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Association of digital photo parameters and NDVI with winter wheat grain yield in variable environments

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Abstract: The normalized difference vegetation index (NDVI) is gaining popularity as a complementary selection tool, even though it requires an instrument not readily available in the developing world. We evaluated several parameters (originating from the analysis of digital photos using BreedPix software) as potential selection criteria in 23 winter wheat yield trials grown over 4 years at 2 sites. NDVI and digital photos were taken at key development stages from stem elongation to maturity. The correlations between digital photo parameters a and u and grain yield, as well as correlations between NDVI and grain yield within individual trials, varied depending on crop stage, moisture availability, and germplasm composition. NDVI, photo-a, and photo-u parameters had equal power in distinguishing high- and low-yielding genotypes in the trials and were significantly associated with yield in approximately 50% of all observations. The association of vegetative indices with grain yield can be improved by evaluating germplasm with a similar maturity range. An important challenge is in utilizing these tools in unreplicated small plots, including head rows where selection efficiency is low.

Key words: Biomass, breeding, physiology, stress, tolerance, wheat

1. Introduction

Winter wheat is a major crop in Central and West Asia, occupying an area of about 13 $\times 10^6$ ha. Irrigated wheat production systems are characterized by relatively mild winters and hot dry summers, and they produce yields of up to 5–6 t/ha. Rainfed dry areas are situated at higher altitudes, with colder temperatures in winter and postanthesis terminal drought, resulting in yields below 2 t/ha. The International Winter Wheat Improvement Program (IWWIP), based in Turkey, and national public breeding programs develop broadly adapted winter wheat germplasms for the region. IWWIP-developed wheat lines are distributed via international nurseries for selection and possible advancement as new varieties. Their superior performance in the region was documented by Sharma et al. (2013). The IWWIP breeding framework in Turkey is incorporated into the national public research system and uses 3–4 key sites for selections and yield trials. A high volume of material is screened annually under both irrigated and rainfed conditions using conventional breeding methodology. The efficiency of evaluation and selection may be improved by utilizing modern phenotyping techniques.

The application of spectral reflectance indices has been gaining popularity as a physiological and breeding tool (see Mullan, 2012). Indices are based on the ability of the crop canopy to reflect radiation; while healthy vegetation absorbs most of the visible light and reflects near-infrared light, unhealthy or sparse vegetation absorbs a small portion of visible light and a larger share of near-infrared light (Araus et al., 2001). Vegetative indices are based on capturing the difference in reflection between these 2 groups of the electromagnetic spectrum. The normalized difference vegetation index (NDVI) has commonly been used to evaluate the status of the crop and associate it with growth traits and grain yield. Aparicio et al. (2002) showed the predictive power of NDVI, measured at Zadoks stages 65 and 75, for total dry matter and leaf area index. NDVI has also been shown to have a positive relationship with grain yield and biomass under well-irrigated conditions and a stronger association with yield under drought conditions (Gutierrez-Rodriguez et al., 2004), although association with yield varies according to when the NDVI is measured (Marti et al., 2007). Genotypes with horizontal orientation of leaves at the stem elongation stage had higher NDVI values compared to erect types, and it was also shown that

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wheat yield was more accurately predicted if NDVI was measured at both the early heading and the filling stage (Feng and Yang, 2011). Hazratkulova et al. (2012) showed that maintaining stable NDVI from booting and heading stage to milk maturity serves as a criterion of heat tolerance due to stay-green character.

Measuring NDVI requires a Green-Seeker instrument, which may not be readily available for national breeding programs, even with the smaller, cheaper version currently on the market. Digital cameras have been suggested as an alternative for estimating wheat traits expressed through spectral reflectance and evaluating ground cover at early crop development stages (Lukina et al., 1999), and they have already proven useful in quantifying the senescence of wheat canopies (Adamsen et al., 1999). Both Lukina et al. (1999) and Adamsen et al. (1999) showed high positive correlation between relevant digital photo parameters and NDVI readings. Digital images have also been used to evaluate the nitrogen status of crops (Li et al., 2010), leaf area index (Liu and Pattey, 2010), and effect of ground cover on soil water evaporation (Mullan and Reynolds, 2010).

