JOSH
JOURNAL OF SPATIAL HYDROLOGY

Journal of Spatial Hydrology
Vol.12, No.1 Fall 2014

# Estimation of crop water stress index in almond orchards using thermal aerial imagery

Sagarika Roy[1]*, and Duke Ophori[1].

## Abstract

An important method for estimating Crop Water Stress Index (CWSI) is by measuring surface temperature of the canopy. A remote sensing method was used to estimate CWSI of an almond orchard in Paramount farm, California. An aerial remote measurement using MASTER (MODIS/ASTER) thermal band data used to measure canopy temperature (Tc). The empirical relationship for canopy- air temperatures difference (Tc-Ta) versus Vapor Pressure Deficit (VPD) represents the crop water stress quantitatively. The results implied that the average value of CWSI for well-irrigated (non-stressed) almonds is 0.24 while the almond yield is affected when the average CSWI values for stressed crop due to lack of irrigation is greater than 0.5. The difference in crop canopy to air temperature (Tc-Ta), measured was negatively related to the VPD [$R^2=0.96$ and $p<0.0001$]. However, the relationship between (Tc-Ta) and VPD used to develop a non-stressed baseline equation for almonds, which estimates CWSI. Determination of CSWI is useful for irrigation scheduling and water management.

Keywords: Crop Water Stress Index, MASTER, canopy, vapor pressure deficit, almond

---

[1] Department of Earth & Environmental Studies. Montclair State University, 1 Normal Avenue, Upper Montclair, New Jersey 07043
roy.sagarika@gmail.com, roys2@mail.montclair.edu

*Corresponding author

## Introduction

Monitoring and detecting crop water stress is important to know whether the crop is healthy or not throughout the growing season. One way to get an indicator for crop water stress is measuring plant water content; fresh biomass minus dry biomass. This is a very time consuming and destructive method, so it is not easily applicable to construct time series of crop water stress. The widely used method was developed by Idso et al. (1981) and Jackson et al. (1981), using remote sensing method in the thermal infrared (TIR) spectrum. Jackson et al. (1981) suggested that the energy balance isolates net radiation from the sun into sensible heat (that heats the air) and latent heat (used for transpiration). The canopy-air temperature difference was explained by the energy balance method on the plant surface (Jackson, 1982, Guyot, 1998, Alves and Pereira, 1998 and Al-Faraj et al., 2001). This is important for estimating Crop Water Stress Index (CWSI) by measuring the surface temperature of canopy (Tc) and air (Ta). Factors such as water stress, stomata conductivity, heat flux, transpiration and the cooling causes plants to close their stomata, as a result, evaporation decreases and the canopy temperature increases, when compared to non-stressed plants (Stokcle and Dugas, 1992). The surface temperature and crop water stress are associated for the reason that as a crop transpires, the evaporated water cools the canopy below the air temperature. Moreover, as a crop becomes water stressed, the transpiration will decrease and the crop surface temperatures will then increase sometimes more than the air temperature (Jackson 1982). In water stressed condition, the plants tend close their stomata as a result, evaporation decreases and the canopy temperature increases, when compared to non-stressed plants. Therefore, the concept of canopy temperature was implemented to determine plant water status (Stokcle and Dugas, 1992). The empirical relationship for canopy- air temperatures difference (Tc-Ta) versus vapor pressure deficit (VPD) was represented to quantify the crop water stress. Reginato and Howe (1985) found that cotton yield was declined when the average CWSI during the season was greater than 0.2. A model developed by Kjelgaard et al. (1996) for evaluating integrated daily evapotranspiration (ET) rates to plan irrigation requirements (how much to irrigate) as a complement to CWSI measurements (when to irrigate); both techniques are irrigation scheduling tools which use much of the same data.

