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Developing new hyperspectral vegetation indexes sensitive to yield and evapotranspiration of dry beans

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Abstract: Dry bean (*phaseolus vulgaris L.*) field experiment was carried out under the subhumid climatic conditions of Bafra, Turkey, to evaluate the possibilities of using hyperspectral reflectance data for estimating yield and water consumption. Three irrigation management treatments that depend on monitoring soil water content and one rain-fed treatment were subjected to dry beans arranged in a randomized complete block design with three replications. In addition to soil water measurements, hyperspectral reflectance observations were made throughout the dry beans' growing season. Actual crop evapotranspiration values were calculated by using a detailed soil water balance approach. After smoothing the hyperspectral reflectance data, the first and second derivatives of spectra were calculated. Statistical analysis methods were applied to determine the most sensitive wavelengths to dry bean yield and evapotranspiration (ETa) for developing new spectral indexes based on measured spectral data. Furthermore, some of the well know spectral vegetation indexes were calculated. Statistical comparison between spectral indexes and yield showed that the difference of the second derivative of spectra in 749 and 697 nm could be a good indicator ($r = 0.998$ and $RMSE = 0.027$) for estimating dry bean grain yield. Similarly, the difference of the second derivative of spectra in 1003 and 717 nm gave the most significant statistical comparison result ($r = 1.0$ and $RMSE = 3.0$) for ETa.

Key words: Hyperspectral reflectance, dry bean, evapotranspiration, spectral index, derivative analysis

1. Introduction

Dry bean is a water-sensitive crop, according to its yield response factor (Ky = 1.1) reported by Doorenbos and Kassam (1979) and midseason crop coefficient (Kcmid = 1.15) given by Allen et al. (1998). Furthermore, some experimental studies show that water stress affects crop evapotranspiration, yield, and quality of dry beans (Boutraa and Sanders, 2001; Efetha et al., 2011; Trapp et al., 2015; Liang, et al., 2021). However, because the total length of the growing season is relatively shorter than that of some other crops with high water consumption, total dry bean evapotranspiration (ETa) and irrigation water requirement of dry beans are relatively low.

Monitoring and evaluation of plant physiological symptoms representing water status help improve irrigation water management. According to the results of some studies on dry beans about physiological aspects of drought, changing root structure and stomatal closure play essential roles during periods under water-limited conditions (Barradas et al., 1994; Boshkovski et al., 2020). Ninou et al. (2013) stated that maximum dry bean grain yield could be associated with full irrigation. Like other agricultural crops, water stress can cause a decrease in the leaf chlorophyll content of common beans (Endres et al., 2010; Köksal et al., 2010).

Spectral reflectance at various wavelengths of the electromagnetic spectrum at leaf or canopy level could be affected by some crops' physiological specifications (Main et al., 2011; Meacham-Hensold et al., 2019; El-Hendawya et al., 2019; Chandel et al., 2021). Spectral reflectance data helps to understand crop properties affected by fertilizer applications, water conditions, diseases, and insects (Pishchik et al., 2016; Kovar et al., 2019). Zhou et al. (2016) concluded that the correlations between remotely sensed indexes and bean yield were significant, and this type of data has a substantial potential to monitor crop stress.

The present study was planned to evaluate the relationships between ETa, dry bean yield, spectral reflectance, the first and second derivative of spectra at various wavelengths between 325 nm and 1075 nm. Field experiments were conducted consist of four different soil water management strategies. As a second aim, new

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spectral indexes depending on spectral reflectance, first and second derivatives of spectra were developed to estimate ETa and yield by using statistical analysis.

2. Materials and methods

Dry bean (phaseolus vulgaris L.) field experiment was carried out at Research Station of Black Sea Agricultural Research Institute (BSARI), located in Bafra, Samsun, Turkey (41°36'8"N, 35°55'8"E), in 2010. This region has a subhumid climatic condition. The annual total average precipitation amount is 694 mm, the mean temperature is 14.4 °C, and the mean relative humidity is 72.7%. The texture of the trial soil profile of 120 cm was clay. The water storage capacity of this soil was nearly 147.0 mm $m^{-}1$. Irrigation water was applied via a drip irrigation system. In this research, a variety of dry beans (Phaseolus vulgaris L.) named Zulbiye was used, which were developed by BSARI.

