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Relationship between spectral reflectance and water stress conditions of Bermuda grass (*Cynodon dactylon* L.)

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Abstract Remotely sensed data is an important tool for precision crop management. Satellite imaging systems and related-hand held instruments are frequently proposed for detection of crop stress caused by water, soil compaction and lack of nutrients, etc. This study was conducted to investigate how Bermuda grass reflectance changes with the onset of water stress. Four different irrigation treatments were examined: 100% (I_1), 75% (I_2), 50% (I_3) and 25% (I_4) of the evaporation measured in the Class A Pan. A non-irrigated plot was used as a control treatment (I_5). Spectral reflectance data were collected using a hand-held spectroradiometer which measured in the blue, green, red and near-infrared. Soil water content was monitored by a neutron probe. Water-stressed Bermuda grass (treatments I_4 and I_5) had lower spectral reflectance in near-infrared and higher reflectance in red wavebands than the other treatments. The results were statistically tested using one-way analysis of variance and Duncan's multiple range test. Highly significant relationships were found between different irrigation treatments and near infrared wavelengths ($P < 0.01$, $R^2 = 0.94$) and between the irrigation treatments and the normalised difference vegetation index (NDVI) ($P < 0.01$, $R^2 = 0.80$). Results indicate that different water stress on Bermuda grass could be determined by using spectral reflectance, especially NDVI and near-infrared reflectance regions. Analysis of experimental data indicated that it is possible to use remotely sensed data to develop maps of water stress conditions of Bermuda grass (*Cynodon dactylon*).

Keywords Bermuda grass; NDVI; remote sensing; spectroradiometer; water stress

INTRODUCTION

Because of rapidly growing population and a dwindling resource base, sustainable development places greater and conflicting demands on available agricultural resources. Especially in the Mediterranean region, this issue is becoming more pressing. Decision-makers need to monitor and analyse the changing resource bases of specific ecosystems, such as grassland ecosystems, in order to make informed decisions. As grasslands in recreational facilities require huge amounts of water, turfgrass managers and experts are particularly concerned about conservation and management of water resources, and are interested in various technologies that can facilitate these efforts in this direction (Li et al. 1998). One of these technologies, remote sensing, is being increasingly used as a tool to assist in grassland research.

In recent decades several remote sensing techniques have been developed to monitor and determine physiological responses of living plants. These sensing techniques can provide non-destructive and quantitative assessments, and allow producers and buyers to make decisions with respect to crop management. Remote sensing data can also provide

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timely and spatially distributed information on the crop's condition, and these data can be incorporated into a farm management scheme (Maas 1998). Applications of remotely sensed data to crops have been researched for various purposes (Fernandez et al. 1994; Cloutis et al. 1996). For instance, the input of spectral reflectance data into yield production models have been shown to improve yield estimates, monitoring plant diseases and stress conditions (Penuelas et al. 1994; Zhao et al. 2005). It is well established that there are strong correlations between remotely sensed data and plant physiological status and photosynthetic functioning (Roth 2002). Reflectance data have been related to plant characteristics such as plant biomass or the fraction of photosynthetically active radiation intercepted.

Early detection of vegetation stress by passive remote sensing depends largely on identifying the spectral region(s) in which vegetation reflectance/emission is most responsive to unfavourable growth conditions. The primary method of remote water stress detection has been through the use of the thermal part of the spectrum. Early studies showed a relationship between plant canopy temperature and water status. These relationships were later used to define a crop water stress index (CWSI) based on canopy temperature and meteorological conditions (Jackson 1982).

Remote sensing technologies are being increasingly used as tools to assist in preparation of grassland resource inventories, analysis, modelling, and forecasting to support decision making (Tueller 1989). Yong et al. (2003) suggested that reflectance-based methods could be used to reliably quantify grass cover from Landsat™ imagery. Researchers have successfully quantified grass cover from satellite images at an overall accuracy of 89% (Yong et al. 2003).

Non-thermal techniques to assess plant water use include establishing the relationship between vegetation indices and crop coefficients and changes in the near infrared area of the spectrum (Barnes et al. 2001). Numerous spectral vegetation indices have been developed to characterise vegetation canopies. The most common of these indices, which utilise red (0.6–0.7 μm) and near infrared (0.7–0.90 μm) wavelengths, are the simple ratio and normalised difference vegetation index (NDVI) (Tucker 1979).

