

## Estimation of green bean yield, water deficiency and productivity using spectral indexes during the growing season

Eyüp Selim Köksal · Tekin Kara · Mehmet Apan · Haluk Üstün · Adem İlbeyi

Published online: 4 October 2008  
© Springer Science + Business Media B.V. 2008

**Abstract** Field experiments were carried out in the 2004 and 2005 growing seasons on drip irrigated dwarf green beans (*Phaseolus vulgaris*, humilis). Soil water content (SWC), spectral reflectance and yield were monitored. Based on these data crop evapotranspiration (ET<sub>c</sub>), soil water deficit index (SWDI), water use efficiency (WUE) and four separate spectral indexes were calculated. In order to determine use opportunities of spectral indexes for estimation of yield, SWDI and WUE, some statistical analyzes were made. Results showed that spectral indexes could be used for monitoring of yield, SWDI and WUE. Especially, Soil Adjusted Vegetation Index (SAVI) had the highest correlations with all three of the parameters. The estimation procedure which was given in this study has a potential use either during, or at the end of the growing season. Estimated values of WUE and SWDI were 3.2 (kg m<sup>-3</sup>) and 0.12, respectively, through SAVI and the given procedure, indicates the optimal water use and yield conditions for dwarf green beans. At this situation, probably ET<sub>c</sub> was 580 mm and yield was 25.5 t ha<sup>-1</sup>.

**Keywords** Irrigation management · Soil water deficit index · Spectral reflectance · water use efficiency

### Abbreviations

ET<sub>c</sub> Crop Evapotranspiration  
ET<sub>p</sub> Potential Crop Evapotranspiration  
LAI Leaf Area Index  
NDVI Normalize Difference Vegetation Index  
SAVI Soil Adjusted Vegetation Index  
SE Standard Error  
SR Simple Ratio

---

E. S. Köksal (✉) · T. Kara · M. Apan  
Agricultural Faculty, Agricultural Structures and Irrigation Department, Ondokuz Mayıs University,  
Kurupelit, Samsun, Turkey  
e-mail: eselim@omu.edu.tr

H. Üstün · A. İlbeyi  
Ankara Soil and Water Resources Research Institute, Lodumlu, Ankara, Turkey

SWC	Soil water content
SWDI	Soil Water Deficit Index
TAM	Total Available Soil Moisture
WI	Water Index
WUE	Water Use Efficiency

## Introduction

Agricultural water use plays the most critical role in water resources management all around the world. Currently, 17% of the total agricultural land is irrigated and 40% of food and fiber demand are supplied from this irrigated land with the use of 70% of available water resources (Anonymous 1996). In Turkey, 36% of available water resources are under control and nearly 74% of this water is used by 25% of irrigable agriculture land. To increase the percentage of controlled water resource requires greater investment. Moreover, improving irrigation efficiency will enable an increase in the proportion of irrigated land with the same water. However, Howell (2001) stated that, in some cases, increasing irrigation efficiencies alone may not result in new water for allocation unless the consumptive use part of the diverted water is actually reduced.

Monitoring the water use in the field is important to develop effective precautions and for this purpose some indicators are required. Yield, Water Use Efficiency (WUE) and Soil Water Deficit Index (SWDI) are some of the principal indicators related to water use and productivity of irrigated agriculture. Sinclair et al. (1984) described WUE as crop yield per unit of water use. Bos (1980, 1985) recommended that WUE for irrigation be based on the yield production above the rainfed or dryland yield divided by the net crop evapotranspiration (ET<sub>c</sub>) difference for the irrigated crop, which he called the yield/ET ratio. Irrigation remains vitally important worldwide as a means to enhance production and increase WUE (Howell 2001). In addition to irrigation water, some agricultural practices affect the WUE. Cotton furrow operation system (Ünlü et al. 2007), wheat nitrogen fertilization (Pala et al. 2007; Angus and van Herwaarden 2001; Oweis et al. 2000), potatoes irrigation frequency (Kang et al. 2004), genetic structure of seed for barley (Sivamani et al. 2000), can be given as examples. In addition, Howell (2001) stated that, many agronomic, engineering, and management technologies can reduce nonproductive water use in irrigated agriculture. SWDI, which depends on the ratio between the actual and potential ET<sub>c</sub>, is essentially an indicator of crop water use (Colaizzi et al. 2003a,b). It is necessary to define the potential and actual ET<sub>c</sub> for calculation of the SWDI. Actual ET<sub>c</sub> can be determined through soil water balance or estimated based on related methods (Allen et al. 1998).

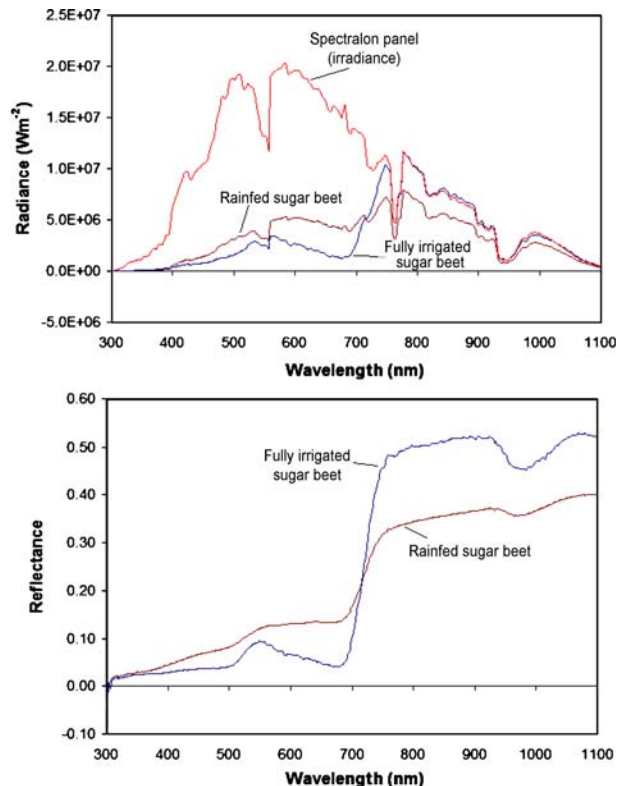
WUE and SWDI calculations could be very hard due to the difficulty of actual and potential ET<sub>c</sub> measurement and/or estimation for large irrigated areas. Because irrigation water applications can vary within the growing period and from site to site. Thus actual ET<sub>c</sub> is dynamic on a spatial and temporal basis. A very large body of research, spanning almost four decades, has demonstrated that much of the required agricultural information can be derived from remotely sensed data (Pinter et al. 2003). The ability to accurately assess water stress symptoms in vegetation using spectral reflectance measurements is an important goal for remote sensing research (Jackson 1986). Vegetation and water stress indices calculated based on remotely sensed data, such as spectral reflectance and infrared surface temperature, can provide spatial and temporal information.