A randomized block design with three replications was used as an experimental method. Although plot dimensions were 3.5 × 6.0 m for sowing, to eliminate boundary effects, harvests were made from an area with dimensions of 2.1 × 5.0 m. Four different water management strategies (S1, S2, S3, and S4) were applied to dry bean crops. Decisions of each irrigation application for S1 treatment were made when nearly 30% (moisture allowable deficit; MAD) of soil water depleted within the 60 cm soil depth. Thus, the irrigation amount for each application was equal to the difference between field capacity (FC) and soil water content. Irrigation timing of S2 and S3 treatments was the same with S1, but they received 30% and 60% less water than S1, respectively. During development, late and end period irrigation was not applied to S4 treatment (rainfed). A well-calibrated neutron probe device was used to monitor the volumetric soil water content of a profile of 120 cm. Based on amounts of irrigation water, rainfall, and soil water content data, ETa of each irrigation treatment were calculated by using the soil water balance residual method given by Evett (2002). Fertilizers were applied according to soil chemical analysis as 0.1 t $ha^{-}1$ N and 0.06 t $ha^{-}1$ P2O5. Dry bean seeds were sown on May 17, 2010, with a row distance of 70 cm, and there was a 30 cm gap between the two consequence crops on a row. Harvest was made on September 29, 2010. The yield of each experimental plot was calculated for 12% moisture content of dry bean grains. Also, the weight for 100 grain was calculated by using the same method.

Hyperspectral radiance and irradiance values between wavelengths of 325–1075 nm measured using a spectroradiometer (model Field Spec Pro FR, ASD, Boulder, USA), at a solar zenith angle between 45° and 50° on cloudless days. Solar irradiance was measured before each radiance measurements by using a 50 × 50 cm spectralon panel. A total of 13 spectral measurements were made from July 05 to August 31. Spectral reflectance (Eq. 1), first derivative (Eq. 2) and second derivative (Eq. 3) of the spectra values were calculated according to equations given in Table 1. Four different spectral vegetation indexes were calculated by using smoothed spectral reflectance values. Equations used to calculate spectral vegetation indexes are also shown in Table 1.

To determine appropriate wavelengths for spectral reflectance, the first derivative of spectra and second derivative of spectra, for estimating yield and ETa of dry beans, linear regression analysis was made. After that, by using selected wavelengths, several equations were developed.

Table 1. Equations used for smoothing spectral reflectance data, calculation of first and second derivatives of spectra, and spectral vegetation indexes.

Equation number	Parameter	Equation	Reference
1	Smoothed spectral reflectance	$R\lambda_i = 0.5Ref\lambda_i+0.25Ref\lambda_{i+1}+0.25Ref\lambda_{i-1}$	Danson et al. (1992)
2	First derivative of spectra	$\rho = (R\lambda_i - 2\rho\lambda_j)/\Delta\lambda$	Shibayama et al. (1993)
3	Second derivative of spectra	$\delta = (\rho\lambda_i - 2\rho\lambda_j + p\lambda_k)/(\Delta\lambda)^2$	Tsai and Philpot (1998)
4	SR (simple ratio)	R_{800} / R_{680}	Aparicio et al. (2000)
5	NDVI (normalized difference vegetation index	$(R_{800}-R_{680}) / (R_{800}+R_{680})$	Tucker (1979)
6	SAVI (soil adjusted vegetation index)	$(1+L)(R_{800}-R_{680}) / (R_{800}+R_{680}+L)$	Huete (1988)
7	DVI (difference vegetation index)	$R_{800}-R_{680}$	Tucker (1979)

Ref; represents reflectance at a wavelength.
Δ; represents the difference between two wavelength.
λ; represents a wavelength.
$\Delta\lambda= \lambda_i-\lambda_j = \lambda_j-\lambda_k = 3.0$ and $\lambda_i<\lambda_j<\lambda_j$.

3. Results and discussion

3.1. Irrigation and crop evapotranspiration

Seasonal irrigation water amounts applied for S1, S2, S3, and S4 treatments were 429.0, 305.0, 180.0, and 15.0 mm, respectively. The total rainfall amount for this period was measured as 377.0 mm. Maximum seasonal ETa values belonged to S1 trial plots (average 616.0 m) and ETa of S2, S3 and S4 were calculated as 528.0, 431.0, 279.0 mm, respectively.

3.2. Yield and weight of grains

In this research, the yield of dry beans was dramatically affected by irrigation levels. By choosing a fully irrigation strategy of S1 treatment 1.825 t ha^{-}1 dry beans could be produced. Also, 70.0% and 30% of fully irrigation amount can prove nearly 1.228 t ha-1 and 1.024,0 t ha^{-}1 yield, respectively. Dry beans produced under rainfed conditions (S4) were 0.651 t ha^{-}1. Research results of the grain weight of 100 dry beans are considered a yield quality indicator and water consumption affect this parameter. 100 grains weight of dry beans of S1, S2, S3, and S4 treatments were 67.9, 63.1, 62.9, and 61.6 gr, respectively. Rios et al. (2013) showed that the maximum castor bean yield was obtained by irrigation strategy, which increases soil moisture near field capacity and water stress caused a reduction in grain yield. Efetha et al. (2011) offered more frequent irrigation and keeping the roots most for maximizing dry bean yield and thousand seed weights. Similar findings related to yield response of dry bean to water stress were reported by Webber et al. (2006); Niou et al. (2013) and Mathobo et al. (2017).