The use of digital photos as a selection tool began with the development of analytical software that could break down the images into descriptive components. This is based on the concept of color spaces: 3-dimensional mathematical systems that describe the range of colors (Trussel et al, 2005). The red-green-blue color space system is based on these 3 main colors and their mixture producing all other colors. Other color spaces used in interpreting the digital photos or any pictures include hue-intensity-saturation, Lab (lightness, and a and b as color opponent dimensions), and Luv (lightness, and a and u as color opponent dimensions). Casadesus et al. (2007) developed the software BreedPix, which utilizes different color space systems to define parameters numerically describing the color or lightness of crop canopy. BreedPix generates 13 parameters originating from different color spaces that describe the wheat canopy based on a single digital photo (Casadesus et al., 2007). The collection of durum wheat breeding lines was studied under irrigated and rainfed environments and both digital photos and NDVI were taken. Parameters derived from digital photos clustered into 3 groups reflecting greenness, brightness, and yellowness. The parameters a and u, which represent the green component of crop canopy, correlated with NDVI taken at the same time, as well as with grain yield (Casadesus et al., 2007). In general, digital photo use in describing crops is based on evaluation of greenness. The IWWIP started utilizing digital photos and NDVI in its breeding and research trials in 2008 and has accumulated a substantial amount of data covering different locations, ranges of germplasms, and various agronomic practices. This study aimed to evaluate the use of parameters derived from digital images and NDVI as supplementary selection tools for winter wheat.

2. Materials and methods

Table 1 summarizes the winter wheat trials analyzed for this study. The historical set trials represented major Turkish varieties released in the last 50 years; all varieties were generally well adapted to local conditions but varied in height and yield capacity. Historical trial 1 comprised the varieties utilized under dry rainfed conditions while trial 2 consisted of varieties for irrigated environments. The advanced yield trial represented modern germplasms developed by the IWWIP, with similar yields, heights, and maturity. Drought yield trials (DYTs) included diverse germplasms from Turkey, Central Asia, East Europe, and the United States that had been preselected for adaptation to the local environment. Both DYT-1 and DYT-2 consisted of 25 genotypes each, but they differed in compositions of the germplasms. In general, all these trials represent the typical breeding material that the IWWIP is dealing with.

Each trial utilized an alpha-lattice experimental design with at least 2 replications and a plot size of 7–8 m^2. We used 2 breeding sites, representing 2 subregions of Turkey's Central Anatolian Plateau: Konya, in the south, has a semiarid climate (310–330 mm of rainfall) and cold winter (January minimum temperature: –4.7 °C), whereas Eskişehir is in a transitional, slightly wetter area (350–370 mm rainfall) with warmer temperatures (January minimum temperature: –3.6 °C). Trials were grown using common agronomic practices: preceding crop or fallow, nitrogen fertilizer (N_{30}) application, and weed control in spring. Most of the trials were subjected to different irrigation treatments, which allowed us to evaluate the material side by side, at contrasting yield levels from <1 t/ha to 5–6 t/ha. Precision drip irrigation technology was used to provide a uniform amount of moisture across trials. Weather conditions varied from year to year: 2008 was characterized by a spring drought, 2009 and 2010 represented more typical Mediterranean conditions, and in 2012 an early but cool spring delayed wheat development by 10 days.

NDVI measurements were taken using a Green-Seeker (NTech Industries), which uses its own light source. The digital photos were taken using a Canon EOS camera. NDVI measurements and digital photos were taken around midday from 40–50 cm above the canopy parallel to the soil. Digital photos were taken using automatic mode without flash. The measurements were taken on sunny, dry days. For the trials in 2008, 2009, and 2010, measurements were taken 2 or 3 times, starting at the booting or heading-flowering stage, depending on the trial and year. In the 2012 DYTs, 10 measurements were taken every 7–10 days

Table 1. Description of winter wheat trials used in the study, 2008–2012.

Trial	Site	Year	Environment	Entries	Reps	Photo/NDVI measurements	DH	Height, cm	Yield, kg/ha
Historical set trial 1	Konya	2008	Rainfed	25	4	2	139	92	3898
	Eskişehir		Rainfed	25	4	2	139	82	3009
	Konya	2009	Rainfed	25	4	2	140	108	4650
	Eskişehir		Rainfed	25	4	2	-	105	4598
Historical set trial 2	Konya	2010	Full-Irrig.	30	3	3	134	90	4373
			Suppl-Irrig.	30	3	3	134	89	3668
			Rainfed	30	3	3	136	57	1118
	Eskişehir	2012	Full-Irrig.	30	3	3	145	96	4203
			Rainfed	30	3	3	143	94	3347
Advanced yield trial 1	Konya	2010	Full-Irrig.	25	2	3	133	83	6104
			Suppl-Irrig.	25	2	3	134	80	5160
			Rainfed	25	2	3	135	50	969
Advanced yield trial 2			Full-Irrig.	25	2	3	133	87	6217
			Suppl-Irrig.	25	2	3	134	83	4258
			Rainfed	25	2	3	136	52	760
Drought yield trial 1	Eskişehir	2012	Irrig.-Uncut	25	2	10	146	80	5006
			Irrig.-Cut[1]	25	2	10	149	75	4472
			Rainfed-Uncut	25	2	10	145	78	2705
			Rainfed-Cut	25	2	10	148	70	1944
Drought yield trial 2			Irrig.-Uncut	25	2	10	148	83	4613
			Irrig.-Cut	25	2	10	153	77	4283
			Rainfed-Uncut	25	2	10	148	81	2437
			Rainfed-Cut	25	2	10	152	74	1914