The NDVI and its various derivatives are most commonly used in estimating the onset of stress (Penuelas et al. 1997). The NDVI has also been used for numerous regional and global applications for studying the distribution and potential photosynthetic activity of vegetation. Bell et al. (2002) reported that NDVI had been used to measure drought stress, turf chlorophyll content and turf quality. Turner et al. (1992) investigated the use of the NDVI derived from ground-level spectrometer measurements to study the effects of grazing, burning and soil depth on various biophysical properties of grassland in eastern Kansas, USA.

Bermuda grass (*Cynodon dactylon*), a warm season species and widely used in Mediterranean region (Arslan & Cakmakci 2004), grows to 10–12 cm high and is tufted, erect, and remains green in summer. The aim of this research was to determine the feasibility of using a multi-band radiometer to detect water stress in Bermuda grass (*Cynodon dactylon*) under Mediterranean climate conditions.

MATERIALS AND METHODS

This research was conducted the Akdeniz University Agricultural Research Centre in Antalya province in the Mediterranean region of Turkey (30°38′30"E, 36°53′15"N). The soils of the research area are classified as Paralithic Xerortent formed on massive travertine and have shallow soil depth and clay-loam texture (Sari et al. 1993; Soil Survey Staff 1999). Selected physical properties of the soils are given in Table 1.

The research area has a typical Mediterranean climate: mild and rainy winters and hot and dry summers. Mean temperature during the experiment (June–August–September was 29.7°C. Ten-day

Table 1 Selected physical properties of the soil at the study site. CL, Clay loam; SL, sandy loam.

Depth (cm)	Textural analysis				Field capacity (%)	Permanent wilting point (%)	Bulk density (g cm^{-3})
	Sand (%)	Silt (%)	Clay (%)	Texture class			
0–30	29.28	40.00	30.72	CL	20.86	13.18	1.37
30–60	59.28	24.00	16.72	SL	13.19	6.35	1.46

averages of selected meteorological data during the study area period are presented in Table 2.

Bermuda grass was cut at 5 cm above ground using a mower when it was 10–12 cm tall (Ritchie et al. 2002). The mowing intervals ranged between 9 and 16 days depending on climatic conditions and development phase. The experimental plots were laid out as randomised blocks and each treatment was replicated three times. Plots were 4 × 5 m, and each plot was surrounded with a 20 cm high earth berm, with a 1 m wide buffer space between the plots. The treatments were fertilised on 27 May 2004 with the $N_{15}P_{15}K_{15}$ type of fertiliser as 5 g m^{-2} and on 29 June, 31 July and 30 August with 5 g m^{-2} N (Martin et al. 1994). As a nitrogen source, the fertilisers of ammonium sulphate was applied on 29 June and ammonium nitrate on 31 July and 30 August.

Monitoring of soil moisture content

The soil water content was monitored daily in each plot by using a neutron probe (a Neutron Scattering Moisture Gauge, Model 4300, Troxler Electronic Lab., Inc., Raleigh, NC) at 15 cm intervals down to 60 cm. One aluminium access tube was installed in the middle of each plot. The soil moisture tension in the upper 10 cm depth was also monitored using tensiometers placed in the middle of the plots. The experimental plots were irrigated by basin irrigation. The irrigation water was delivered to the plots by a gated pipe whose length and inside diameter were 3.5 m and 40 mm, respectively. The amount of applied water was measured by a water meter placed in the entrance of the pipe. Irrigation treatments were based on the evaporation data (Epan, mm) obtained from a Class A pan located next to the plots. The pan was located on a wooden support at a height of 15 cm above the soil surface and readings were recorded daily. The experiment consisted of four irrigation treatments: I_1 = 1.00 Epan, I_2 = 0.75 Epan, I_3 = 0.50 Epan and I_4 = 0.25 Epan. A non-irrigated plot was also established to determine the highest level of water stress (I_5). The irrigation interval was 2 days for all treatments. The water balance equation was used to determine seasonal water use (Kirda et al. 1996).