There are numerous studies addressing the use of spectral reflectance to obtain the leaf/canopy water status and water stress (Luquet et al. 2003; Ceccato et al. 2001; Penuelas et al.

1993, 1997; Shibayama et al. 1993; Danson et al. 1992). Spectral reflectance at a given wavelength is the ratio of radiance to the irradiance. Under sunny conditions a target receives both direct and diffuse radiation and this incoming radiation called irradiance ( $\text{W m}^{-2}$ ). The radiation that is reflected from the target is called radiance ( $\text{W m}^{-2}$ ). In order to measure detect reflectance, hand-held radiometers can be used such as spectroradiometer or infrared thermometer receiving radiation reflected from a target with in the field of view. According to this, radiance of a crop canopy could be measure by means of a spectroradiometer. In order to detect irradiance, a panel (e.g., spectralon or  $\text{BaSO}_4$ ) which is able to reflect the incoming radiation completely could be used (Jackson et al. 1980). Figure 1 shows the radiance and reflectance data of sugar beet crops which growth under fully irrigated and rainfed conditions. The spectral reflectance values of the region between 300–1100 nm were given at 2 nm intervals. From this data, reflectance of each individual wavelength can be obtained such as 900, 800, 680 nm. On the other hand spectral data related to bands (e.g., Red and Near Infra Red) could be calculated (Köksal 2006).

A spectral vegetation index is a quantity obtained directly or rationing, differencing, or otherwise transforming spectral reflectance data to represent plant canopy characteristics (Jackson et al. 1980). Numerous spectral indexes have been developed for detection of crop properties such as water stress, yield, LAI and biomass. The most known spectral indexes which depends on the spectral reflectance of Red and Near Infra Red Regions are SR (Tucker 1979; Aparicio et al. 2000), NDVI (Tucker 1979; Penuelas et al. 1997), SAVI (Huete 1988) and WI (Penuelas et al. 1997).

**Fig. 1** Radiance and reflectance characteristics of fully watered and water stressed sugar beet at 300–1,100 nm spectral region (Köksal 2006)



The objective of this study is to determine the relationship between ET<sub>c</sub>, SWDI, WUE and total yield and to define the use possibilities of the spectral vegetation indexes for estimation of total yield, SWDI and WUE either at the end of the growing season or during the irrigation water management period.

## Materials and methods

### Field experiments

This study was conducted at the Ankara Soil and Water Resources Research Institute (39° 53' N and 32° 45' E, altitude 924 m) under semi arid climatic conditions of Ankara, Turkey, during the cropping season of 2004 and 2005. The dwarf green beans (*Phaseolus vulgaris*, *humilis*) were planted at 0.70 m row spacing on May 10th in, 2004 and on May 12th in 2005. Final plant density was nearly 65 crops m<sup>-2</sup>. Some physical properties of soils were analyzed by the Soil and Water Laboratory of Institute. The average sand, loam and clay percentages were 37.3%, 25.3% and 37.3%, respectively. The average gravimetric-based field capacity, wilting point and volumetric mass values were 27.6%, 16.9% and 1.17 g cm<sup>-3</sup>, respectively. The total available soil moisture (TAM) was 125.2 mm/m.

The experimental design was a completely randomized block design with three replications. Due to the difficulty of soil water content based scheduling under drip irrigated conditions, the irrigation treatments were based on US Weather Bureau Class A pan evaporation. According to the results of previous studies completed at the same region on beans, optimum percentages for Class A pan evaporation were differed from 60 to 120% and irrigation intervals were varied between 5 to 10 days (Ayla 1993; Üstün and Ayla 1993; Üstün et al. 1997). In this study, the irrigation interval was set at one week. Fixed irrigation water was applied to all treatments in the experiment to sprout and grow to a height of nearly 15 cm. The irrigation treatments of experiment were received 120% (B1), 90% (B2), 60% (B3), 30% (B4) and 10% (B5) of Class A pan evaporation and B6 was rainfed (Table 1).

Irrigation water was supplied via drip irrigation method and the amount was measured by water meter. The pressure of each plot was stabilized according to pressure meters mounted on the pipe of each plot. A lateral drip line was designed for each row. The diameter of the lateral pipes was 16 mm with 4 l/h in-line drippers spaced at 50 cm. Fertilizer was applied based on soil analysis recommendations, as before sowing with 60 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and 23.4 kg ha<sup>-1</sup> N and five times during the growing season with 5.3 kg ha<sup>-1</sup> N. The yield was harvested at 1 week intervals and the first and last harvests were carried out on 15 June 2004, 19 June 2005 and 01 October 2004 and 29 September 2005, respectively.

**Table 1** Description of irrigation treatments

Treatments	Description
B1	120% of the A pan evaporation
B2	90% of the A pan evaporation
B3	60% of the A pan evaporation
B4	30% of the A pan evaporation
B5	10% of the A pan evaporation
B6	Rain fed

## Field measurements

During the growing period, spectral reflectance, climatic parameters and soil water content were measured. Climatic parameters and soil water contents were observed throughout the growing season and spectral measurements were carried out from mid July to mid September.

### *Spectral reflectance measurements and indexes*

Spectral observations were made by using a spectroradiometer (Model LI-1800, Licor, Inc., Lincoln, NE, USA) with 15° field of view lenses. The radiance of the crops in the region ranging from 300 to 1100 nm was detected at 2 nm intervals from 1.5 m above the crop with nadir orientation of telescope body by means of a tripod. As a result, samples about 40 cm in diameter were obtained. Irradiance spectra of sunlight were taken before and after each crop measurement with a spectralon panel (Lapsphere, North Sutton, USA) and the average was used as the reflectance standard. All measurements were made three times and the LI-1800 computed the average of these measurements and stored them as a text file. Reflectance of individual wavelength was calculated by dividing the vegetation radiance measurements with the irradiance measurements which were made by spectralon panel. All spectral data collections were made at solar zenith angles of 45°–50° on cloudless days and at least two measurements were taken each week.