3.3. Spectral reflectance and derivatives

Figure 1 gives seasonal average smoothed spectral reflectance, first and second derivatives of spectra, obtained from 13 spectral measurements, between 325 and 1075 nm wavelengths. The graphical aspect of dry bean spectral reflectance was low between 325 and 700 nm and high at 740–1075 nm (Figure 1a). Because water stress affected the vegetation levels of crops, spectral reflectance values differed from one irrigation treatment to the other in these two separate electromagnetic spectrum regions. At the wavelength of 560 nm, all irrigation treatments' spectral reflectance was peaked, and they were very close to each other. However, between 600 and 700 nm wavelengths, the array of spectral reflectance values of irrigation treatments from high to low was S4, S3, S2, and S1.

The first derivative of spectra gives valuable information related to vegetation level, which occurred according to the water stress degree of dry beans (Figure 1b). There are four spectral regions of the first derivative of spectra that reflected the difference among the treatments. The wavelengths belong to peak values calculated for these four regions were 524 nm, 572 nm, 721 nm, and 932 nm. The first derivative of spectra values of spectral regions centered with 524 nm and 721 nm were concordant with irrigation levels.

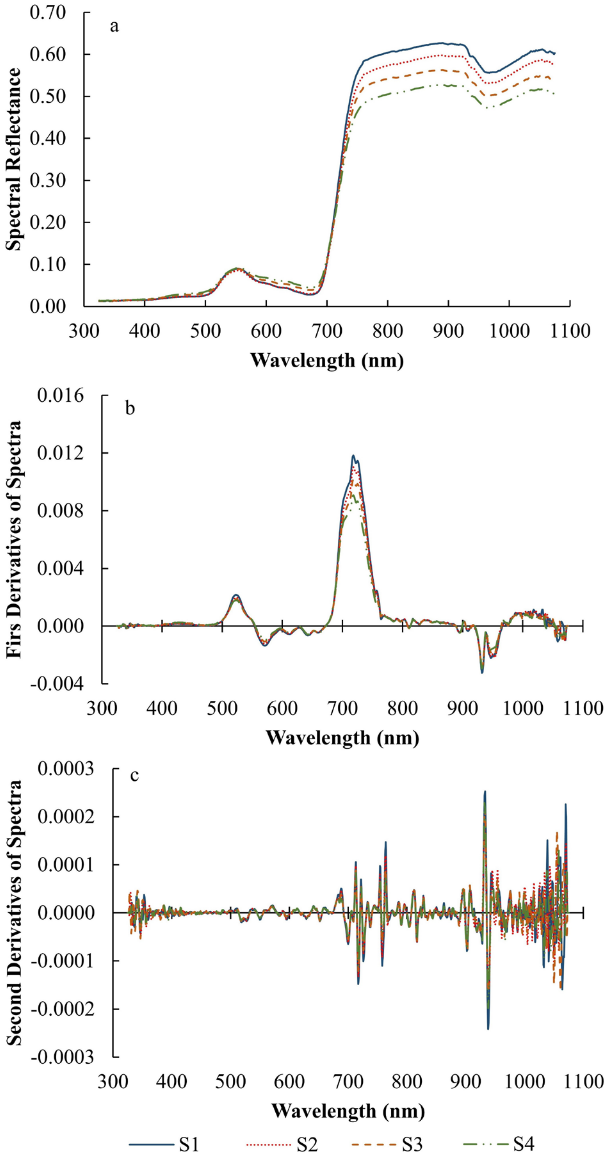

Figure 1. Seasonal average of smoothed spectral reflectance (a), first (b), and second derivative (c) of spectral between 325 and 1075 nm wavelengths.

This trend was the opposite for the spectral regions in which the first derivative of spectra values peaked at 572 nm and 935 nm. Spectral regions of the electromagnetic spectrum sensitive to vegetation changes due to the water levels were different in the second derivative of spectra than the first derivative of spectra (Figure 1c). There are more than 10 different spectral regions in which the second derivative of spectra has peak values. However, some of these spectral regions' array of these values were concordant with irrigation strategies. Thus, their correlations were statistically significant.