Colour status and visual colour density were considered as turfgrass quality criteria. The turfgrass colour was evaluated using the Munsell colour scale, which is a scientific grading of colours according to the colour tone of the plant tissues (Wilde & Voigt 1977). The turfgrass colour during the experiment was evaluated at 10-day intervals with the colour name, colour number, and page number recorded each time (Table 3). The observed grass colours were numbered in such a way that dark green corresponded to 9 and light green to 1. As the numbers change from 9 to 1 the corresponding colours turn from dark green to light green to yellow (representing that grass is dead or at dormancy). Both the colour tone and general visual status and grass density of the plots

Table 2 Ten-day averages of selected weather variables during the study period.

Months	Temperature (°C)	Barometric pressure (kPa)	Relative humidity (%)	Wind speed (m s^{-1})	Sunshine duration (h)	Evaporation (mm)	Total rainfall (mm)
Jun							
1–10	25.96	100.59	64.58	2.11	12.04	8.30	–
11–20	29.89	100.16	50.81	2.13	12.11	9.88	4.7
21–30	30.93	100.18	55.02	2.48	12.07	10.20	2.3
Jul							
1–10	32.77	99.88	45.41	1.23	13.10	12.45	–
11–20	32.30	99.93	42.49	1.49	12.25	12.90	–
21–31	31.45	99.92	55.81	1.29	12.50	10.86	–
Aug							
1–10	30.03	99.82	70.94	1.17	11.12	7.40	–
11–20	30.75	99.96	54.15	1.45	12.13	9.80	–
21–31	30.63	100.13	50.12	1.71	11.81	10.32	–
Sep							
1–10	27.99	100.82	46.75	2.19	10.56	9.55	–
11–20	26.05	101.14	48.44	1.96	10.27	8.50	–
21–30	28.17	101.17	55.23	2.33	9.56	7.10	1.5

were also taken into consideration when the colours were evaluated to determine the grading numbers in the field (Throssell et al. 1987).

Radiometric measurements

Spectral measurements were made using a four channel portable spectroradiometer (Model 100AX, Exotech Inc., Gaithersburg, Maryland, USA) at four different wavelength bands: blue (450–520 nm), green (520–600 nm), red (630–690 nm) and near-infrared (NIR) (760–900 nm). The spectroradiometer had a 15° field-of-view (FOV) and was placed 2 m above the crop canopy (approximately 0.20–0.25 m^2 canopy view) (Ray et al. 1980). Measurements were taken from the same locations in each plot. Three reflectance measurements were made over each plot and later converted into percent reflectance by dividing the average of the three replicates by the reflectance of a $BaSO_4$ reference panel taken near the time of the canopy measurements (Rudorf & Batista 1990; Jackson et al. 1992; Zarco-Tejada et al. 2003; Sari et al. 2005). All spectral measurements were made in clear and open-air conditions between 9:30 a.m. and 10:30 a.m. (Filiberti et al. 1993).

The averages of the spectral reflectance values were then converted to Wm^{-2} by using the calibration coefficients given in the Exotech manual (Exotech Spectroradiometer Manual, Exotech Inc., USA, 1983).

The NDVI was also evaluated for determination of Bermuda grass water stress under different levels of irrigation. The NDVI has been proposed by many researchers (e.g., Penuelas et al. 1997; Korobov & Railyan 1993) to evaluate crop stress. The NDVI is calculated as NDVI = (NIR – RED)/(NIR + RED) (Rouse et al. 1974).

Data analysis

The means of the spectral reflectance at each blue, green, red and NIR wavelength between five treatments were statistically tested using one-way analysis of variance and the Duncan multiple range test (Siegel & Castellan 1988). The statistical tests were applied at different growing time periods (e.g., first, second week) to detect possible spectral differences between treatments at different stages of plant maturity (Mutanga et al. 2003).

RESULTS

A time series plot depicting the change in soil moisture as a function of irrigation treatment is given in Fig. 1. Seasonal average tensiometer readings at the depth of 10 cm during the experiment for I_1, I_2, I_3, I_4 treatments and non-irrigated (I_5) plots were 9.50, 10.20, 18.70, 73.40 and 75.45 kPa, respectively.