In this study, SR (Tucker 1979), NDVI (Penuelas et al. 1997), SAVI (Huete 1988) and WI (Penuelas et al. 1997) were used for estimation of total yield, SWDI and WUE. These indexes were calculated according to Eqs. 1, 2, 3 and 4. In order to evaluate the detection ability of these spectral indexes, some statistical analyses were made.

$$SR = \frac{R800}{R680} \quad (1)$$

$$NDVI = \frac{R800 - R680}{R800 + R680} \quad (2)$$

$$SAVI = \frac{R800 - R680}{R800 + R680 + L} (1 + L) \quad (3)$$

$$WI = \frac{R900}{R970} \quad (4)$$

where, R970, R900, R800 and R680 are the reflectance values at 970, 900, 800 and 680 nm wavelengths, respectively.  $L$  is the adjustment factor to reduce soil noise problems. Huete (1988) stated that the optimal  $L$  values exhibit differences according to vegetation density. In this study, according to Köksal (2008)  $L$  values were used for LAI under and over 4.0 as 0.4 and 0.08, respectively.

### *Leaf area measurements and leaf area index*

The leaf area obtained from one representative plant was multiplied by the number of plants in 1 m<sup>2</sup> area to obtain LAI (m<sup>2</sup>/m<sup>2</sup>; Thenkabail et al. 2000). Leaf area was measured by

running the leaves over a leaf area meter Model LI-3000A, Licor, Inc., Lincoln, NE, USA). LAI values were used for calibration of L parameter of SAVI in Eq. 3.

#### *Soil water content measurements and ET<sub>c</sub> calculation*

ET<sub>c</sub> was calculated as the soil water balance residual for the time periods between two successive Soil Water Content (SWC) measurements dates (Jensen et al. 1990). SWC measurements were made in the centre of trial plots with a neutron probe at 0.16, 0.45, 0.75, 0.95 and 1.15 m depth before each irrigation water applications. In addition, gravimetric water content for 0.3 m soil depth was defined. Since, irrigation rate did not exceed the infiltration rate, there was no runoff in the experimental plots. Effective rooting depth of dwarf green beans was 60 cm. In order to consider the percolation, moisture measurements related to 120 cm soil profile were used for soil water budget calculations.

#### *Water use efficiency and soil water deficit index*

Most researchers describe WUE as the ratio of total yield to ET<sub>c</sub> (Sinclair et al. 1984; Howell 2001; Bos 1980, 1985; Hatfield et al. 2001; Pala et al. 2007). In this study WUE (kg m<sup>-3</sup>) of each irrigation treatment based on Eq. 5. SWDI was defined according to Colaizzi et al. (2003b) by using Eq. 6. ET<sub>c</sub> calculated for B1 treatment was used as potential ET<sub>c</sub> (ET<sub>p</sub>) for SWDI calculation in Eq. 6.

$$\text{WUE} = \frac{\text{Yield}}{\text{ET}_c} \quad (5)$$

$$\text{SWDI} = 1 - \frac{\text{ET}_c}{\text{ET}_p} \quad (6)$$

#### Statistical analyses

Statistical analyses were performed using Statistical Discovery Software (JMP) and MsExcell. At first, total yield, ET<sub>c</sub>, WUE, SWDI and seasonal average values of SR, NDVI, SAVI and WI were statistically analyzed. A wide range of data gathered from six irrigation treatments was used together. In order to determine the appropriate time to use spectral index for estimation purposes, daily values of SR, NDVI, SAVI and WI values of all irrigation treatments for each day of measurement were analyzed with total yield, WUE and SWDI.

#### Results

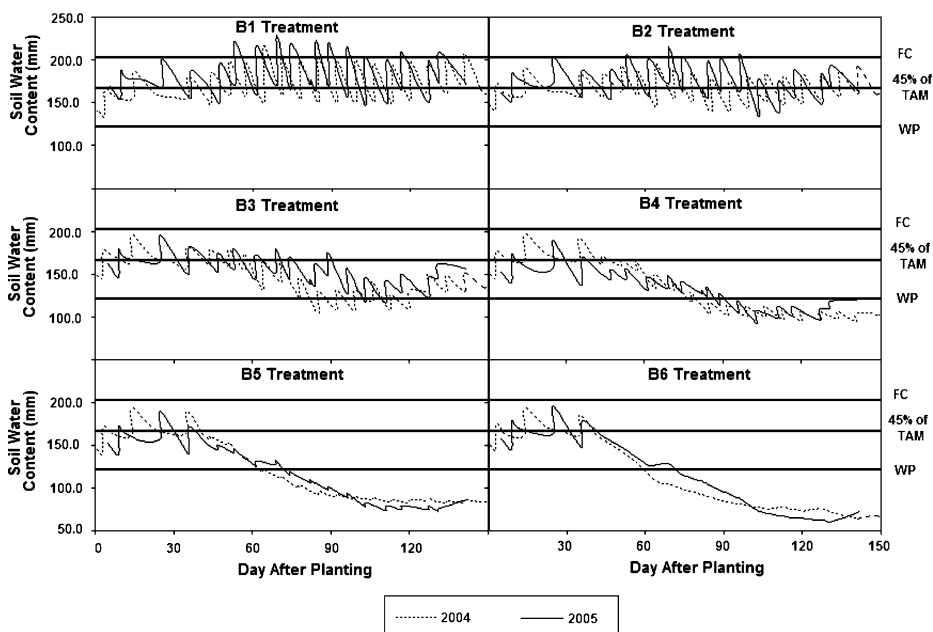
In order to ensure a good plant stand, 112.0 mm and 128.0 mm irrigation water was applied to all treatments in 2004 and 2005, respectively. After that, applied amount of irrigation water was varied between 112.0 mm and 814.0 mm in 2004 and 128.0 mm and 805.0 mm in 2005. ET<sub>c</sub> values were calculated between 297.9 mm and 840.4 mm in 2004 and 345.7 mm and 874.2 mm in 2005. During the growing seasons of 2004 and 2005, 75.0 mm and 131.0 mm precipitation occurred, respectively (Table 2). Green beans were harvested

**Table 2** Total applied amount of water, seasonal crop evapotranspiration, rainfall and yield

Irrigation treatments	2004				2005			
	Irrigation water (mm)	ETc (mm)	Yield (tha <sup>-1</sup> )	Total rainfall (mm)	Irrigation water (mm)	ETc (mm)	Yield (tha <sup>-1</sup> )	Total rainfall (mm)
B1	814.0	840.4	26.55	75.0	805.0	874.2	25.18	131.0
B2	636.0	682.7	30.36		635.0	714.2	25.21	
B3	463.0	570.1	26.43		466.0	592.7	25.02	
B4	288.0	436.7	16.43		298.0	444.9	16.48	
B5	171.0	343.9	9.99		185.0	384.8	9.29	
B6	112.0	297.9	6.08		128.0	345.7	6.73	

once per week and total yield were changed between 6.08–30.36 t ha<sup>-1</sup> in 2004 and 6.73–25.21 t ha<sup>-1</sup> in 2005, respectively. Maximum total yield was obtained from the B2 irrigation treatment which received the second highest irrigation water amount.

