yield** (Lb $acre^{-1}$)	**Straw biomass** (Lb $acre^{-1}$)	Protein (%)
90	Duranking (L)	12114.7 a	18733 a	12.0 d
90	Topper (L)	9472.2 ab	16535 a	13.1 cb
90	*Kronos (M)	9001.3 bc	15408 a	12.9 c
90	Havasu (M)	9829.4 ab	17359 a	12.6 cd
90	Orita (H)	10917.0 ab	18421 a	14.7 a
90	*Ocotillo (H)	7881.4 c	15540 a	13.7 b
200	Duranking (L)	10278.6 a	17155 ab	14.7 cb
200	Topper (L)	8332.9 ab	16983 ab	14.1 c
200	*Kronos (M)	7812.3 ab	14856 ab	14.3 cb
200	Havasu (M)	9878.4 a	16603 ab	13.7 c
200	Orita (H)	8851.0 ab	17682 a	15.6 a
200	*Ocotillo (H)	6862.6 b	14551 b	14.4 b
310	Duranking (L)	9243.3 a	17664 a	14.8 b
310	Topper (L)	8150.5 a	16808 ab	14.2 c
310	*Kronos (M)	7808.1 a	16651 ab	14.8 cb
310	Havasu (M)	8770.6 a	14848 ab	14.5 cb
310	Orita (H)	8260.0 a	14362 ab	16.1 a
310	*Ocotillo (H)	6081.0 b	13758 b	14.9 b

*Lodged during grain filling.

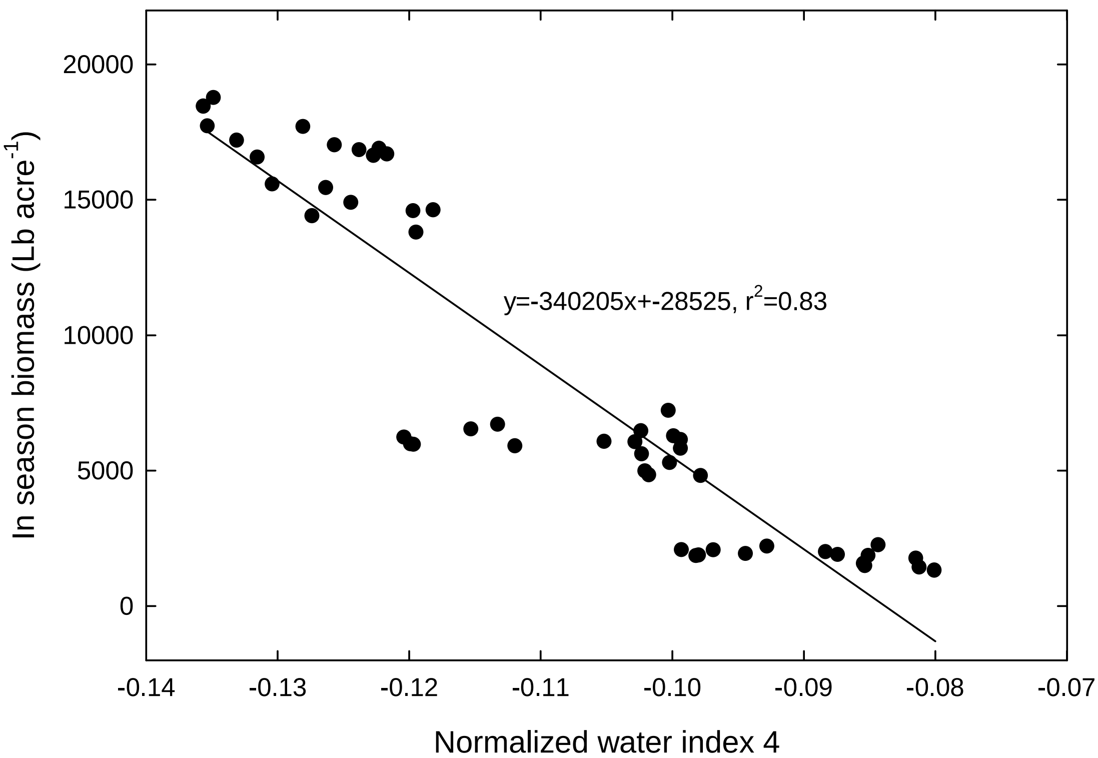

Figure 1. Relationship between the normalized water index 4 (x) and biomass (y) determined at jointing, booting, and anthesis in six durum wheat varieties in three nitrogen treatments.