Seasonal amount of irrigation water applied, soil water depletion and water use are presented in Table 4. The amounts of seasonal water use in I_1, I_2, I_3, and I_4 treatments were 1186, 900, 614 and 353 mm, respectively.

The best visual quality was observed in the I_1 and I_2 treatments, with little to no difference between these observations during the experiment (Table 5). In treatment I_3, visual quality decreased slightly as the growing season progressed. Visual quality was unacceptable in treatment I_4 and the grass density decreased in this treatment. In the non-irrigated plot (I_5), the grass turned yellow completely at the end of June and the grass density decreased significantly.

Spectral reflectance values of Bermuda grass obtained by spectroradiometer readings during the

Table 3 Page numbers of Munsell colour chart, colour numbers and visual quality values.

Page nos of the chart	Colour nos (value/chroma)	Visual quality value	Colour changing
5GY	3/4	9	Dark green
5GY	4/4	8	
5GY	4/6,8	7	
5GY	5/4,6,8,10	6	
5GY	6/4,6,8,10	5	
5GY	7/4,6,8,10	4	
2.5GY	7/4,6,8	3	
2.5GY	8/4,6,8	2	Light green
2.5Y and 5Y	All colours	1	Dormancy

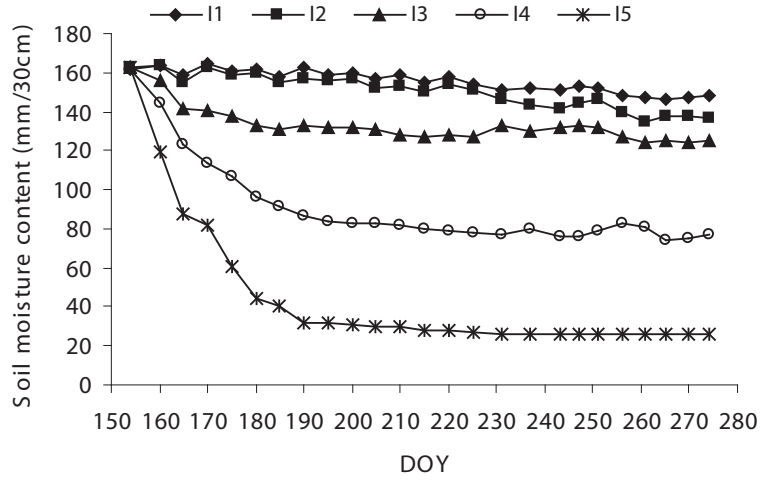


Fig. 1 Time series of soil moisture content during the study period for each irrigation treatment (I_1–I_4), and the study control treatment (I_5, no irrigation). DOY, Day of the year.

Table 4 Total amount of irrigation water, soil water depletion, rainfall and seasonal water use of the crop.

Treatments	Soil water depletion (mm)	Irrigation water applied (mm)	Rainfall (mm)	Seasonal water use (mm)
I_1	8.88	1168.20	8.5	1185.58
I_2	14.71	877.18	8.5	900.39
I_3	21.79	584.10	8.5	614.39
I_4	52.64	292.08	8.5	353.22
I_5	84.23	–	8.5	92.73

Table 5 Changing of visual quality values during the experiment.

	Visual quality values					
Treatments	Initial	Jun	Jul	Aug	Sep	Seasonal average
I_1	7	7	6	6	7	6.5
I_2	7	7	6	6	7	6.5
I_3	7	6	5	5	6	5.5
I_4	7	5	3	3	3	3.5
I_5	7	4	1	1	1	1.75

experiment are given in Fig. 2. Reflectance values from I_1 and I_2 were similar to those characteristically found in healthy crops. The seasonal average reflectance values in blue, green, red and near-infrared wavebands of electromagnetic spectrum (EMS) for the I_1 treatment were 2.68, 6.35, 3.08 and 31.59 Wm^{-2}, respectively, and those for the I_2 treatment were 2.75, 6.44, 3.22 and 31.34 Wm^{-2} in blue, green, red and near-infrared wavebands.

