EVALUATING WATER STATUS IN POTATO FIELDS USING COMBINED INFORMATION FROM RGB AND THERMAL AERIAL IMAGES

R. Rud, Y. Cohen, V. Alchanatis, A. Cohen, M. Sprintsin, A. Levi and R. Brikman

Institute of Agricultural Engineering
Agricultural Research Organization (ARO), Volcani Center
Bet-Dagan, Israel

B. Heuer, J. H. Lemcoff and T. Markovits

Institute of Soil, Water and Environmental Sciences
Agricultural Research Organization (ARO), Volcani Center
Bet-Dagan, Israel

Z. Dar

The Agricultural Extension Service
Ministry of Agriculture State of Israel
Bet-Dagan, Israel

C. Rosen, D. Mulla and T. Nigon

Department of Soil, Water, and Climate
University of Minnesota
St. Paul, Minnesota, USA

ABSTRACT

Potato yield and quality are highly dependent on an adequate supply of water. In this study the combined information from RGB and thermal aerial images to evaluate water status in potato fields was examined. Irrigation experiments were conducted on commercial potato fields (Desiree; drippers). In 2011, three water levels (100%, 70%, and 50%) were induced with three replicates and two thermal and RGB aerial images were acquired. Vegetation indices were extracted from the RGB and used for distinguishing vegetation from soil. Canopy temperature was then delineated from the thermal images. Crop water stress index (CWSI) was calculated for each replicate, using various minimum reference temperatures (*Twet*) and the empirical evaluation of maximum reference (*Tdry*; $Tair+5^0 C$). Statistical tests and comparison with stomatal conductance measurements were made to evaluate the differences between water levels while employing the various CWSI values. CWSI effectiveness in identification of water status is discussed.

Keywords: Potato, CWSI, Remote Sensing, Thermography, Irrigation

INTRODUCTION

Potato is an important and high value crop. Potato yield and quality are highly dependent on an adequate supply of water (Heuer and Nadler, 1995; Alva, 2008). The relatively shallow root system of the potato crop increases its sensitivity to water stress when it is grown on coarse-textured soils in semiarid zones and its sensitivity to nitrate leaching in temperate zones. Applying the right amount of water in the right place at the right physiological stage is a challenge for potato growers. Potato growers usually increase irrigation (and fertilization) levels beyond the recommendations in response to uncertainties regarding the recommendations suitability. Recently, the global attention to the lack of high quality water for irrigation has prompted efforts to identify strategies that will improve water efficiency in the major crops like potato.

Remote sensing techniques using the thermal part of the spectrum can provide indication on the plant's water status. Early studies showed a relationship between plant canopy temperature and water status (Ehrler, 1973). Costa et al., (1997) proposed a water stress index for potato plants which combined atmospheric demand for water and canopy temperature. These relationships were later refined to define a crop water stress index (CWSI) based on canopy temperature and meteorological conditions (Idso et al., 1981). A major limitation of applying this technique robustly is the need of pure canopy temperature. To overcome this, thermal images were combined with images in the VIS-NIR (Moran et al., 1994; Möller et al., 2007; Sela et al., 2007; Tilling et al., 2007). Nevertheless, the quality of canopy temperature data is influenced by the spatial resolution of the combined sources of images. It necessitates the availability of two different sensors to provide the images in the VIS-NIR and Thermal Infrared (TIR) ranges.

An additional challenge applying the CWSI for monitoring crop water status is the need for minimum and maximum temperature references (*Twet* and *Tdry*, respectively). The CWSI has a normalized span of values indicating range of well-watered to stressed situation with relation to extreme conditions designated by the referenced *Twet* and *Tdry* temperature. There are various approaches for calculating CWSI values, employing *Twet* and *Tdry* from different sources (Ben-Gal et al., 2009). Ben-Gal showed that applying theoretical (based on meteorological models) or empirical CWSI using ground-based TIR and RGB images, resulted in high correlation to plant (olives) and soil status measurements for both cases.

In this study we examine the effectiveness of different minimum temperature to calculate CWSI to evaluate water status of potato plants and introduce a statistical approach to calculate minimum temperature based solely on aerial thermal images.