Jackson et al. (1981) and Idso et al. (1981) used classical methods for monitoring crop water stress, which includes in-situ measurement such as soil water content, plant properties or meteorological variables for estimating water loss from the plant-soil system during a given period. Ground measurements are difficult and time consuming for each point scale and cannot obtain accurate spatial estimation. Indirect measurement of canopy temperature radiance using thermal band of the MODIS/ASTER simulator (MASTER) sensor is related to crop water stress because under non-stressed condition the transpiration cools the leaves, therefore, Tc-Ta is negative. MASTER simulator has the characteristics of both the EOS Terra Advanced Space borne Thermal Emission Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectro-radiometer (MODIS) sensors (Hook et al., 2000). This sensor has 50 spectral bands over the spectral range 0.4 to 12 µm (visible through thermal infrared) at a variety of spatial resolutions. In this study, CWSI was applied because there is full canopy cover and the soil heat flux is assumed negligible. For partially vegetated field, Water Deficit Index (WDI) is estimated (Moran et al., 1994). WDI employ the combination of spectral vegetation indices and surface temperature based on the same theory as CWSI. To understand crop water use and irrigation requirement, the analysis of CWSI are based on three main environmental variables: plant canopy temperature (Tc), air temperature (Ta) and atmospheric vapor pressure deficiency (VPD).

The objective of this study is to integrate meteorological data and remote sensing to obtain spatial water stress spatially using the baseline parameters of almond for calculating CWSI.

## Study area and Data

This study focused on calculating the CWSI for an almond field in Paramount Farm (35$^{o}$30’N, 119$^{o}$39’W), California (Figure 1). The valley occupies two-thirds of the southern Central Valley in California. San Joaquin River flows in the northern part of the San Joaquin Valley and drains to the San Francisco Bay. About 4 percent of the basin area is urban. Southern San Joaquin is the world’s largest supplier of almonds with more the 4,000 acres of almond orchards which is over a 4-billion dollar industry. Geographically, the southern part of the San Joaquin Valley is the Tulare Basin, bordered by the Sierra Nevada on the east, the Tehachapi Mountains on the south, and Coast Ranges on the west. The northern extent corresponds to the Kings River. The main land-use is agriculture.

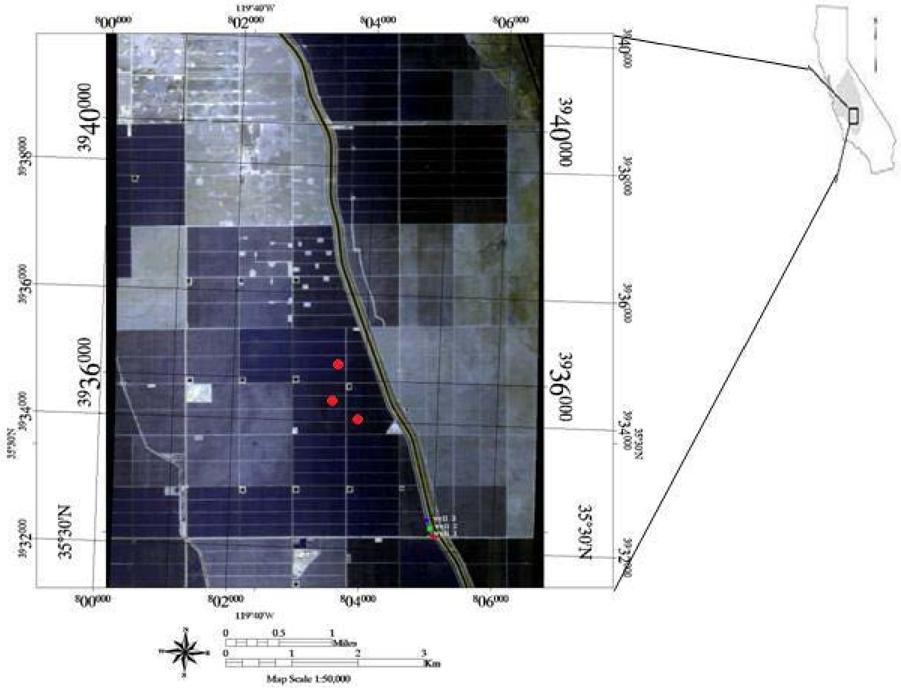

**Figure 1**. False color composite (Band 1, Band 2 and Band 6) of MASTER image for Paramount Farm in Southern San Joaquin Valley , California. Red dot in the image shows the location of the thermal IR radiometer measurements.