Figure 2 shows the soil water content course of irrigation treatments for 60 cm soil profile, in 2004 and 2005 growing season. Using 120% of A pan evaporation as irrigation water, the soil water content was varied over the field capacity between DAP 50 and 100. After DAP 100 with this irrigation program soil water varied between field capacity and 50% of TAM. Higher than 60% and percentage of A pan evaporation prove a moisture variation over permanent wilting point. As a consequence, it is very hard to obtain an economical yield with an irrigation schedule which is based on a percentage of A pan evaporation under 30.



**Fig. 2** Soil water course of irrigation treatments in 2004 and 2005. *FC* Field capacity, *TAM* total available moisture and *WP* wilting point

The highest correlations were obtained from the polynomial (quadratic equation) relationships between total yield, seasonal ETc, SWDI and WUE (Fig. 3). ETc over nearly 750 mm did not increase the total yield. According to this, when dwarf green beans use 750 mm water, 25,5  $\text{tha}^{-1}$  yield can be produced. Under these conditions SWDI will be nearly 0.3. Because WUE is the ratio between total yield and ETc, it considers the relative increase of total yield per unit water. Although B1 and B2 irrigation treatments were received more irrigation water than B3, WUE values of B3 were higher than that of B1 and B2. The correlation of the polynomial relationship between WUE and total yield were greater than linear. According to WUE, it is reasonable to offer the 60% of A pan evaporation for irrigation scheduling of dwarf green beans. In addition to this, Duncan analyzes (not given) related to total yield and water treatments, showed similar results.

Linear regression analyzes were made between total yield, seasonal SWDI, WUE, and daily spectral vegetation indexes (NDVI, SAVI, SR and WI). The path of correlation coefficients for these relationships throughout the measurement period was given graphically in Figs. 4, 5 and 6. In these graphs, 0.5 and 0.01 probability level were shown.

In general, the significance of the relationships was less than 0.01 probability level and correlations were high. After around DAP 80 total yield estimation by means of these indexes can give reliable results (Fig. 3). SAVI, which calibrated based on LAI, has the highest correlation. After DAP 70, spectral vegetation indexes and seasonal SWDI have significant linear relationship ( $P < 0.05$ ). Especially, NDVI, SAVI and SR have potential for SWDI estimation (Fig. 5). While, the highest correlations (from 0.84–0.94) were defined between SWDI and SAVI ( $P < 0.01$ ), the SWDI-WI has the lowest. Some significant relationships ( $P < 0.05$ ) were found between WUE and spectral indexes (Fig. 5). The correlations were poorer than that of total yield and SWDI. These relationships become significant after DAP 100 except for SAVI. After DAP55, the variation in WUE could explained by SAVI significantly ( $P < 0.05$ ). As a result, SAVI has the highest correlations with three of total yield, seasonal SWDI and WUE.

Total yield, seasonal average SWDI, WUE and SAVI have statistically linear relationships and the correlation coefficients were 0.98, 0.91 and 0.74, respectively ( $P < 0.01$ ). Based on these results, use of SAVI for total yield, SWDI and WUE estimation can be attributed to a formulation as Eqs. 7, 8 and 9, respectively. In these equations, “a” is the slope and “b” is the offset of the linear regressions between total yield, SWDI, WUE and SAVI.

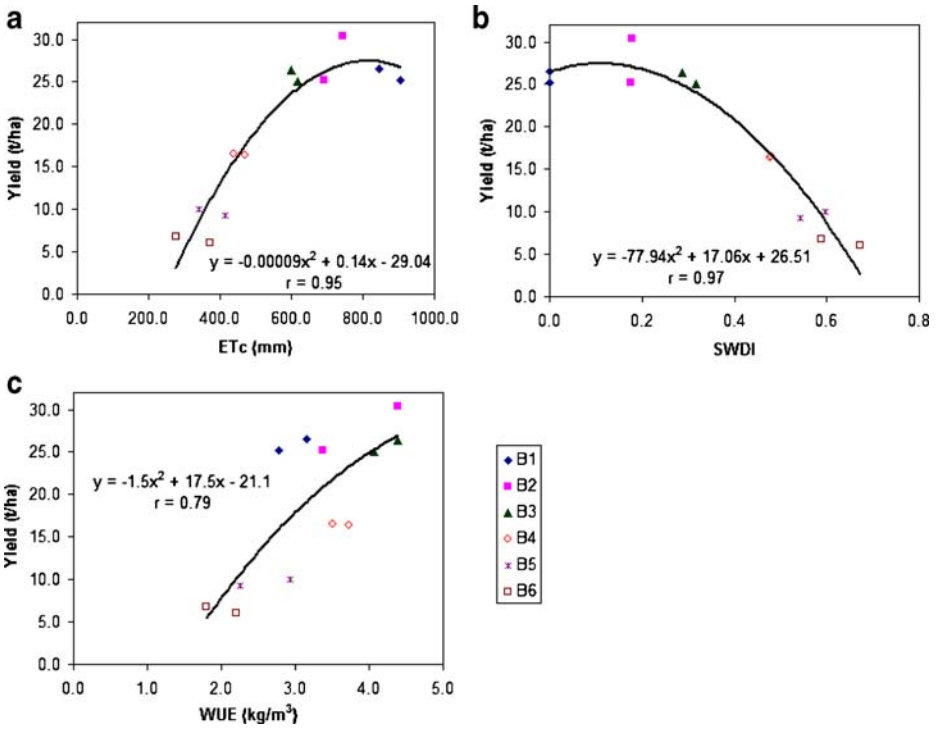
$$\text{Yield} = a_{\text{Yield-SAVI}}(\text{SAVI}) + b_{\text{Yield-SAVI}} \quad (7)$$

$$\text{SWDI} = a_{\text{SWDI-SAVI}}(\text{SAVI}) + b_{\text{SWDI-SAVI}} \quad (8)$$