MATERIALS AND METHODS

Calculation of CWSI utilizing various approaches

Indirect measurements of water stress in plants are based on the inversed correlation between leaf temperature and stomatal opening (Fuchs, 1990). CWSI

is based on the differences of temperature between an arbitrary sampled leaf and a well watered leaf. The latter is referred to as lower boundary of canopy temperature with fully open stomata (undisturbed transpiring leaf). Since canopy temperature is influenced by meteorological conditions, CWSI is a normalized form of temperature differences relative to an upper temperature boundary. The upper boundary represents temperature of a non-transpiring leaf with stomata completely closed. CWSI is defined as follows (Idso et al., 1981):

$$(1) \qquad CWSI = \frac{Tl - Twet}{Tdry - Twet}$$

where *Tl* is a sampled leaf or canopy temperature, and *Twet* and *Tdry* are the minimum and maximum boundary temperature, respectively.

The upper and lower boundary temperatures can be derived empirically, theoretically, or statistically. In this study *Tdry* was used only in its empirical form, i.e. $Tair+5^0\ C$ as it was found a suitable estimate of the maximum leaf temperature for various crops (Alchanatis et al., 2010; Möller et al., 2007; Ben-Gal et al., 2009). On the other hand, three forms of *Twet* were examined:

1. Empirical: *Twet* was determined based on reference measurement of artificial wet reference surface (AWRS) (Meron et al., 2003).
2. Theoretical: *Twet* was calculated based on radiative energy balance (Jones, 1999; Ben-Gal et al., 2009).
3. Statistical: *Twet* was determined as the mean of the lowest 5% of the canopy temperature in the whole experimental field. In this approach it is assumed that certain areas in the field are well-irrigated or over-irrigation.

The statistical approach was recently suggested for variable-rate fertilization (Schepers and Holland, 2011) but was not utilized in other research employing remotely sensed techniques for monitoring plant water status.

Canopy temperature (denoted *Tl* in eq. 1) was extracted in two ways:

1. Using RGB image: Vegetation indices in the VIS-NIR were used to distinguish between vegetation and soil to extract vegetation pixels and mask the TIR images. RGB images were co-registered with TIR images and vegetation indices (eq. 2). The vegetation index was based on the RGB image bands, formulated as a combined modification of two known indices, the NDVI and the SIPI (Rouse et al, 1973; Peñuelas et al., 1995). It was calculated as follows:

$$(2) \qquad VI_{RGB} = \frac{green - red}{green + blue}$$

where *green, red* and *blue*, are reflectance value in each RGB image bands. Alternatively, in the case of aerial images, an unmixing approach was used with RGB images to determine the fraction of vegetation within each pixel of the TIR image.

2. Using TIR images: Separation between vegetation and background was based on Meron et al. (2010):

$$(3) \qquad Tair - 10^{o}c < Tl < Tair + 7^{o}c$$

where *Tair* is the air temperature as measured at the time of the TIR image acquisition.

Then the mean canopy temperature, the mean of the lowest 33% percent of the canopy temperature of each replicate, was used as *Tl* (Meron et al., 2010).

Table 1 describes the different approaches used for calculating CWSI values.

Table 1. List of CWSI types examined

	CWSI type	*Tl*	*Twet*
Ground-based images	CWSIe-ground	RGB	Empirical (AWRS)
Aerial images	CWSIe-TIR[1]	TIR	Empirical (AWRS)
	CWSIe-RGB	RGB (unmix.)	Empirical (AWRS)
	CWSIs-TIRs[2]	TIR (stats)	TIR (stats)
	CWSIt-TIRs[2]	TIR (stats)	Meteor. conditions
	CWSIe-TIRs[2]	TIR (stats)	Empirical (AWRS)

1 and 2 are the mean canopy temperature and the mean of the lowest 33% of the canopy temperature of each replicate.

Study site

A field experiment was conducted in the spring growing season of 2011 in a commercial potato field (*Solanum tuberosum* L. cv. Desiree) at Kibbutz Ruhama, Israel (31.38º N, 34.59º E). The soil at the site is classified as Loessial arid brown soils.

The experiment was set up as strips of irrigation rates over an area of 62 m x 180 m. Each treatment included 3 replicates. Irrigation rate was scheduled every 2-3 days according to 50%, 70% and 100% of the pan-evaporation rate. Irrigation was applied with drippers. Summing up irrigation with rain amounts, plots under 50%, 70% and 100% treatments received 154 mm (58%), 200 mm (75%), and 268 mm (100%) throughout the measurement period (March to May).

Measurements of plant status and meteorological conditions

Water status measurements of stomatal conductance (SC) were done using the LI-COR® 1600 leaf porometer (LI-COR Biosciences, Lincoln, NE, USA) around the time of solar zenith (1130-1430 local time). Four leaves were measured from each replicate. The samples were taken at the terminal sunlit leaflet of the fourth leaf from the apex of the shoot.