An airborne image (Figure 1) was obtained from MASTER simulator onboard the NASA DC-8 aircraft at an altitude of 11,500 m on July 24, 2009 with a spatial resolution of 7.2 m. The image acquired around 12:00 PM PST. Furthermore the MASTER level 1-B image was radiometrically and geometrically corrected. Canopy surface temperature measured with Infrared Thermometer (IRT) and calibrated using thermal infrared band of MASTER image. Air temperature, relative humidity, vapor pressure, wind speed, solar radiation were obtained from the California Irrigation Management Information System (CIMIS) station in Belridge (station number 143) at Kern County, California.

## Methodology

Idso et al. (1981) developed empirical linear relationships between canopy and air temperature difference dT (Tc-Ta) and Vapor Pressure Deficit (VPD). The lower limit of dT versus VPD represents that the crop is well watered (minimum stress). Upper limit of dT versus VPD means the crop is not transpiring and dry (maximum stress) (Reginato, 1983; Stegman and Soderlund, 1992; Stockle and Dugas, 1992). Application of CWSI with satellite- or aircraft-based measurements of surface temperature is generally applied to full-canopy conditions so that the surface temperature is equal to canopy temperature. Decreased water uptake closes stomata of the leaves resulted in reduction of transpiration. The leaf or canopy temperature can be used to quantify plant water stress. The Crop Water Stress Index is calculated using the procedure of Idso et al. (1981)

$$CWSI = \frac{(dT - dT_l)}{(dT_u - dT_l)} \qquad (1)$$

where dT is the difference between air temperature (Ta) and canopy temperature (Tc) which is Tc-Ta. $dT_u$ is the upper limit of the air temperature and canopy temperature difference (non-transpiring, dry), and maximum stress baseline. $dT_l$ is the lower limit of the air temperature and canopy temperature difference (transpiring, well-watered) and non water stress baseline. The values for the CWSI are within zero and one where zero indicates no stress and value of one indicates maximum stress. The thermal data from IR radiometer was used to calibrate thermal IR band (band 42) of MASTER image. This was used to measure the surface canopy temperature of the almonds in the MASTER image by using the algorithm obtained from Vicente et al., 1992.

$$\mathrm{Tc} = \frac{\mathrm{hc}}{\lambda \mathrm{k}[\ln\left(\frac{2\mathrm{hc}^2}{\lambda^5} + \mathrm{L_{BB}}\right) - \ln(\mathrm{L_{BB}})]} \qquad (2)$$

where Tc is surface temperature of canopy (K), λ is wavelength of band 42 of MASTER sensor (m), h is the plank constant (6.626068 x 10-3 m$^2$kg/s), c is the speed of light, k is the Boltzmann’s constant (1.3806503 x $10^{-23}$ m$^2$kg/s$^2$/K), LBB is the radiance of blackbody at same temperature as surface (W/m$^2$/sr/m)

There are many methods to compute the upper and lower limit of CWSI equation. However, Idso et al. (1981) is widely used. He suggested that the changes in upper limit and lower limit is due to variation in Vapor Pressure Deficit (VPD). Therefore, VPD is calculated as:

$$\mathrm{VPD} = \mathrm{VPsat} - \mathrm{VP} \qquad (3)$$

where VPsat is the maximum vapor pressure at the given temperature and pressure (i.e the maximum water vapor the air can hold) and VP is the actual vapor pressure (i.e. partial pressure of the water vapor in the atmosphere). The air temperature and RH measurements were used to calculate the VPD of the air as (Allen et al. 1998):

$$es = 0.6108 \times \exp[17.27Ta/(Ta + 237.3)] \qquad (4)$$

$$ea = es \times (RH/100) \qquad (5)$$

$$\mathrm{VPD} = es - ea \qquad (6)$$

where es is the saturation vapor pressure at the given temperature (kPa), ea is the actual vapor pressure (kPa), Ta is the air temperature (K), RH is the relative humidity (%) and VPD is the vapor pressure deficient (kPa). The canopy-air temperature difference for a well-watered crop (lower limit) and severely stressed crop (upper limit) can be calculated for equation 1 as:

$$dT_l = \mathrm{Intercept} + \mathrm{Slope}\ (\mathrm{VPD}) \qquad (7)$$

$$dT_u = \mathrm{Intercept} + \mathrm{Slope}\ [es\ (Ta) - es(Ta + \mathrm{Intercept})] \qquad (8)$$

where es (Ta) is the saturation vapor pressure at air temperature (kPa), and

es (Ta + Intercept) is the saturation vapor pressure at air temperature plus the Intercept value for the crop. Thus, with a measure of humidity, air temperature, and canopy temperature, it is now possible to determine CWSI.

Figure 2 illustrates an example of a VPD baseline of alfalfa (Idso and Jackson, 1981). The upper line represents non-transpiring vegetation suggested as maximum water stress. All measurements should lie between these two lines. The exact position of baseline parameters anticipated to position between these two lines determines the amount of water stress. CWSI value is allocated between 0 and 1, where 0 is on the baseline and 1 is on the upper line. The blue line is the baseline of lower limit of Tc-Ta (i.e., non water-stressed baseline $dT_l$). The red line is the canopy-air temperature difference for a non-transpiring crop $dT_u$. In Figure 2, Idso and Jackson et al. (1981) illustrates an approach to obtain the parameters of $dT_u$ and $dT_l$ based on given slopes and intercept values of alfalfa. For example, the blue line represent slope and intercept values of alfalfa that is -1.92 and 0.51 respectively. Slope and intercept values have been determined for a number of crops as shown in the Table 1. Although, the slope and intercept values of almond are not calculated. Consequently, for a given vapor pressure deficit, the CWSI can be calculated if the slope and intercept values are known.

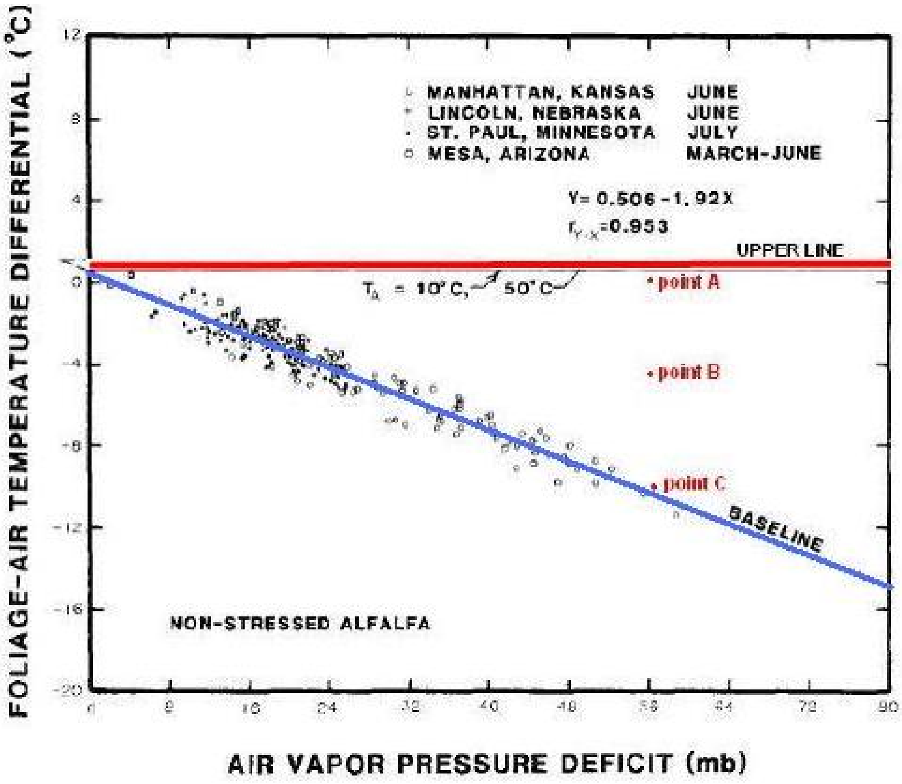

**Figure 2**. CWSI diagram, with 3 hypothetical measurements. Point A is in severe water stress because CWSI is around 1, point B suffers water stress with a CWSI of 0.5, and point C does not suffer from any water stress, so CWSI is close to 0. (Figure adapted from Idso and Jackson et al., 1981.)