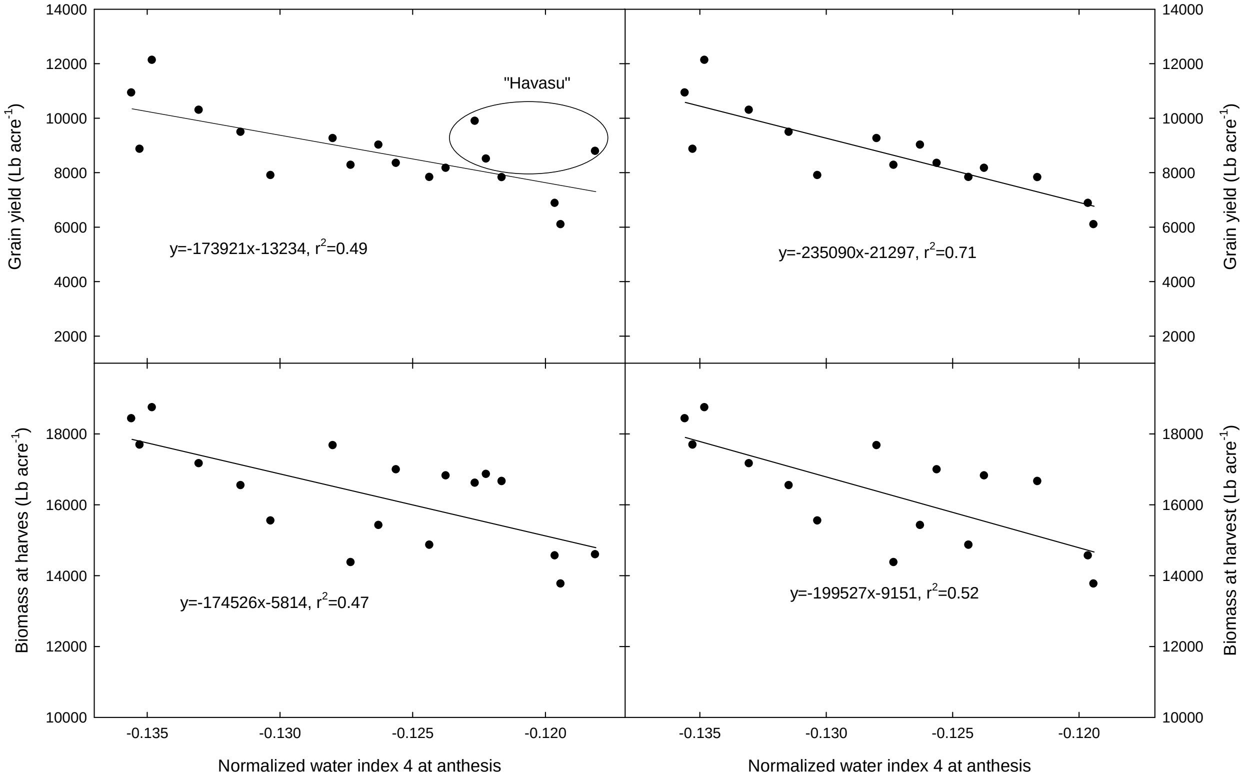

Figure 2. Relationship of the normalized water index 4 determined at anthesis (x) with grain yield and biomass (y) of six durum wheat varieties (Left) and five durum wheat varieties (Right, variety Havasu is not included) in three nitrogen rates.