[1]Removal of the aboveground biomass and prior to stem elongation.

from stem elongation until wax maturity. Digital images were processed using BreedPix. Several parameters were obtained for each image but, based on the conclusions of Casadesus et al. (2007), we used parameters a (greenness component from Lab color space), b (yellowness from Lab color space), and u (greenness from Luv color space) for analysis. Statistical analysis consisted of ANOVA, t-criteria for comparing means, calculation of coefficients of correlations, and regression analysis using JMP statistical software.

3. Results

The average grain yield of each trial was plotted against the average values of plant height (Figure 1a), photo-a (Figure 1b), and photo-u (Figure 1c) parameters and NDVI (Figure 1d), measured at the stage of grain formation. There were significant associations for all these traits with grain yield, varying from $r^2 = 0.40$ for photo-u to $r^2 = 0.67$ for photo-a. The magnitude of plant height and NDVI association with yield is around $r^2 = 0.50$. The significant relationship of spectral reflectance parameters with yield shows that, as a whole, they reflect the crop status and amount of biomass.

The 10 photo and NDVI observations taken during the DYTs in 2012 allowed these trials to serve as a model for evaluating relationships between spectral reflectance parameters and agronomic traits. In previous years, only 2–3 measurements were taken normally starting from preheading. Variation in mean values of photo-a (Figure 2a), photo-b (Figure 2b), photo-u (Figure 2c), and NDVI (Figure 2d) in irrigated and rainfed DYT-1 is shown at different stages. The first irrigation was given at the booting stage, in early May, when visible symptoms of drought appeared. With the exception of photo-b, the other 3 parameters demonstrated gradual diversions in their values under rainfed conditions compared to the irrigated trial, which were significant starting from the grain formation stage. Differences between the 2 treatments started to manifest after anthesis; yields under