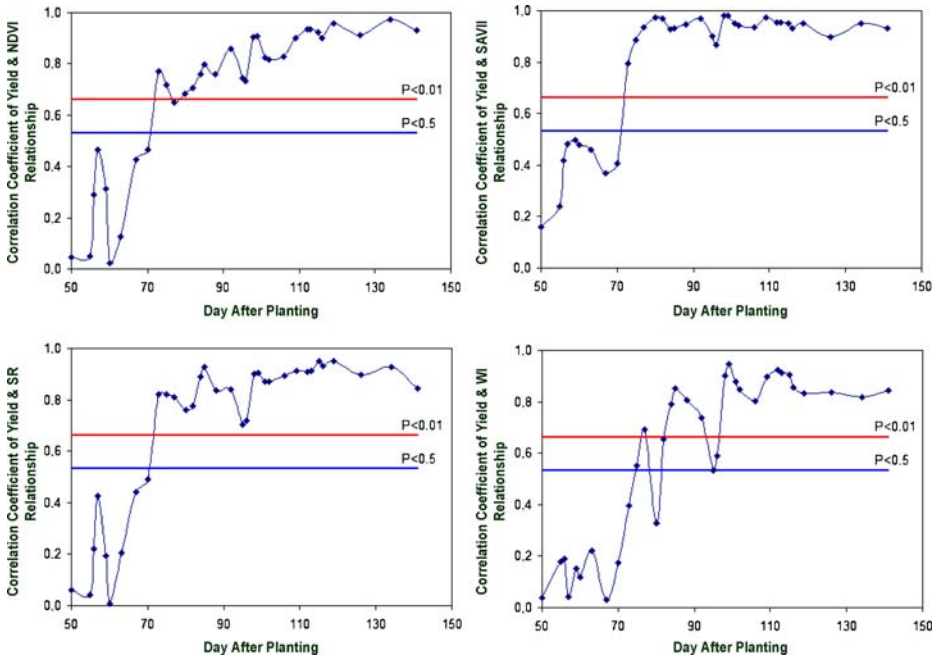
$$\text{WUE} = a_{\text{WUE-SAVI}}(\text{SAVI}) + b_{\text{WUE-SAVI}} \quad (9)$$

Figure 7 shows the course of slope and offset values of linear regression equations between total yield, seasonal average SWDI, WUE and daily SAVI. As can be seen from the graphs, these coefficients were varied in the time regularly. Statistical analysis showed that there was a significant difference ( $P < 0.01$ ) between the slope and offset values based on DAP. Regression analysis between DAP and these values indicated that the best fit was polynomial. According to this, it is possible to calculate the slope and offset values of Eqs. 7, 8 and 9, based on DAP, by means of the quadratic equations given in Fig. 7.

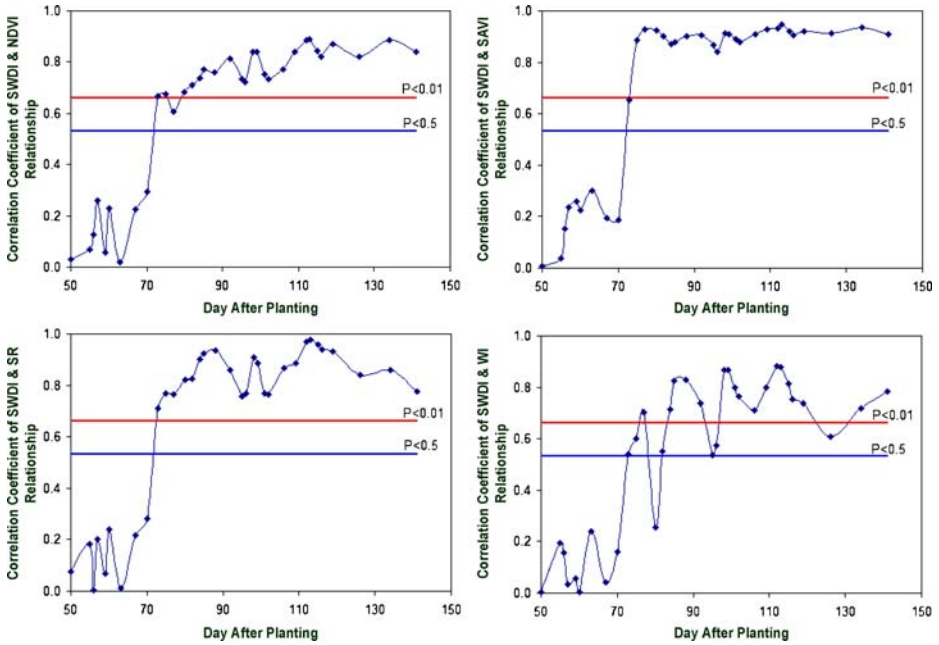




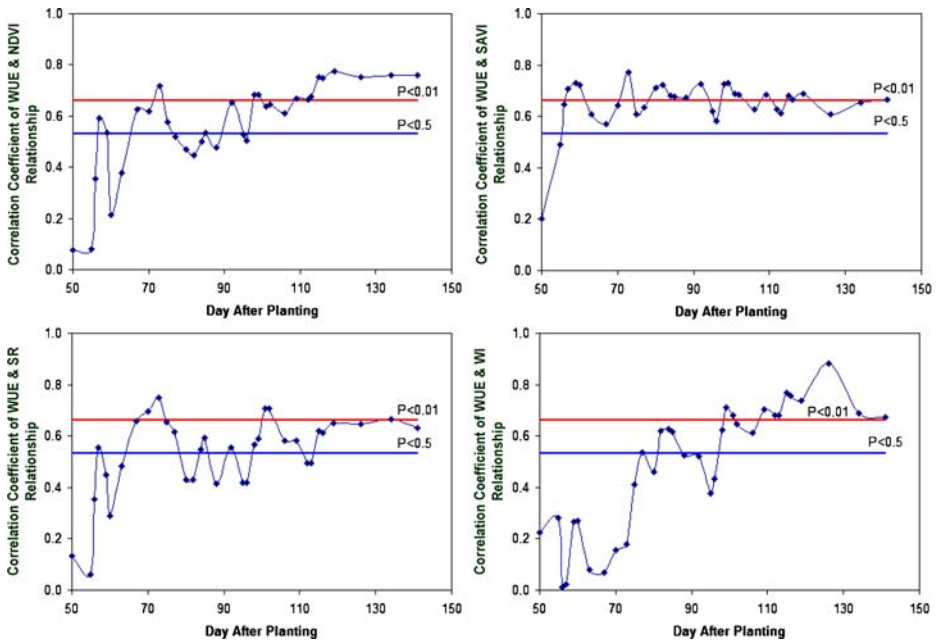
**Fig. 3** Relationship between *ETc*, *SWDI*, *WUE* and yield