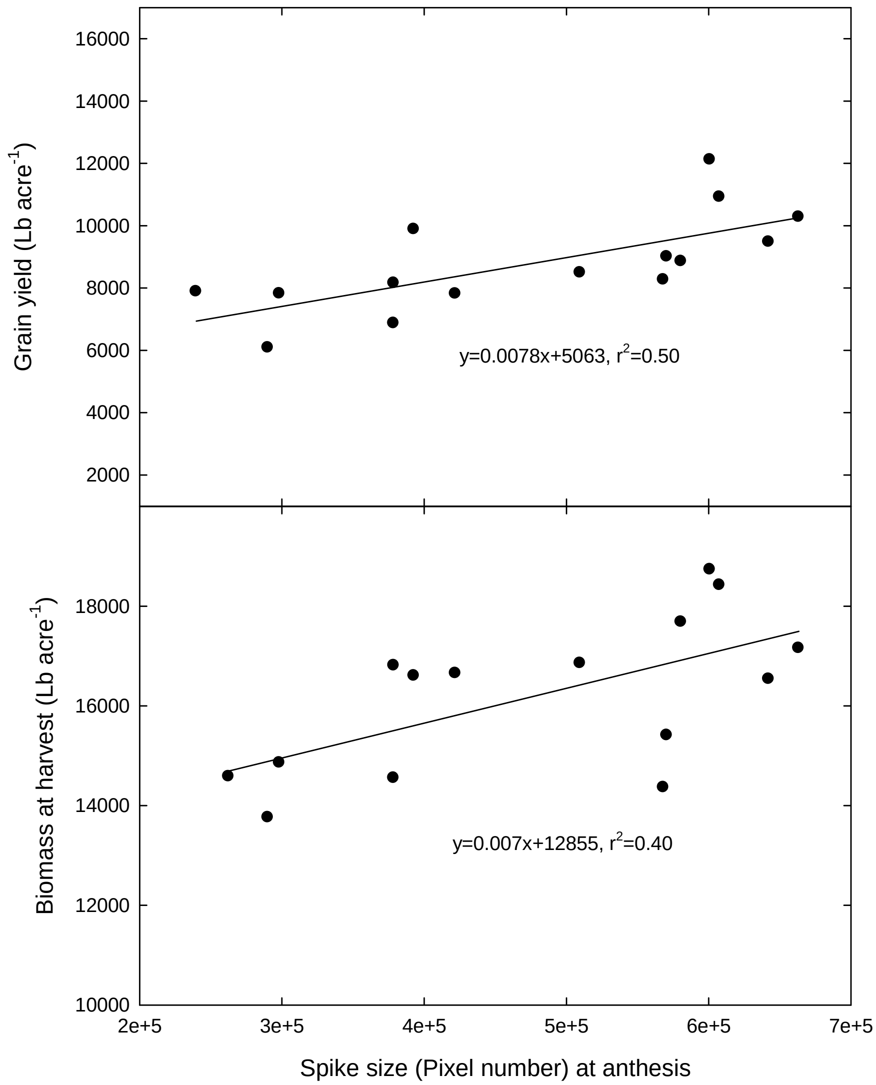

Figure 3. Relationship of spike size measured as pixel number at anthesis (x) with grain yield and biomass (y) of six durum wheat varieties in three nitrogen treatments.

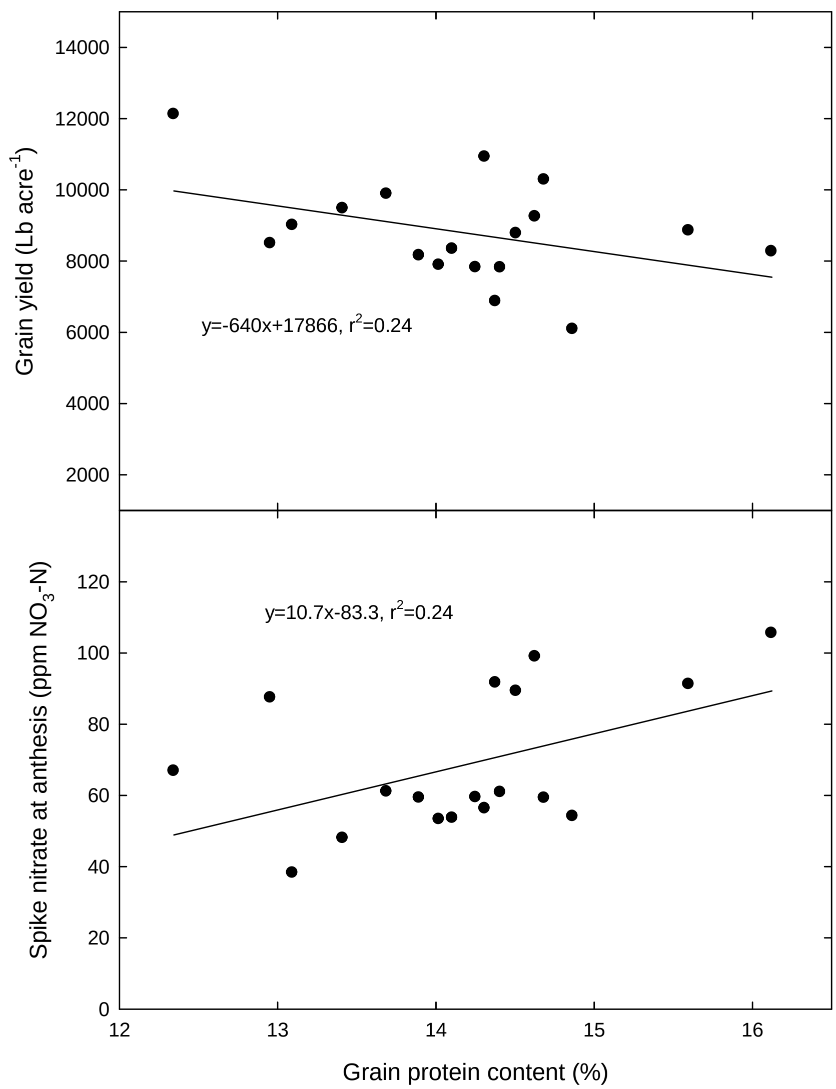

Figure 4. Relationship of the grain protein content (y) with spike nitrate content (x) determined at anthesis and grain yield (x) in six durum wheat varieties and three N treatments.