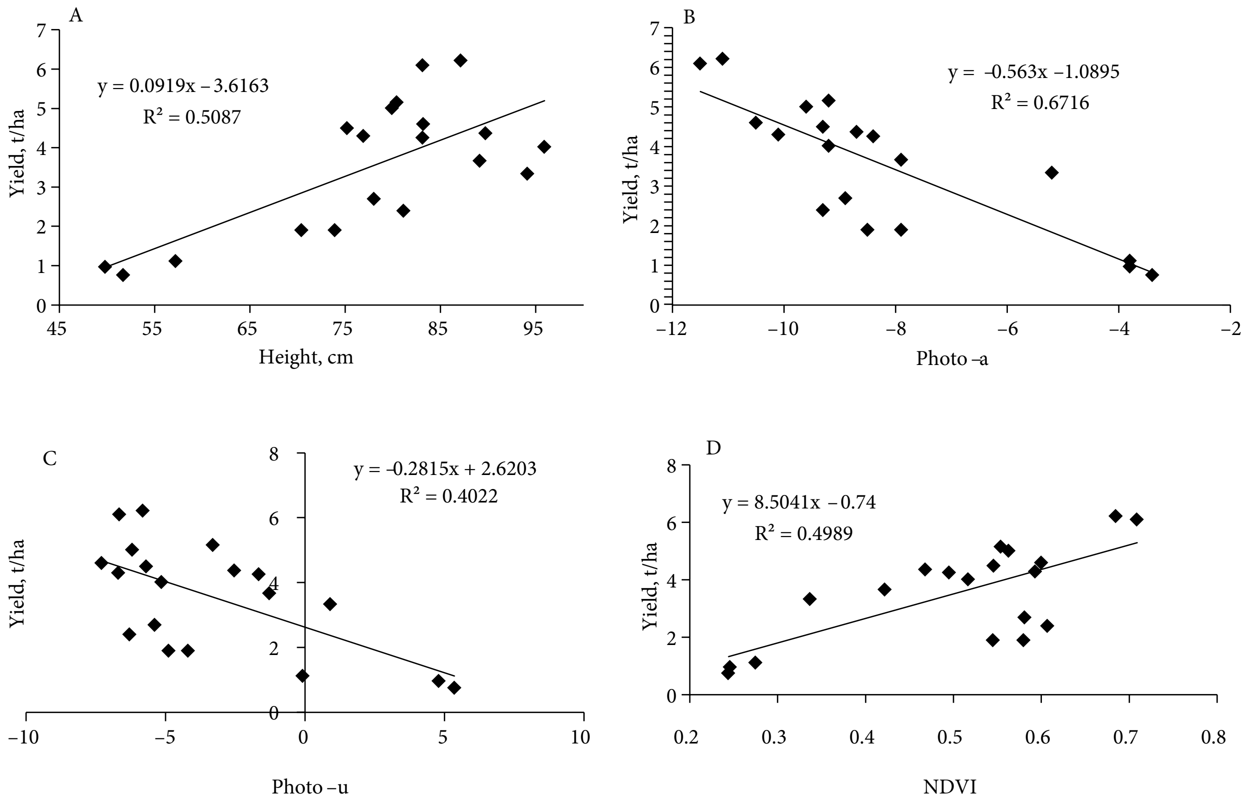

Figure 1. Relationship between grain yield and plant height (A), photo-a (B), photo-u (C), and NDVI (D) at grain formation stage in 19 independent yield trials.

irrigated conditions were 4739 kg/ha compared to 2324 kg/ha in rainfed conditions. Photo-a and photo-u reflected the difference in biomass and grain yield associated with this moisture stress through color difference, while NDVI reflected the same differences through spectral reflectance.

The coefficients of correlation between digital photo parameters and grain yield and between NDVI and grain yield in DYT-1 and -2 are presented in Table 2. There are clear differences between the 2 trials. Under irrigation, DYT-1 showed consistent, significant, and relatively high correlations of yield with photo-a (0.13–0.53), photo-u (0.19–0.58), and NDVI at early stages prior to flowering. These correlations were even more significant under rainfed conditions: 0.47–0.71 for photo-a and 0.50–0.72 for photo-u, respectively, indicating that the correlation of vegetative indices with grain yield was higher under moisture stress environments in this trial. DYT-2 gave different relationships between the same traits. Photo-a and photo-u correlated with grain yield only under irrigation prior to heading and at the late maturity stage. There was a significant correlation between NDVI and grain yield under irrigation after anthesis, but correlations of these vegetative indices with yield under rainfed conditions were only observed for the final 3 maturity stages.

The substantial differences between the 2 trials grown side-by-side in the same field are primarily due to variation in maturity range. In DYT-1, the difference between the earliest and latest heading genotypes was 10 days, while in DYT-2 it was 20 days. This affected grain yield, and the coefficient of correlation between days to heading and grain yield varied between 0.07 (irrigated) and 0.35 (rainfed) in DYT-1, while in DYT-2 it was negative and highly significant (–0.71 irrigated and –0.69 rainfed). The 5 highest-yielding entries in this trial were 7–10 days earlier compared to the 5 lowest-yielding (Table 3). Later-maturing genotypes remained green for longer times and this was reflected in photo parameters as well as NDVI, but they also suffered from higher temperatures and moisture stress and reduced yield. Photo-a and photo-u showed very similar correlation results in both trials, since they reflect crop greenness, though they come from different color spaces. Photo-b correlation directions are normally opposite to photo-a and u, since they reflect the plant's yellowness component. NDVI changes during vegetation from low to high to low (Figure 2D) and, therefore, correlation with yield in early stages may change its direction in later stages depending on the environment. In both DYTs, correlation between NDVI and yield was