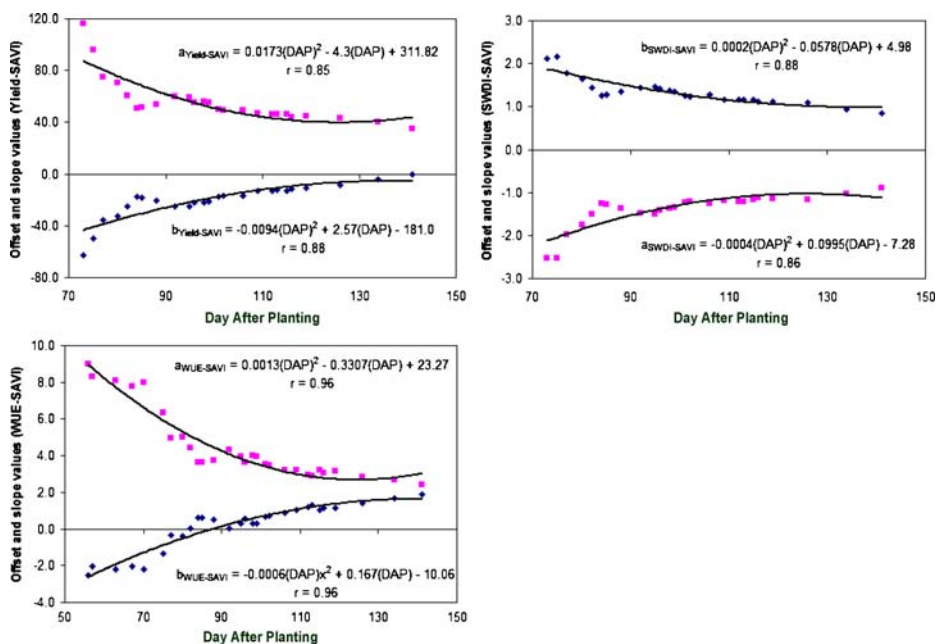
**Fig. 4** Correlation path of relationships between *yield* and *NDVI*, *SAVI*, *SR* and *WI* throughout the 2004 and 2005 growing seasons



**Fig. 5** Correlation path of SWDI and spectral vegetation indexes relationships throughout the 2004 and 2005 growing seasons



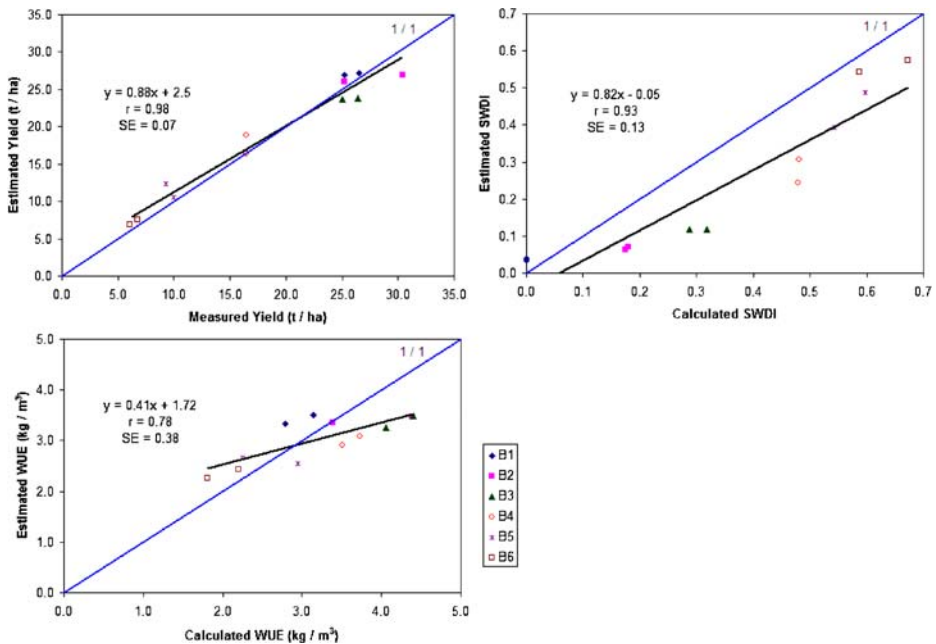
**Fig. 6** Correlation path of WUE and spectral vegetation indexes relationships throughout the 2004 and 2005 growing seasons



**Fig. 7** Variation of slope and offset values of *yield*, *SWDI*, *WUE* and *SAVI* regression and quadratic equation of relationship between *DAP*, *slope* and *offset* values

Consequently, estimation of total yield, SWDI and WUE with the use of SAVI can be made in two steps. The first step is the calculation of slope and offset values of Eqs. 7, 8 or 9. The second step will be the use of Eqs. 7, 8 or 9 with the calculated slope and offset values for estimation. As an example, for DAP 113, the slope and offset values could be determined as  $-10.91$  and  $43.14$ , respectively, from the total yield and SAVI graphs in Fig. 7. After that, for DAP 113 Eq. 7 will be determined as  $\text{Yield} = 43.14 \text{ SAVI} - 10.91$ . If the SAVI value of DAP113 measured as  $0.87$ , total yield will be estimated as  $26.6 \text{ t ha}^{-1}$ . Another example could be solved for DAP 126 and SAVI value of  $0.3$  to estimate the SWDI. For this reason the offset and the slope values could be calculated as  $-1.09$  and  $0.87$  and Eq. 8 become  $\text{SWDI} = -1.09 \text{ SAVI} + 0.87$ . As a result, SWDI could be calculated a value of  $0.55$ , for DAP 126. The reliability of the approximation can be improved by using more than one SAVI value measured in various DAP. Because, only one SAVI value represents one time of day and/or period and the conditions of the measurement time can negatively affect the accuracy of estimation.

The comparison of estimated and measured total yield, calculated SWDI and WUE were illustrated in Fig. 8. In these statistics, measured total yield, calculated SWDI and WUE were the original values obtained from the field experiments. Estimated total yield, SWDI and WUE were the seasonal average of daily values. All the interception points of estimated and measured values were close to the  $1/1$  line. High correlation ( $r=0.98$ ) was indicate that total yield could be estimated during the growing season with SAVI by means of this approximation. On the other hand some previous studies have shown that total yield estimation trough spectral indexes are possible (Raun et al. 2001; Kleman and Fagerlund 1987; Moran et al. 1989).



**Fig. 8** Comparison of estimated and measured yield, calculated *SWDI* and *WUE*

Estimation of *SWDI* through *SAVI* has a correlation of 0.93 and Standard Error (*SE*) was calculated as 0.13. As stated in previous studies, water stress and spectral vegetation indexes have indirect relationships based on the vegetation amount (Penuelas et al. 1993; Thomas et al. 1971). This significant relationship between calculated and estimated *SWDI* could be explained by the same concept. *SWDI* calculation depends on actual and potential *ETc*, and consists of some experimental errors. Estimated *SWDI* values were lower than the measured for all six irrigation treatments. On the other hand, according to 1/1 line, differences between estimated and calculated values of various water and vegetation level were similar. The highest differences were determined for B3 and B4 treatment which received 60 and 30% of A pan evaporation. In these treatments, vegetation of green beans was not so poor and the irrigation program of the B3 was evaluated as viable based on the statistical analysis between total yield and *ETc*. According to these result, estimated values of *SWDI* through *SAVI* up to 0.12 indicates non-water stressed conditions. Some previous studies propose estimation of water stress by means of spectral indexes (Pinter 1983; Saha et al. 1986; Luquet et al. 2003; Cure et al. 1989; Cohen 1991; Riggs and Running 1991; Danson et al. 1992; Penuelas et al. 1993, 1997).