**Table 1**. Baseline parameters for various crops – sunlit conditions (Idso, 1982)

| Crop | Intercept | Slope |
|---|---|---|
| Alfalfa | 0.51 | -1.92 |
| Barley (pre-heading) | 2.01 | -2.25 |
| Barley (post-heading) | 1.72 | -1.23 |
| Bean | 2.91 | -2.35 |
| Beet | 5.16 | -2.3 |
| Corn (no tassels) | 3.11 | -1.97 |
| Cowpea | 1.32 | -1.84 |
| Cucumber | 4.88 | -2.52 |
| Lettuce, leaf | 4.18 | -2.96 |
| Potato | 1.77 | -1.83 |
| Soybean | 1.44 | 1.34 |
| Tomato | 2.86 | -1.96 |
| Wheat (pre-heading) | 3.38 | -3.25 |
| Wheat (post-heading) | 2.88 | -2.11 |

## Results and Discussion

The canopy-air temperature difference for lower limit (well irrigated) and upper limit (stressed crop) is calculated using intercept and slope values. These values are used to calculate the CWSI, which is often referred to as the “empirical” CWSI. In the first calibration, Tc-Ta of MASTER imagery was negative, and the average temperature difference is ± 5.02 °C. This is a problem because the test field was well watered and the occurred transpiration should cause a canopy temperature lower than the air temperature. On the contrary, the ground based thermal IR radiometer measurements of Tc-Ta was negative. Therefore, another calibration was conducted. The canopy temperatures measured by the thermal IR radiometer are averaged for three different trees to get a representative temperature for those almond trees. The locations of these trees are identified in the MASTER image as shown in Figure 1; therefore, the temperatures from the nine surrounding pixels were averaged in the MASTER data. The difference between the MASTER temperatures and the thermal IR radiometer temperatures were calculated and then averaged. The average difference of 7.87 °C was applied to the MASTER data.

There are no studies on baseline parameters for almond crop. Therefore, in this study, slope and intercept parameters are computed using thermal remote sensing. A linear regression was executed to determine the relationship between Tc-Ta and VPD. The baseline equation was developed for almond orchards shown in Figure 3. The value for the upper line, is created above the plot that appeared to be in the most water stress. The upper limit is: $dT_u$ = (Tc − Ta) u, was 274 °K (~1°C) when the air temperature at solar noon was 298 °K. In a similar study, Throssell et al. (1987)

determined that the upper limit for Kentucky bluegrass was 12.71 °C. The equation that defines the lower baseline is: $dT_l$ = Tc-Ta = −1.16 VPD + 31.6 ($R^2$ = 0.96, $p < 0.0001$) shown in Figure 3. The slope and intercept values of almond is -1.16 and 31.6 respectively. These values are similar to baseline parameters of various crops illustrated by Idso (1982) as shown in Table 1.