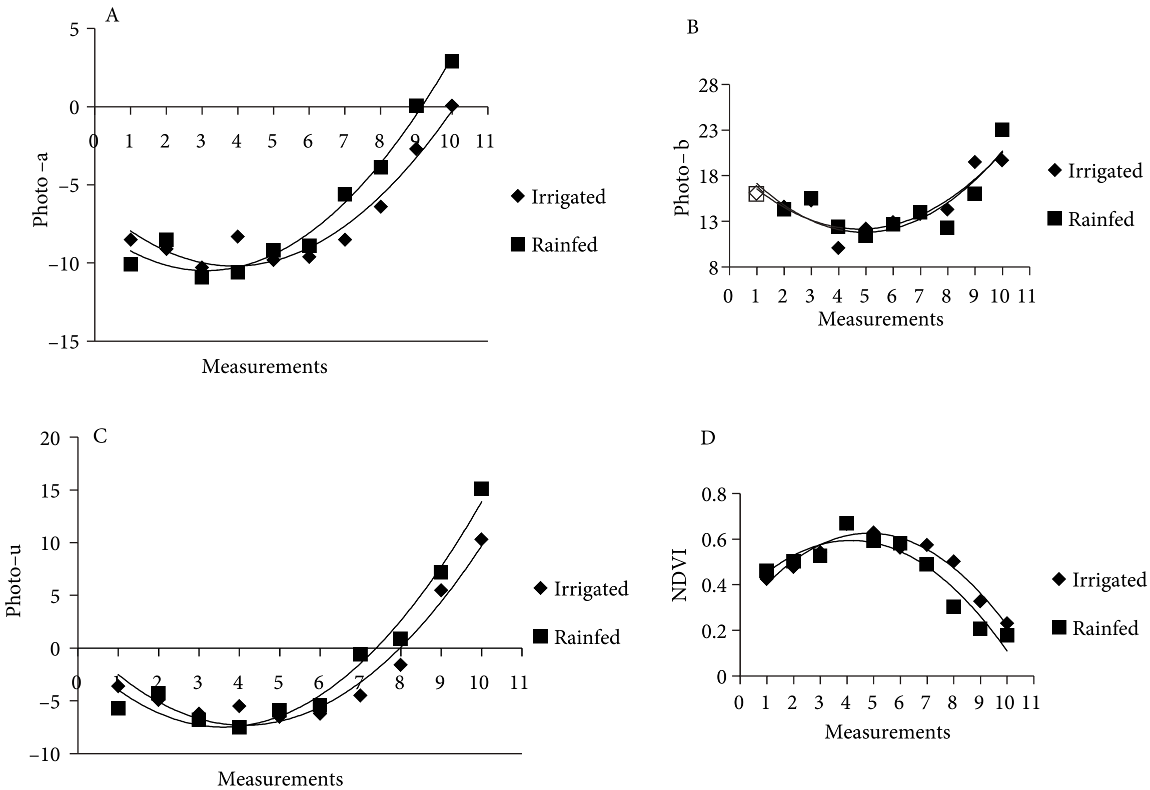

Figure 2. Variation of photo-a (A), photo-b (B), photo-u (C), and NDVI (D) under irrigated and rainfed conditions at different growth stages: 1: stem elongation; 2: booting; 3: preheading; 4: heading; 5: anthesis; 6: grain formation; 7: milk; 8: late milk; 9: wax; 10: late wax. DYT-1, Eskişehir, 2012.

positive until after anthesis, and then it changed to negative as the crop matured. This means that later and greener genotypes had higher NDVI but suffered from terminal moisture stress and high temperatures.

Figure 3 presents the changes of photo-a and NDVI for the highest- and lowest-yielding genotypes in DYT-1. The graphs clearly show that both vegetative indices differentiate between high- and low-yielding genotypes, starting from the early preheading stages, though the differences in photo-a and NDVI values between these 2 groups gradually disappeared after anthesis. Differences between the mean values of photo-a and NDVI at preanthesis are greater under moisture stress, compared to irrigated conditions. The same relationships for DYT-2 would show different results with a more pronounced NDVI gap between high- and low-yielding genotypes after anthesis.

The mean values of photo parameters, NDVI, and key agronomic traits for the high- and low-yielding genotypes in all trials used in the study are summarized in Table 3. All 23 trials had significant yield differences between the highest- and lowest-yielding genotypes. This difference was also reflected in significant differences in photo-a (9 trials), photo-u (8 trials), and NDVI (10 trials). Overall, less than 50% of the trials demonstrated significantly different vegetative indices between high- and low-yielding groups. Mean values of days to heading were significant in 10 trials, including 6 rainfed trials with different degrees of moisture stress. In all drought trials, later-developing germplasms suffered a yield penalty and were among the low-yielding groups.

4. Discussion

There are several options for active and passive sensors for estimating the biomass, nitrogen status, and other crop parameters that are utilized with variable degree of efficiency (Erdle et al, 2011). However, in this study, the parameters derived from NDVI and digital photos using BreedPix software were used as a simple and affordable option. It appears that utilization of photos has no disadvantage compared to NDVI. The photo-a and photo-u parameters predicted grain yield as accurately as NDVI. These parameters are similar to NDVI in their responses to the stage of measurement, as well as the diversity of the germplasms tested (especially in regard to maturity). Photo-b is less suitable for use as a vegetation

Table 2. Coefficients of correlation between grain yield and digital photo parameters and NDVI in drought trials 1 and 2 (irrigated and rainfed), 2012.