Spectral reflectance values in the I_3 treatment diverged from I_1 and I_2 at the end of June. The average reflectance values of I_3, in blue, green, red and near-infrared wavebands of EMS, was 3.06, 6.88, 3.97 and 29.26 Wm^{-2}, respectively. The reflectance values of I_4 treatment were 3.64, 7.54, 5.25 and 26.02 Wm^{-2}, respectively, higher than the values observed in the I_1, I_2 and I_3 treatments.

Changes in reflectance values in the I_5 treatment (non-irrigated) were similar to the other treatments from the start of the experiment until mid June. However, reflectance values in the blue, green and red wavebands increased, and those in the NIR

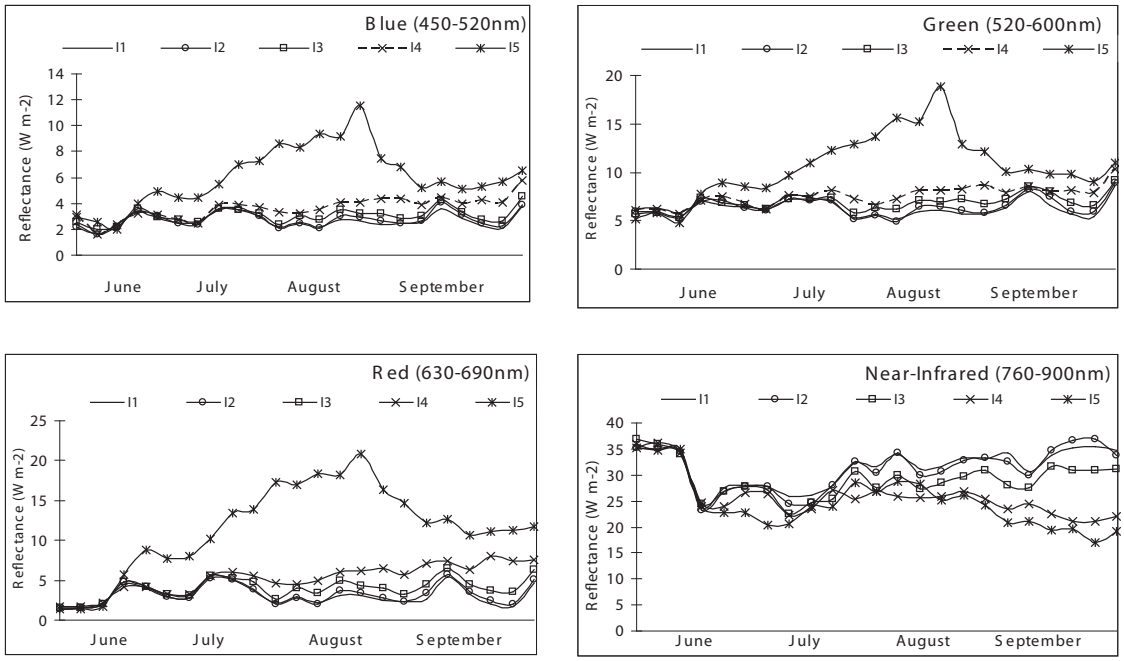


Fig. 2 Spectral reflectance values of Bermuda grass during the study period for each irrigation treatment (I_1–I_4), and the study control treatment (I_5, no irrigation).

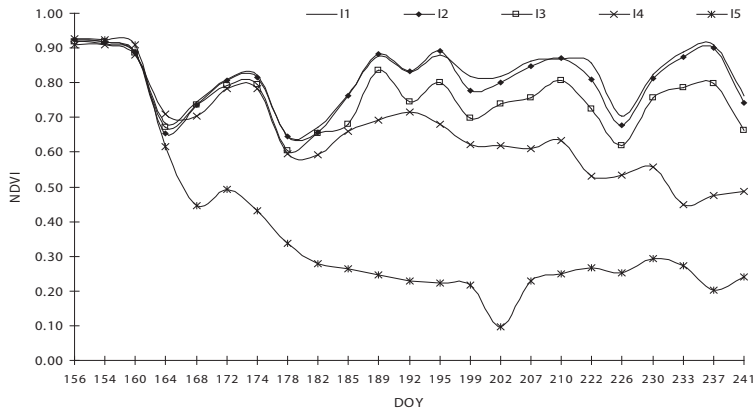


Fig. 3 Time series of normalised difference vegetation index (NDVI) values during the study period for each irrigation treatment (I_1–I_4), and the study control treatment (I_5, no irrigation).

waveband depending on soil water content. The seasonal average reflectance values of non-irrigated treatment (I_5) in blue, green, red and near-infrared wavebands of EMS were 6.15, 10.66, 11.61 and 24.84 Wm^{-2}, respectively. The reflectance values of non-irrigated I_5 plots in blue, green and red portions were higher and the reflectance value in the near-infrared portion were lower than the values obtained in the other treatments.