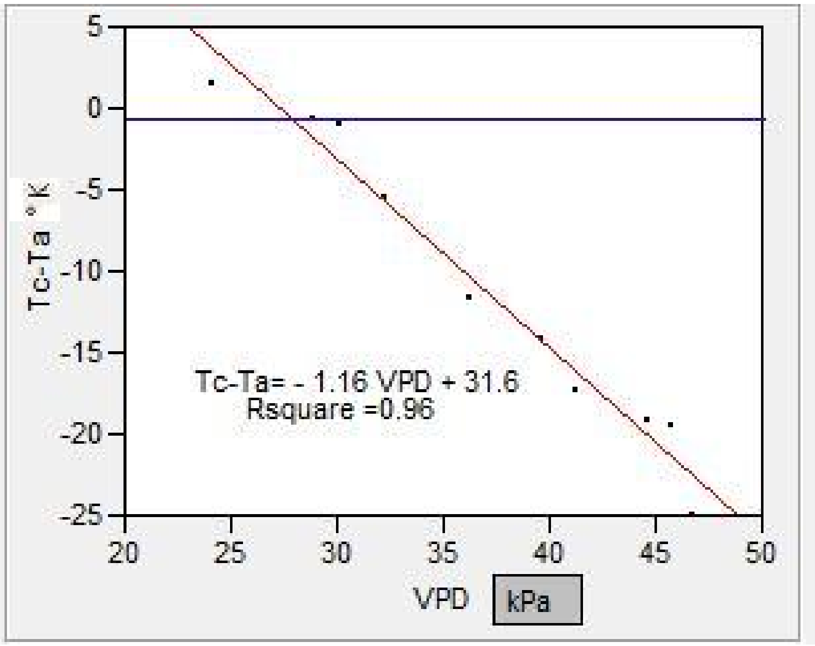

**Figure 3.** Non-stressed baselines for CWSI calculation of almond orchards ($p < 0.0001$).

The average value of CWSI for well-irrigated (non-stressed) almonds is 0.24 while the average CSWI values for water-stressed is between 0.5 to 0.7. Bare land show white tone illustrating the absence of vegetation and hence it is maximum dry with CWSI appearing between 0.8 to 1 as shown in Figure 4.