Plant stage	Photo-a		Photo-b		Photo-u		NDVI	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
DYT-1								
Stem elong.	–0.53**	–0.71***	0.15	0.53**	–0.58**	–0.72***	0.61***	0.72***
Booting	–0.44*	–0.68***	0.04	0.32	–0.50**	–0.70***	0.60**	0.69***
Preheading	–0.46*	–0.58**	0.07	–0.01	–0.50**	–0.64***	0.64***	0.66***
Heading	0.13	–0.50**	0.32	0.28	0.19	–0.52**	0.65***	0.68***
Anthesis	–0.56**	–0.47*	0.05	0.13	–0.59**	–0.50**	0.63***	0.67***
Grain form.	–0.61***	–0.48*	0.15	0.10	–0.65***	–0.53**	0.42*	0.71***
Milk	–0.45*	–0.36	0.09	0.28	–0.46*	–0.23	0.28	0.40*
Late milk	–0.21	0.49*	0.11	0.28	–0.08	0.47*	0.33	0.00
Wax	–0.05	0.29	0.20	0.14	0.03	0.24	–0.02	–0.47*
Late wax	0.02	0.25	–0.15	0.23	–0.06	0.24	–0.06	–0.40*
DYT-2								
Stem elong.	–0.57**	–0.37	0.49*	0.38	–0.56**	–0.41*	0.36	0.31
Booting	–0.47*	–0.38	0.36	0.32	–0.43*	–0.38	0.32	0.34
Preheading	–0.57**	–0.29	0.33	0.22	–0.53**	–0.27	0.30	0.04
Heading	0.33	–0.10	0.55**	0.37	0.43*	–0.16	–0.29	–0.05
Anthesis	0.10	–0.13	0.39*	0.45*	0.21	–0.20	–0.34	–0.31
Grain form.	0.17	–0.19	0.04	0.40*	0.25	–0.22	–0.59**	–0.28
Milk	0.29	0.11	0.04	0.39*	0.36	0.14	–0.62***	–0.31
Late milk	0.32	0.28	0.06	0.38	0.29	0.48*	–0.46*	–0.29
Wax	0.50**	0.30	0.33	0.48*	0.51**	0.48*	–0.49*	–0.49*
Late wax	0.55**	0.22	0.55**	0.33	0.58**	0.32	–0.56**	–0.60**

*, **, ***: Significant at P < 0.05, 0.01, and 0.001, respectively.

index, probably due to the fact that its high values reflects plant yellowness while low values indicate plant bluishness and, therefore, it is not helpful in identifying more vigorous and green genotypes. These conclusions concur with those of Casadesus et al. (2007), whose software was used for this study. The availability and practicality of digital cameras make them ideally suited as an additional source of information in breeding programs, especially in developing countries where modern phenotyping tools are not yet readily available. On the other hand, BreedPix software, though not highly challenging, requires time and training to utilize efficiently. It is also not maintained on a website for download with clear explanation and instructions to use.

Our results showed that NDVI significantly correlated with grain yield in approximately 50% of 120 observations across 23 trials × environments with contrasting moisture availability and yield, thereby confirming the suitability of using vegetative indices (such as digital photo parameters and NDVI) as additional selection criteria for grain yield in breeding programs. The predictive value of NDVI for grain yield and other traits can be improved via some modifications in NDVI calculations, such as degree of NDVI reduction after anthesis (Hazratkulova et al., 2012), NDVI ratio before and after anthesis, and cumulative NDVI after anthesis (Li et al., 2011). There is value in relating spectral reflectance parameters to canopy and air temperature to reduce the effect of weather and differences related to maturity variation between genotypes (Kimball et al., 2012). All these approaches enhance the predictive power of vegetation indices and can also be applied to photo parameters.

The optimal stages for measuring NDVI vary depending on the germplasm and environment (Marti et al., 2007; Li et al., 2011). Breeding programs usually pay little attention to field observations prior to heading, as there is limited

Table 3. Agronomic traits, digital photo parameters, and NDVI of the 5 highest- (HY) and lowest-yielding (LY) entries in the trials.