Time series of NDVI

Although there were variances in NDVI values due to mowing during the experiment, the seasonal average NDVI values of the I_1, I_2, I_3, I_4 treatments and the

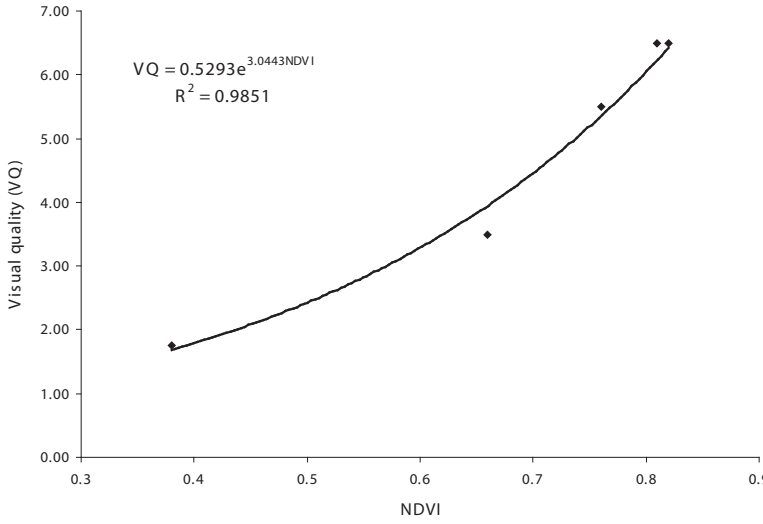


Fig. 4 Relationship between normalised difference vegetation index (NDVI) and visual quality for Bermuda grass.

non-irrigated plot (I_5) were 0.82, 0.81, 0.76, 0.66 and 0.38, respectively. The NDVI values decreased as a function of increasing of crop water stress (Fig. 3).

Monthly and seasonal average of visual colour values for the treatment and non-irrigated plots are presented in Table 5. Our results showed that a non-linear relationship is present between the visual colour values in the I_1, I_2, I_3, I_4, I_5 treatments and NDVI (Fig. 4).

DISCUSSION

For cool season turfgrass under Mediterranean conditions, Baştuğ & Buyuktas (2003) reported that the best turfgrass quality could be obtained when the tensiometer readings in the root depth were kept about 8–11 kPa. The tensiometer readings in I_1 and I_2 treatments were about this range.

Meyer & Gibeault (1986) reported that warm season turfgrass in northern California, USA, could be grown successfully when irrigated as much as 60% of reference crop evapotranspiration which corresponded to a depth of 1203 mm water. In Arizona, USA, Garrot & Mancino (1994) stated that water requirements of low-maintenance Bermuda grass under arid conditions between mid April and mid November were 1105 mm when mowed once a month and irrigated biweekly. They also reported that 930 mm of water would be enough under normal conditions to meet quality and colour standards of turfgrass. Considering that this study was conducted under arid summer season conditions when the demand for irrigation was high, it is seen that the seasonal water use obtained from I_1, I_2, I_3, and I_4 treatments were in accordance with the already published results. Additionally, it can be classified that I_1 and I_2 treatments were well watered (non-stressed), I_3 and I_4 were moderately stressed and stressed treatments, respectively.

Reflectance in the red (550–625 nm), and blue (450–550 nm) wavelengths has been commonly used to estimate green biomass, concentrations of chlorophyll, corotenoid, and nitrogen, as well as dry matter and water content of leaves (Carter 1994; Penuelas et al. 1994; Zarco-Tejada et al. 2003; Sari et al. 2005). As seen in Fig. 2, the crop energy absobtion in blue and red wavebands of EMS decreased in certain intervals, and reflectance values also decreased in the near-infrared portion during the experiment periods. This was mainly caused by temporary stress conditions due to mowing.