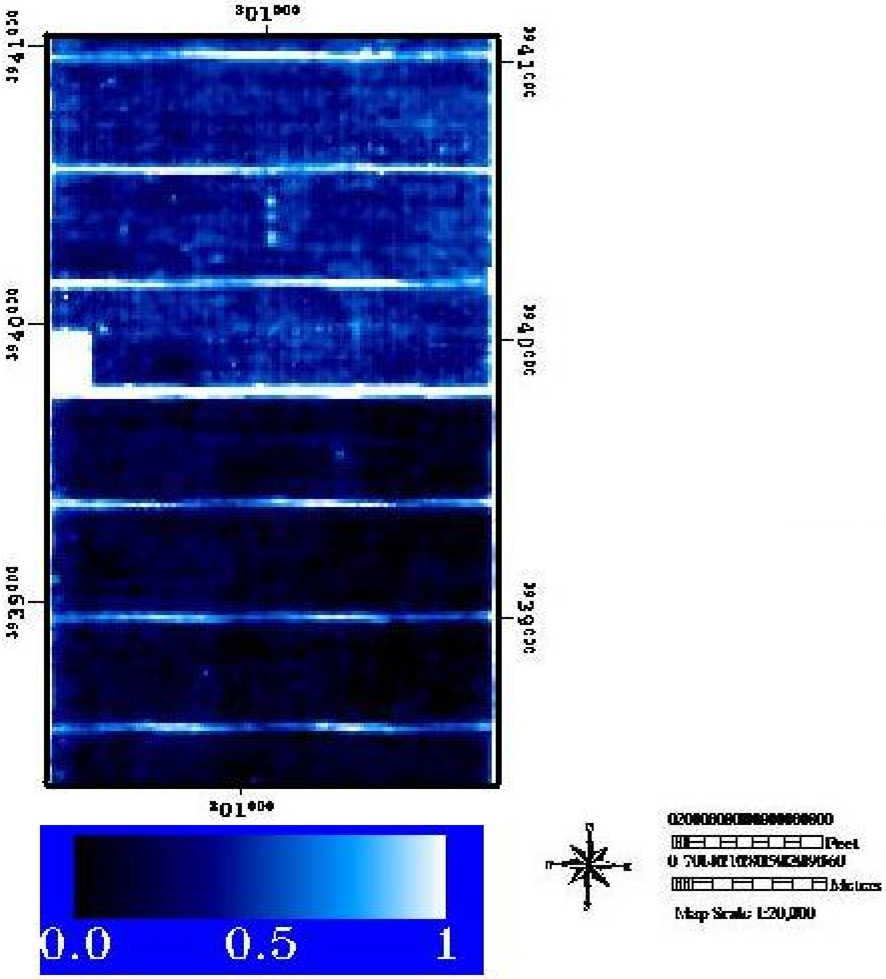

**Figure 4**. CWSI value of almond orchards

## Conclusion

Remotely sensed thermal infrared based crop water stress provides a useful tool for understanding crop water requirements. MASTER sensor's TIR measurement is useful to evaluate spatial distribution of plant transpiration in high spatial resolution. TIR measurement offers direct link between the process of transpiration and thermal response of canopy. Idso et al. and Jackson et al. (1981) suggested the theory behind the energy balance that isolates net radiation from the sun into sensible heat (that heats the air) and latent heat (used for transpiration). They used classical method to study in-situ measurement of soil water content, plant properties or meteorological variables to estimate water lost from the plant-soil system during a given period. In this study, calibration of in-situ thermal data was done by taking the difference between the MASTER temperature and the thermal IR radiometer temperature for each tree and averaged this difference, which was 7.87°C. It is found so far that the upper limit is dTu = (Tc − Ta) u, was 274 °K (~1°C) when the air temperature at solar noon was 298 °K. The analysis shows that the average value of CWSI for well-irrigated (non-stressed) almond crop was 0.24 while the almond yield is affected when the average CSWI values for water stressed crop is greater than 0.5.

In conclusion, remotely-sensed thermal infrared measurements offer monitoring and managing plant ecosystem health. CWSI provided a useful tool for the evaluation of crop water status especially in arid agricultural land. Therefore, CWSI is a promising tool for irrigation scheduling for almonds and other agricultural crops.

## References

Alves, A. Perrier, and Pereira L.S. (1998) Aerodynamic and surface resistances of complete cover crops: how is the “Big Leaf”?, *Trans.* American Society of Civil Engineers Vol.41(1): 345–351.

Al-Faraj, A., Meyer G.E., and Horst G.L. (2001) crop water stress index for tall fescue (Fetusca arundinacea Schreb.) irrigation decision-making: a traditional method, Comput. Electron. Agric., 31: 107–124.

Guyot, G. (1998) Physics of the Environment and Climate. Wiley-Praxis Series in Atmospheric Physics and Climatology. John Wiley and Sons-Praxis Publishing Association, pp 632.

Idso, S.B. (1982) Non-water-stressed baseline: a key to measuring and interpreting plant water stress. Agriculture Meteorology; 27: 59–70.

Jalali-Farahani H.R., D.C. Slack, D.M. Kopec and A.D. Matthias. (1993) Crop water-stress index models for Bermuda grass turf—a comparison. Agron. J.; 85 (6): 1210–1217.

Jackson, R.D., S.B. Idso, R.J. Reginato, and P.J. Pinter Jr. (1981) Canopy temperature as a crop water stress indicator. Water Resources Research*;* 17: 1133.

Jackson R.D. (1982) Canopy Temperature and Crop Water Stress Index. Advances in Irrigation Journal; 1: 43–85.

Moran M.S., T.R. Clarke, Y. Inoue and A. Vidal. (1994) Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sens. Environ; 49:246–263.

Reginato, R.J. (1983) Field quantification of crop water stress. *A*SAE.*;* 26: 772–775.

Stegman, E.C., M. Soderlund (1992) Irrigation scheduling of spring wheat using infrared thermometry. ASAE.;35: 143–152.

Stokcle C.O., and W.A. Dugas (1992) Evaluating canopy temperature-based indices for irrigation scheduling. Irrig. Sci.;13: 31–37.

Throssell, R.N., Carrow, and G.A. Milliken (1987) Canopy temperature based irrigation scheduling indices for Kentucky bluegrass turf. Crop Sci.; 27: 126–131.

Vicente Caselles, Jose A Sobrino, and Cesar Coll (1992) A Physical model for interpreting the land surface temperature obtained by remote sensors over incomplete canopies. Remote Sensing of Environment.; 39: 203-211.