3.4. Statistical comparisons and new equations for yield and evapotranspiration

Variation of correlation coefficients among the 325–1075 nm wavelengths, calculated for linear comparisons between yield, ETa, and spectral reflectance, first and second derivatives of spectra were given in Figure 2, graphically. Each of these graphs also include four horizontal lines that indicating $p < 0.01$ ($r = 0.917$ and $r = -0.917$) and $p < 0.05$ ($r = 0.811$ and $r = -0.811$) statistical significance levels for linear relationships (both positive and negative directions). Numerous wavelength combinations were calculated based on r values given in Figure 2, and all of them were compared with yield and ETa separately. For both yield and ETa, the highest r and the lowest RMSE were

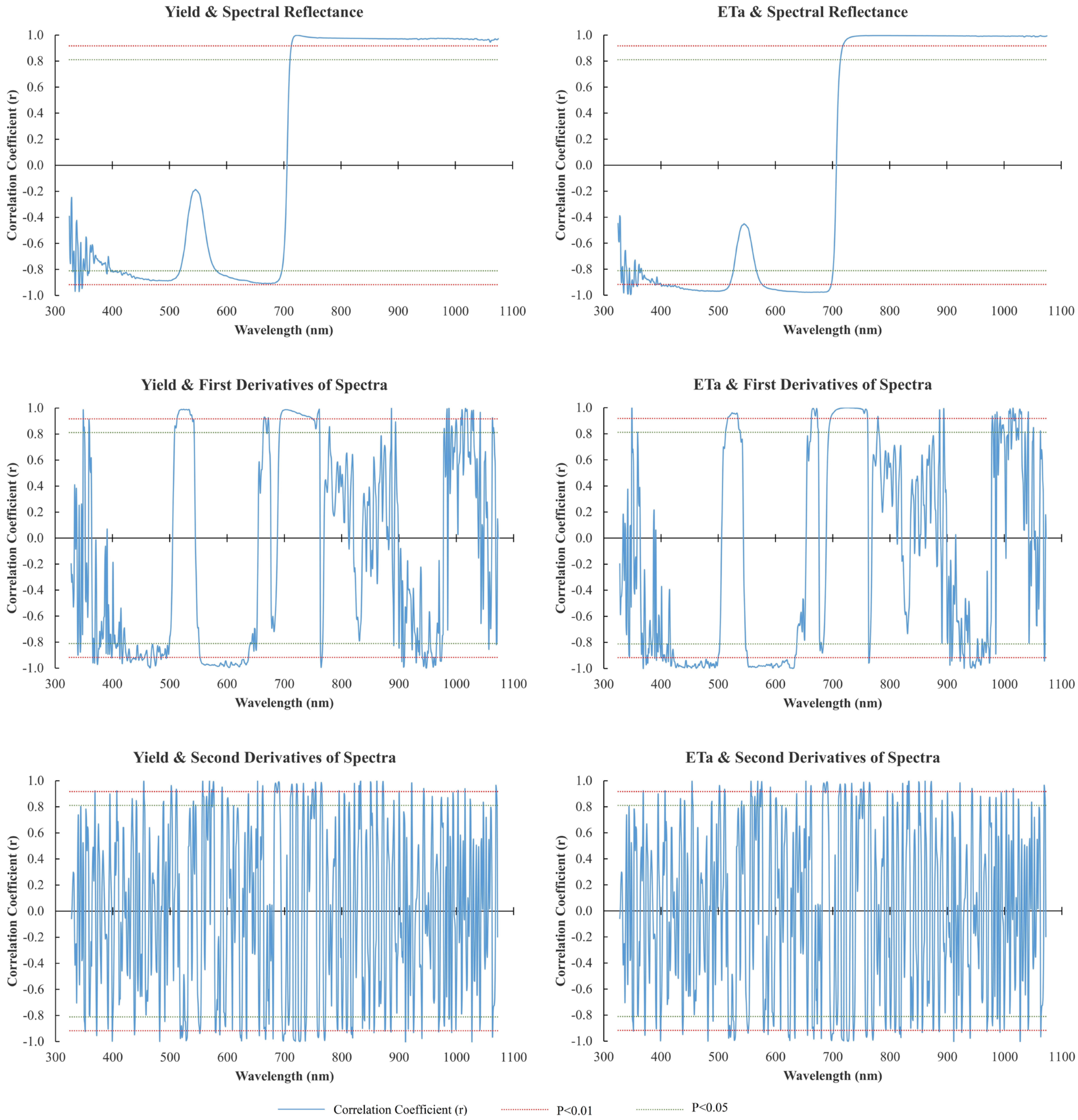

Figure 2. Fluctuations of correlation coefficients among 325–1075 nm wavelengths calculated for linear relationships between yield, evapotranspiration, smoothed spectral reflectance, first and second derivatives of spectra.