The most important reason for low reflectance values in blue and red wavebands is incoming energy absorbtion through the chlorophyll pigments of the leaves for photosynthesis (Curran et al. 1991; Gitelson & Merzlyak 1997; Sari et al. 2005).

Understanding the spectral features of Bermuda grass is important to monitor the seasonal canopy properties and biochemical changes. Seasonal average spectral reflectance values of the treatments are presented in Table 6. Bermuda grass in the study showed lower reflectance values in the blue and red wavelengths and significantly higher reflectance

values in the green and near-infrared wavelengths for all irrigation treatments, similar to the findings of Rees (1990) and Gitelson & Merzylak (1997). The highest water stress level was obtained from the I_5 treatment, the non-irrigated control treatment. Due to high water stress, the I_5 treatment absorbed less energy in blue and red wavebands and exhibited lower reflection in the near-infrared waveband (Table 6). As can be seen in Table 6, energy use increased in the blue and red wavebands, and reflection increased in the near-infrared waveband, depending on water stress levels. Aldakheel et al. (2004) and Moran et al. (1989) found water-stressed canopies to have a lower spectral reflectance in the NIR wavebands than unstressed canopies.

There were also significant reflectance differences of the Bermuda grass in the different irrigation treatments (I_1, I_2 I_3, I_4 and non-irrigated (I_5)). There were highly significant relationships between different irrigation treatments and blue, green, red and near infrared wavelengths ($P < 0.01$, $R^2 = 0.74$, 0.74, 0.72, 0.94 and 0.80) during the vegetation periods (Table 6). The results of tensiometer readings and turfgrass visual quality evaluations of the treatments showed that the crop was water stressed, and visual quality decreased in the I_3 treatment.

However, there was no significant difference among I_1, I_2 and I_3 in blue, green and red wavebands of EMS. The I_3 treatment had a critical level of water stress compared to the others. Bermuda grass in I_3 and I_4 treatments could not absorb the energy in the blue and red portions, whereas it had a high reflectance in the green portion. In near-infrared waveband, the crop could not reflect harmful rays because of water stress condition (Sari et al. 2005). These results are consistent with visual quality evaluation and the root zone tensiometer readings (Table 3).

Although I_3 had water stress, Bermuda grass energy absorbtion continued for photosynthesis and showed a pattern similar to I_1 and I_2 treatments in blue, green and red wavebands. As a result, the blue, green and red portions of EMS could not detect water stress conditions, as the Bermuda grass did not give enough response in this range of EMS, in spite of water stress. However, in the near-infrared portion, there was a statistically significant difference between I_3 and the well watered treatments (I_1 and I_2). The highest reflectance values obtained from I_1 and I_2 treatments indicate that the crop was healthy enough and lower reflectance values in the I_3 treatment indicates the crop was affected by water stress (Aldakheel et al. 2004).

The lowest reflectance values were obtained from the I_4 treatment and the non-irrigated (I_5) plots in the NIR waveband. These crops could not reflect the energy in this waveband because of increasing water stress. However, the results showed that there was no statistically significant difference between I_4 and I_5 in the NIR waveband, whereas tensiometer readings and visual quality values were significantly different (Table 6). The NIR waveband could not effectively distinguish water stress levels in the I_4 treatment and the non-irrigated (I_5) plots. The NIR portion of the EMS was a good indicator of crop water stress levels, but was not good enough under high water stress level conditions.

The reflectance values in some spectral wavebands had advantages for determination of the crop water stress but were not sufficient individually. Korobov & Railyan (1993) found that the near-infrared and red portions of the spectrum had the highest correlation with plant physiological variables. The NDVI is an important tool for determining of crop water stress levels (Penuelas et al. 1997). For this

Table 6 Average reflectance values of blue, green, red and near-infrared wavelength. Data are means of three treatments. Treatments with no common letters in column are significantly different ($P < 0.05$, Duncan's multiple range test). NDVI, Normalised difference vegetation index.