*WUE* is an indicator of the productivity of water. Because of this, it depends on both total yield and *ETc*. However, numerically *WUE* values could be high for lower irrigation conditions or low for non-water stressed situations. The results of this study indicated that, for dwarf green bean, maximum *WUE* values could be obtained with the application of an irrigation schedule based on 60% of A pan evaporation. Excessive (higher *ETc*) or deficit water application (more or less than 60% of A pan) will cause low *WUE* value, because of either high *ETc* or less yield. As can be seen from Fig. 8 the relationship between calculated and estimated *WUE* is significant ( $P < 0.01$ ). The interception points of the two data sets

were close to the 1/1 line. Estimated value of WUE between 3 and 3.5 indicates a condition of optimum total yield and unimportant level of irrigation water deficiency.

## Conclusion

In this field experiment, different levels of irrigation water based on Class A pan evaporation were applied to dwarf green beans. Based on this, crop water use, water stress, vegetation amount and total yield were varied from one irrigation treatment to another. All the indicators investigated in this study were achieved by these variations.

Total yield has significant quadratic relationships with ET<sub>c</sub>, SWDI and WUE. These polynomial relationships showed that the optimal irrigation water level for dwarf green bean under a semi-arid climate condition is 60% of A pan evaporation. In this situation ET<sub>c</sub>, SWDI and WUE should be nearly 580 mm, 0.12 and 3.2 kg/m<sup>3</sup>. The application of this irrigation amount can produce nearly 25.5 t ha<sup>-1</sup> green beans.

Seasonal average values of spectral indexes (NDVI, SAVI, SR and WI) have significant relationships with total yield, seasonal average SWDI and WUE. However, the relationship between daily values of spectral indexes and observed parameters becomes statistically significant after DAP 80. Generally, the highest correlations were obtained with SAVI. According to this, the estimation of total yield, seasonal average SWDI and WUE through spectral indexes could be reliable after DAP 80 and the most appropriate index is SAVI.

Slope and offset values for the equation of linear regression between SAVI and total yield, SWDI and WUE have polynomial relationships with DAP. Based on this, estimation procedure of observed parameters by means of SAVI could be run in two steps as (1) calculation of slope and offset values based on related quadratic equation and DAP, (2) estimation of total yield, SWDI or WUE with the linear equation. As a conclusion, spectral indexes are useful estimation tools for yield, SWDI and WUE of dwarf green beans. Through these indexes, water use and productivity could be monitored and used as a decision support tool for water management in irrigated agriculture.

**Acknowledgement** This research is funded by the Ankara Soil and Water Resources Research Institute. The author is indebted to the following: İsmail Kabasakal, İbrahim Çolak and Muhterem Özçelik for their help in the field work; and the staff of the Ankara Soil and Water Resources Research Institute for their cooperation.

## References

- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration; guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, United Nations, Rome
- Angus JF, van Herwaarden AF (2001) Increasing water use and water use efficiency in dryland wheat. *Agron J* 93:290–298
- Anonymous (1996) Food production: The critical role of water. FAO technical background documents. 6–11. World Food Summit 2:13–17
- Aparicio N, Viellegas D, Casadesus J, Arous JL, Royo C (2000) Spectral vegetation indices as nondestructive tools for determining durum wheat yield. *Agron J* 92:83–91
- Ayla Ç (1993) Comparison of potential evapotranspiration with actual consumptive use of bean, strawberry, wheat and sugarbeet by weighing lysimeter under Ankara conditions, Vol, 181, Rep. No, 88, Ankara Research Institute of Rural Affairs, Ankara Turkey
- Bos MG (1980) Irrigation efficiencies at crop production level. *ICID Bull* 29:18–25