Trial	Site	Year	Environment	Stage	Grain yield, t/ha[1]		Photo-a		Photo-u		NDVI		Days to heading		Plant height	
					5HY	5LY	5HY	5LY	5HY	5LY	5HY	5LY	5HY	5LY	5HY	5LY
HIST-1	Konya	2008	Rainfed	Heading	4.77^{a}	3.25^{b}	4.75	4.30	3.86	3.97	0.50	0.43	139.2	140.0	90.9	86.1
	Eskişehir		Rainfed	Heading	3.74^{a}	2.17^{b}	13.93	11.08	9.14	6.91	0.72	0.70	138.8	139.8	86.4	81.1
	Konya	2009	Rainfed	Heading	5.26^{a}	4.04^{b}	19.08	19.35	14.25	14.76	0.74	0.71	138.3	142.3	104.8	109.3
	Eskişehir		Rainfed	Heading	5.19^{a}	4.04^{b}	15.41	16.46	10.50	11.05	0.70	0.69	-	-	99.3	103.3
HIST-2	Konya	2010	Full irrigation	Grain form	5.29^{a}	3.38^{b}	8.92^{a}	8.11^{b}	2.59	1.59	0.73^{a}	0.68^{b}	132.1	133.9	90.9	86.7
			Supplementary irrigation	Grain form	4.52^{a}	2.85^{b}	8.39^{a}	7.20^{b}	2.01	0.38	0.77^{a}	0.73^{b}	133.1	135.9	89.4	85.2
	Eskişehir	2012	Rainfed	Heading	1.86^{a}	0.36^{b}	11.22	9.81	5.79	5.42	0.62	0.58	132.0^{a}	138.5^{b}	61.2^{a}	53.4^{b}
			Irrigated	Heading	5.13^{a}	2.57^{b}	8.10^{b}	10.14^{a}	5.10^{b}	7.32^{a}	0.56^{b}	0.62^{a}	143.4	146.4	89.5^{b}	106.0^{a}
			Rainfed	Anthesis	4.01^{a}	2.68^{b}	9.78	9.95	6.78^{a}	5.76^{b}	0.32	0.34	141.8^{b}	144.9^{a}	87.5^{b}	96.0^{a}
AYT-3	Konya	2010	Full irrigation	Grain form	7.00^{a}	5.14^{b}	14.47^{b}	15.87^{a}	11.33^{b}	12.47^{a}	0.75^{b}	0.77^{a}	134.5	133.1	86.3	82.5
			Supplementary irrigation	Anthesis	6.02^{a}	4.08^{b}	11.67	12.41	8.30	8.37	0.75	0.77	132.2^{b}	135.4^{a}	80.4	76.0
			Rainfed	Anthesis	1.53^{a}	0.36^{b}	6.62	7.65	1.26	1.44	0.41^{b}	0.50^{a}	134.0^{b}	138.4^{a}	51.8^{a}	44.7^{b}
AYT-5			Full irrigation	Grain form	7.06^{a}	5.47^{b}	10.93	11.64	5.50^{b}	6.49^{a}	0.69	0.71	132.2^{b}	134.5^{a}	86.7	89.7
			Supplementary irrigation	Grain form	5.00^{a}	3.48^{b}	9.41^{a}	6.94^{b}	3.09^{a}	0.54^{b}	0.55^{a}	0.42^{b}	135.6^{a}	133.1^{b}	88.0^{a}	78.4^{b}
			Rainfed	Anthesis	1.30^{a}	0.41^{b}	5.78	6.22	1.07	1.83	0.42	0.45	134.9^{b}	137.5^{a}	56.2^{a}	47.6^{b}
DYT-1	Eskişehir	2012	Irrigated uncut[2]	Grain form	5.63^{a}	4.35^{b}	10.74^{a}	8.27^{b}	7.54^{a}	4.64^{b}	0.61^{a}	0.55^{b}	146.7	147.0	85.5	74.5
			Irrigated cut	Grain form	5.04^{a}	3.83^{b}	9.75^{a}	7.76^{b}	6.04^{a}	4.18^{b}	0.59^{a}	0.48^{b}	149.6	147.5	78.5^{a}	65.0^{b}
			Rainfed uncut	Grain form	3.99^{a}	1.52^{b}	10.10^{a}	8.23^{b}	7.34^{a}	5.00^{b}	0.62^{a}	0.53^{b}	143.5^{b}	146.9^{a}	76.0^{b}	79.5^{a}
			Rainfed cut	Grain form	2.69^{a}	1.28^{b}	9.16^{a}	7.46^{b}	5.15	4.02	0.58	0.50	149.2	148.1	75.5	69.5
DYT-2			Irrigated uncut	Grain form	5.20^{a}	3.83^{b}	10.39	10.89	6.97	7.91	0.56^{b}	0.63^{a}	143.7^{b}	153.1^{a}	79.5	78.7
			Irrigated cut	Grain form	4.79^{a}	3.84^{a}	10.39	10.16	7.00	6.61	0.58	0.60	152.7	153.3	79.5	75.0
			Rainfed Uncut	Grain form	3.47^{a}	1.53^{b}	9.47	9.04	6.63	6.04	0.60	0.63	145.2^{b}	152.0^{a}	83.0	78.7
			Rainfed cut	Grain form	3.80^{a}	1.07^{b}	8.01	8.97	4.67	5.49	0.56	0.61	150.8	154.7	72.5	72.5

[1]Mean values designated by different letters are significantly different at $P < 0.05$.
[2]Additional treatment for DYT: removal of aboveground biomass prior to stem elongation to apply more stress on crop. Uncut: without biomass removal; cut: biomass removed.