	Reflectance values (W m^{-2})				
Treatments	450–520 nm	520–600 nm	630–690 nm	760–900 nm	NDVI
I_1	2.68 c	6.35 c	3.08 c	31.59 a	0.82 a
I_2	2.75 c	6.44 c	3.22 c	31.34 a	0.81 a
I_3	3.06 c	6.88 c	3.97 c	29.26 b	0.76 b
I_4	3.64 b	7.54 b	5.25 b	26.02 c	0.66 c
I_5	6.15 a	10.66 a	11.61 a	24.84 c	0.38 d
Anova	$P < 0.01$ $R^2 = 0.74$	$P < 0.01$ $R^2 = 0.74$	$P < 0.01$ $R^2 = 0.72$	$P < 0.01$ $R^2 = 0.94$	$P < 0.01$ $R^2 = 0.80$

reason, NDVI analysis was also evaluated to determine water stress conditions (Table 6). As seen in Table 6, NDVI values decreased with increasing crop water stress level. Reflectance values in NDVI and with the NIR region for the I_1, I_2 and I_3 treatments had similar patterns. However, NDVI analysis was able to distinguish the I_4 and non-irrigated I_5 treatments while the NIR region was not ($P < 0.01$, $R^2 = 0.80$).

The emphasis of this study was not on the effects of prolonged water stress that are clearly visible to the eye, but rather subtle changes in the crop water status that grass managers contend with as a crop irrigation approaches. Pre-visual detection of water stress using hand-held radiometers would permit more accurate timing of irrigations before the crop is adversely affected. Fry & Butler (1989) and Jalali-Farahani et al. (1993) reported that turfgrass visual quality decreased depending on water stress level increases. As seen in Table 5, the visual quality results are consistent with these reports.

Bermuda grass is widely used in golf courses and residential areas in the Mediterranean region, and colour quality is extremely important. As observed in Fig. 4, there was a significant non-linear relationship between NDVI and visual quality values ($P < 0.01$, $R^2 = 0.98$), and this relationship is one of the valuable results of this study. Fry & Butler (1989) reported for tall fescue (*Festuca arundinacea* Schreb.) that the colour quality decreased with increasing water stress. In general, several studies indicated that the colour quality grading numbers ranged from 1 to 9 with an acceptable minimum visual quality number of 6 (Kopp & Guillard 2002). In this study, an acceptable colour quality was obtained in the I_1 and I_2 treatments whereas the I_3 and I_4 treatments did not produce a desirable colour quality. Such a relationship could be used by turfgrass managers to investigate seasonal changes in turfgrass colour. Bell et al. (2002) reported that NDVI would be most beneficial for evaluating turf colour. When compared with human evaluators and machine evaluation over time, the researchers found that NDVI was more consistent than human evaluators.

Our results showed that the effects of different irrigation levels on Bermuda grass (*Cynodon dactylon*) could be determined by using spectral reflectance, especially in the NIR reflectance region and a ratio of the two wavebands (NDVI). Moreover, NDVI was more efficient than NIR reflectance regions for estimating the onset of stress. These results were in agreement with the previous studies conducted on different plant species (Sinclair et al. 1971; Yoder & Pettigrew-Crosby 1995; Blackburn 1998; Yang & Ko 1998; Mutanga et al. 2003).

CONCLUSIONS

This study was conducted to investigate how Bermuda grass reflectance in the blue, green, red, and near-infrared wavebands changes as a function of water stress. Four different irrigation treatments were examined: 100% (I_1), 75% (I_2), 50% (I_3) and 25% (I_4), which were compared to a non-irrigated control (I_5). Spectral reflectances were collected using a hand-held spectroradiometer. Highly significant relationships between irrigation treatments and near infrared wavelengths ($P < 0.01$, $R^2 = 0.94$) were observed during the study period. Except for the first week, a significant relationship was found between vegetation index (NDVI) and irrigation treatments ($P < 0.01$, $R^2 = 0.80$). Based on the results, it is concluded that water stress of Bermuda grass will be best indicated by NDVI. Additionally, analysis of the data indicated that it is possible to use remotely sensed data to develop maps of water stress conditions of Bermuda grass (*Cynodon dactylon*).

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