- Bos MG (1985) Summary of ICID definitions of irrigation efficiency. *ICID Bull* 34:28–31
- Ceccato P, Flasse S, Tarantola S, Jacquemoud S, Gregoire JM (2001) Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sens Environ* 77:22–33, doi:[10.1016/S0034-4257\(01\)00191-2](https://doi.org/10.1016/S0034-4257(01)00191-2)
- Cohen WB (1991) Temporal versus spatial variation in leaf reflectance under changing water stress conditions. *Int J Remote Sens* 12:1865–1876, doi:[10.1080/01431169108955215](https://doi.org/10.1080/01431169108955215)
- Colaizzi PD, Barnes EM, Clarke TR, Choi CY, Waller PM (2003a) Estimating soil moisture under low frequency surface irrigation using crop water stress index. *J Irrig Drain Eng* 129(1):27–35, doi:[10.1061/\(ASCE\)0733-9437\(2003\)129:1\(27\)](https://doi.org/10.1061/(ASCE)0733-9437(2003)129:1(27))
- Colaizzi PD, Barnes EM, Clarke TR, Choi CY, Waller PM (2003b) Water stress detection under high frequency sprinkler irrigation with water deficit index. *J Irrig Drain Eng* 129(1):36–43, doi:[10.1061/\(ASCE\)0733-9437\(2003\)129:1\(36\)](https://doi.org/10.1061/(ASCE)0733-9437(2003)129:1(36))
- Cure WW, Flagler RB, Heagle AS (1989) Correlations between canopy reflectance and leaf temperature in irrigated and droughted soybeans. *Remote Sens Environ* 29:273–280, doi:[10.1016/0034-4257\(89\)90006-0](https://doi.org/10.1016/0034-4257(89)90006-0)
- Danson M, Steven MD, Malthus TJ, Clark JA (1992) High-spectral resolution data for determining leaf water content. *Int J Remote Sens* 13:461–470, doi:[10.1080/01431169208904049](https://doi.org/10.1080/01431169208904049)
- Hatfield JL, Sauer TJ, Prueger J (2001) Managing soils to achieve greater water use efficiency: a review. *Agron J* 93:271–280
- Howell TA (2001) Enhancing water use efficiency in irrigated agriculture. *Agron J* 93:281–289
- Huete AR (1988) A soil adjusted vegetation index (SAVI). *Remote Sens Environ* 25:295–309, doi:[10.1016/0034-4257\(88\)90106-X](https://doi.org/10.1016/0034-4257(88)90106-X)
- Jackson RD (1986) Remote sensing of biotic and abiotic plant stress. *Annu Rev Phytopathol* 4:289–297
- Jackson RD, Pinter PJ Jr, Reginato RJ, Idso SB (1980) Hand-held radiometry. A set of notes developed for use at the workshop on hand-held radiometry. Phoenix, Ariz., February 25–26, 1980
- Jensen ME, Burman RD, Allen RG (1990) Evapotranspiration and irrigation water requirements. Manuals and reports on engineering practices no. 70. ASCE, New York
- Kang Y, Wang FX, Liu HJ, Yuan BH (2004) Potato evapotranspiration and yield under different drip irrigation regimes. *Irrig Sci* 23:133–143, doi:[10.1007/s00271-004-0101-2](https://doi.org/10.1007/s00271-004-0101-2)
- Kleman J, Fagerlund E (1987) Influence of different nitrogen and irrigation treatments on the spectral reflectance of barley. *Remote Sens Environ* 21:1–14, doi:[10.1016/0034-4257\(87\)90002-2](https://doi.org/10.1016/0034-4257(87)90002-2)
- Köksal ES (2006) Determination of the Effects of Different Irrigation Levels on Sugar beet Yield, Quality and Physiology Using Infrared Thermometer and Spectroradiometer, University of Ankara, PhD. Thesis, Ankara
- Köksal ES (2008) Evaluation of spectral vegetation indices as an indicator of crop coefficient and evapotranspiration under full and deficit irrigation conditions. *Int J Remote Sens*. doi:[10.1080/01431160802226000](https://doi.org/10.1080/01431160802226000)
- Luquet D, Begue A, Vidal A, Clouvel P, Dauzat J, Oliosio A et al (2003) Using multidirectional thermography to characterize water status of cotton. *Remote Sens Environ* 84:411–421, doi:[10.1016/S0034-4257\(02\)00131-1](https://doi.org/10.1016/S0034-4257(02)00131-1)
- Moran MS, Pinter P Jr, Clothier BE, Allen SG (1989) Effect of water stress on the canopy architecture and spectral indices of irrigated alfalfa. *Remote Sens Environ* 29:251–261, doi:[10.1016/0034-4257\(89\)90004-7](https://doi.org/10.1016/0034-4257(89)90004-7)
- Oweis T, Zhang H, Pala M (2000) Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean Environment. *Agron J* 92:231–238, doi:[10.1007/s100870050027](https://doi.org/10.1007/s100870050027)
- Pala M, Ryan J, Zhang H, Singh M, Harris HC (2007) Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. *Agric Water Manage* 93:136–144, doi:[10.1016/j.agwat.2007.07.001](https://doi.org/10.1016/j.agwat.2007.07.001)
- Penuelas J, Filella I, Biel C, Serrano L, Save R (1993) The reflectance at the 950–970 nm region as an indicator of plant water status. *Int J Remote Sens* 14(10):1887–1905, doi:[10.1080/01431169308954010](https://doi.org/10.1080/01431169308954010)
- Penuelas J, Pinol J, Ogaya R, Filella I (1997) Estimation of plant water concentration by the reflectance Water Index WI (R900/R970). *Int J Remote Sens* 18(13):2869–2875, doi:[10.1080/014311697217396](https://doi.org/10.1080/014311697217396)
- Pinter PJ Jr, Hatfield JL, Schepers JS, Barnes EM, Moran MS, Daughtry CST et al (2003) Remote sensing for crop management. *Photog Eng Remote Sens* 69(6):647–664
- Pinter PJ Jr (1983) Monitoring the effect of water stress on the growth of alfalfa via remotely sensed observations of canopy reflectance and temperature. 18th Conference on Agriculture and Forest Meteorology, April 26–28, 1983. Boston Pp:91–94
- Raun WR, Solie JB, Johnson GV, Stone ML, Lukina EV, Thomason WE et al (2001) In-season of potential grain yield in winter wheat using canopy reflectance. *Agron J* 93:131–138
- Riggs GA, Running SW (1991) Detection of canopy water stress in conifers using the airborne imaging spectrometer. *Remote Sens Environ* 35:51–68, doi:[10.1016/0034-4257\(91\)90065-E](https://doi.org/10.1016/0034-4257(91)90065-E)

- Saha SK, Gopalan AAKS, Kamat DS (1986) Relation between remotely sensed canopy temperature, crop water stress, air vapour pressure deficit and evapotranspiration in chickpea. *Agric For Meteorol* 38:17–26, doi:[10.1016/0168-1923\(86\)90047-X](https://doi.org/10.1016/0168-1923(86)90047-X)
- Shibayama M, Takahashi W, Morinaga S, Akiyama T (1993) Canopy water deficit detection in paddy rice using a high resolution field spectroradiometer. *Remote Sens Environ* 45:117–126, doi:[10.1016/0034-4257\(93\)90036-W](https://doi.org/10.1016/0034-4257(93)90036-W)
- Sinclair TR, Tanner CB, Bennett JM (1984) Water-use efficiency in crop production. *Bioscience* 34:36–40, doi:[10.2307/1309424](https://doi.org/10.2307/1309424)
- Sivamani E, Bahieldin A, Wraith JM, Al-Niemi T, Dyer WE, David Ho TH et al (2000) Improved biomass productivity and water use efficiency under water deficit conditions in transgenic wheat constitutively expressing the barley HVA1 gene. *Plant Sci* 155:1–9, doi:[10.1016/S0168-9452\(99\)00247-2](https://doi.org/10.1016/S0168-9452(99)00247-2)
- Thomas JR, Namken LN, Oether GF, Brown RG (1971) Estimating leaf water content by reflectance measurements. *Agron J* 63:845–847
- Thenkabail PS, Smith RB, Pauw ED (2000) Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. *Remote Sens Environ* 71:158–182, doi:[10.1016/S0034-4257\(99\)00067-X](https://doi.org/10.1016/S0034-4257(99)00067-X)
- Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens Environ* 8:127–150, doi:[10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0)
- Ünlü M, Kanber R, Onder S, Sezen M, Diker K, Ozekici B et al (2007) Cotton yields under different furrow irrigation management techniques in the Southeast Anatolia Project (GAP) area, Turkey. *Irrig Sci* 26:35–48, doi:[10.1007/s00271-007-0070-3](https://doi.org/10.1007/s00271-007-0070-3)
- Üstün H, Ayla Ç (1993) Consumptive use and phosphorus-irrigation relations of dry beans under Kesikköprü conditions, Vol, 177, Rep. No, 85, Ankara Research Institute of Rural Affairs, Ankara Turkey
- Üstün H, Aran A, Yıldırım O (1997) Determination of drip irrigated green bean irrigation water requirement under Ankara condition, Vol, 207, Rep. No, 113, Ankara Research Institute of Rural Affairs, Ankara Turkey