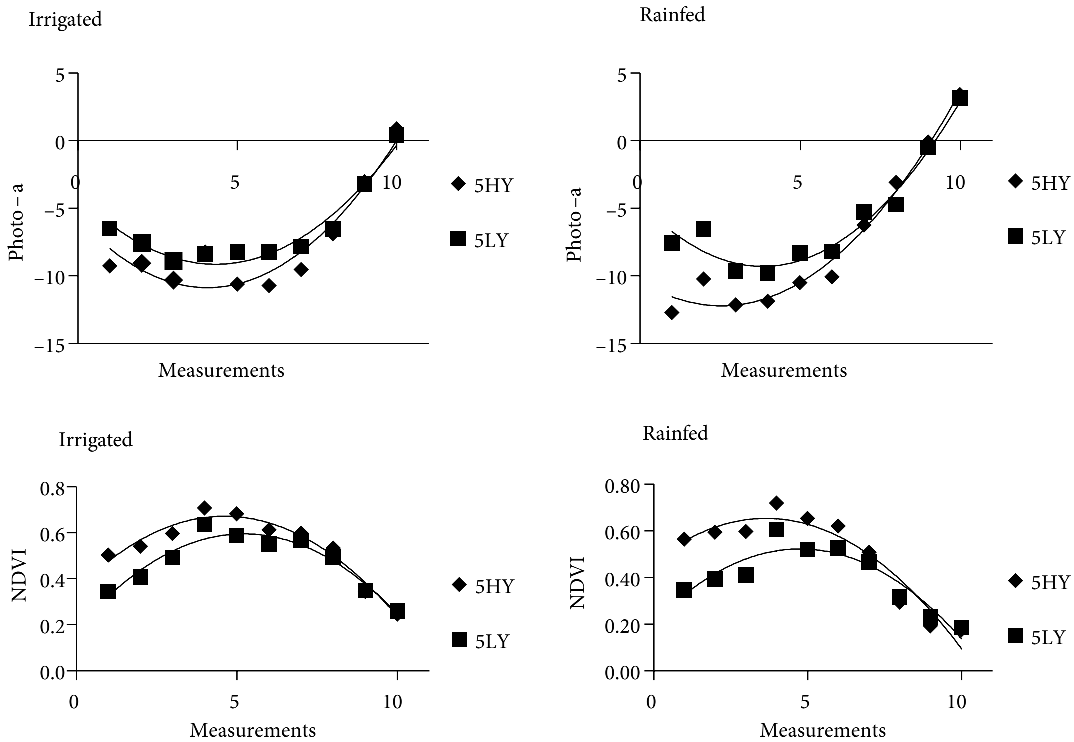

Figure 3. Variation of photo-a and NDVI at different growth stages for the 5 highest- (5HY) and 5 lowest-yielding (5LY) entries in DYT-1 under irrigated and rainfed conditions (Eskişehir, 2012).

visual variation between different genotypes, but our results suggest the importance of early measurements of spectral indices from stem elongation to anthesis, since substantial differences were observed for NDVI and photo parameters between high- and low-yielding genotypes. We generally agree with the conclusions of Aparicio et al. (2002) that spectral vegetation indices accurately predict crop status when analyzed across a broad range of growth stages, environments, and genotypes. However, their value as indirect genotypic selection criteria lacked predictive values for specific environment/growth stage combinations and requires further fine-tuning. One important issue of using the vegetative indices is their nonlinear variation during vegetation, which results in changes of correlation directions from negative to positive depending on the crop stage. This requires a better understanding of what biological processes and differences between the genotypes are reflected at the specific time of measurement. Multispectral cameras may provide higher definition and association with productivity, but their cost is prohibitive for many breeding programs in the region. In general, as the technology develops, more advanced sensor tools will be available and may improve the efficiency of selection.

From the practical wheat breeding perspective, there is limited value in using spectral vegetation indices for evaluation of biomass and grain yield in replicated yield trials at advanced breeding stages. Normally, the precision of replicated trials is high enough for an effective selection based on grain yield and other agronomic traits. The improvement of selection efficiency is needed in unreplicated trials, as well as in head-rows and segregating populations, to identify the most promising lines and crosses. Both digital cameras and the portable Green-Seeker allow measurements on small plots, including one-row plots. The germplasms evaluated for NDVI and photo parameters need to be grouped according to maturity, and possibly plant height, to reduce the effect of these traits on spectral reflectance. Overall, digital image parameters and NDVI may serve as useful tools for improving selection efficiency of grain yield under both irrigated and moisture stress conditions.

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