obtained by using selected wavelengths based on the second derivative of spectra. The difference between the second derivative of spectra of 749 and 697 nm wavelengths could be a new and good indicator for estimating dry beans yield. Accordingly, the derivative dry beans yield index (DBYI) could be formulated as given in Eq. 8 ($R^2 = 0.996$; RMSE = 0.027 t ha^{-1}; Yield= 66136 DBYI – 1.47). The difference between the second derivative of spectra in 1003 and 717 nm wavelengths could be offered as a new water indicator, called derivative dry beans water index and formulated as in Eq. 9 ($R^2 = 0.999$; RMSE = 3.0 mm; ETa = 3914726 DBWI – 44.3).

Since multispectral data is not suitable for calculating the first and second derivatives of spectra, equations developed for spectral reflectance are required to estimate dry beans yield and ETa. Multispectral bands, including 724 and 497 nm wavelengths, could be used to calculate the reflectance-based dry beans yield index (RBYI) (Eq. 10). Using RBYI, dry beans yield ($R^2 = 0.98$; RMSE = 0.055 t ha^{-1}; Yield = 21.921 RBYI – 5.40) could be estimated. Similarly, a new index called reflectance-based dry beans water index (RBWI) (Eq. 11) was developed, depending on 970 and 497 nm wavelengths ($R^2 = 0.986$; RMSE = 15.0 mm; Yield = 3620.3 RBYI – 1302.5), to estimate the seasonal evapotranspiration level of dry beans.

$$DBYI = \delta749 - \delta697 \quad (8)$$

$$DBWI = \delta1003 - \delta717 \quad (9)$$

$$RBYI = \delta724 - \delta497 \quad (10)$$

$$RBYI = \delta970 - \delta497 \quad (11)$$

In this study, spectral indexes abbreviated as SR, NDVI, SAVI, and DVI were also investigated for yield and ETa estimation of dry beans. The highest correlation for yield was determined with DVI as 0.937 (RMSE = 0.107 t ha^-1). The relationship between ETa and DVI was also significant. The r of this comparison was the highest one (r = 0.993 and RMSE = 10.8 mm) among the other spectral indexes investigated in this study. Moreover, statistical comparisons of these indexes showed that the two new indexes offered above are statistically more significant than those for dry bean yield and ETa estimation.

The results of this study are concordant with the findings of previous researches on beans and some other crops. El-Hendawya et al. (2019) and El-Hendawya et al. (2017a) reported significant relationships between spectral reflectance indices and water status-related phonological parameters of spring wheat. Elsayed et al., (2021) was used artificial intelligence methods to improve statistical relationships of spectral reflectance-based indexes and some plant traits (yield and water-related parameters. Another study was made by Bal et al. (2021) on winter wheat and spectral reflectance data and they found water stress affected spectral signatures and spectral indexes. A detailed review about the use of spectral reflectance-based indexes to detect irrigated areas was given by Karthikeyana et al. (2020). Hinojosa et al. (2019) found a significant statistical relationship between quinoa yield and NDVI. Candel et al. (2021) determined five sensitive wavelengths to wheat water stress as 974, 1195, 1455, 1791, and 1935 nm. Similarly, El-Hendawy et al. (2017b) offered the use of combined spectral indexes depending on near-infrared and shortwave infrared region spectral reflectance for wheat. According to a study carried out on soybean, spectral reflectance indexes could be useful for estimating yield and water status (Elmetwalli et al., 2020). Boshkovski et al. (2020) and Boshkovski et al. (2021) determined significant relationships between spectral reflectance indexes and common beans' plant tissue mineral elements, photosynthesis, and enzyme activity under water stress.

4. Conclusion

The results of this study showed that water stress affects both yield and grain quality of dry beans, and maximum yield and grain weight could be obtained by full irrigation (429 mm). Under drip irrigation conditions, the seasonal ETa of dry beans was 616.0 mm. In order to make a suitable irrigation schedule, rainfall amounts must be considered. Crop vegetation specifications and hyperspectral reflectance signatures were changed due to different levels of ETa and vegetation growth situations. This variation was offered a significant opportunity to estimate the yield and ETa of dry beans using remotely sensed data.

According to the result of this study related to hyperspectral reflectance data, four new indexes (DBYI, DBWI, RBYI, and RBWI) were developed for yield and evapotranspiration estimation of dry beans. These new indexes could be valuable tools for yield and water use estimation and classification of dry beans.

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