Global radiation, wind speed, air temperature and relative humidity were measured 1 m above the canopy by a meteorological station positioned within the experimental plot. The sampling rate was every 10 sec' (excluding wind - every 1

sec'), and 1-min averages were recorded by a data logger (Campbell Scientific, Logan, UT, USA). Meteorological measurements were done throughout all hours of data collection.

Image acquisition and processing

TIR and RGB images of each plot were taken around the time of solar zenith (1130-1430 local time). Table 2 depicts details of the cameras that were used for aerial and ground TIR image acquisition, and on the acquired image properties. Both cameras are sensitive in the spectral band of 7.5-13 μm and have 0.1^{o} K sensitivity with 24° FOV.

Table 2. Cameras and image details

	Camera model	Sensor	Accuracy	Acq. height	Spatial res.
		pixel	^{o}K	m	m
Ground TIR images	SC2000, FLIR systems	320×240 microbolo-meter sensor	±2	10	0.02
Aerial TIR images	IDM200, JeanOptics	640×480 microbolo-meter sensor	±1.5	420	0.35

Ground-based TIR and RGB images were acquired at four dates during the season, and in two of them aerial images were also acquired. Ground TIR and RGB images were aligned and registered. Then, the co-registered images were used for segmentation of sunlit leaves using vegetation indices and local geo-statistical measures as described above. Analysis is described for only one date. For the extraction of canopy temperature from the aerial thermal images, an unmixing procedure was used.

To examine the efficiency of the various types of CWSI to predict canopy water status, statistical regression models were built between each CWSI type and SC.

RESULTS AND DISCUSSION

The response of potato plants to irrigation treatments throughout the season is presented in Figure 1(a) by the average SC value of each treatment. In the first date, high SC were obtained with no differences between the treatments. From the second date, SC was higher with higher amount of irrigation. As expected, CWSI (extracted from the ground based images) decreases with increasing SC. (Figure 1(b)). The higher SC values for all treatments in the first date show that the plants

did not suffer from water deficit. In this period the soil is still wet from the winter rains, the plants are still small and the weather is temperate.
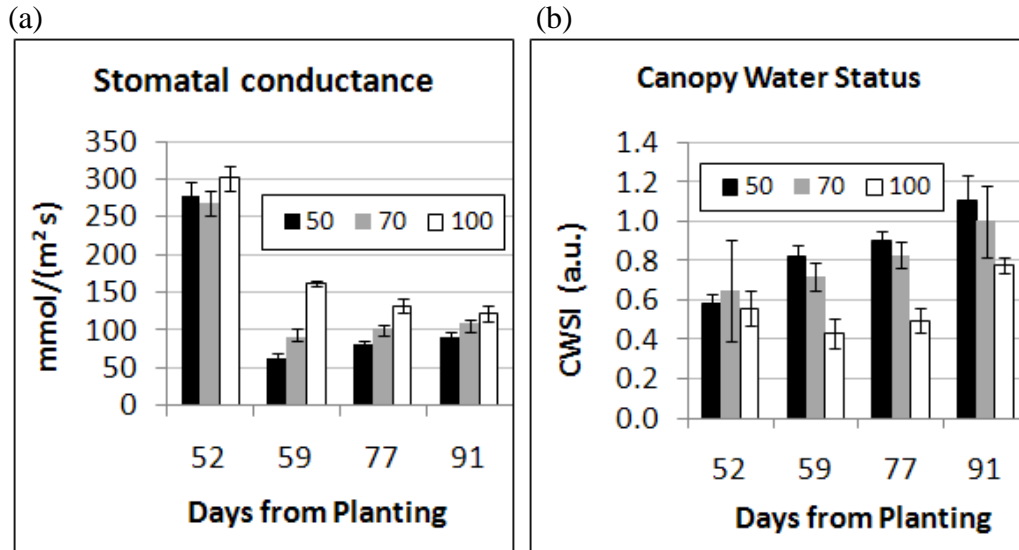
(a)
(b)

Figure 1. Response of potato plants to irrigation throughout the growing season represented by (a) stomatal conductance and (b) CWSI extracted from ground-based images. Error bars are confidence interval at $p=0.05$. Irrigation treatments (50, 70, and 100) are percentage from commercial application quota.

Empirical CWSI calculated for all dates using ground-based images demonstrated high correlation with SC ($0.78 \leq R^2 \leq 0.92$; excluding the first date). Figure 2 presents values of each CWSI type for one date (77 days after planting). Significant differences in the calculated thermal index were obtained between all irrigation treatments utilizing CWSIe_TIR, CWSIe_TIRs, CWSIt_TIRs and CWSIs_TIRs (Figure 2).
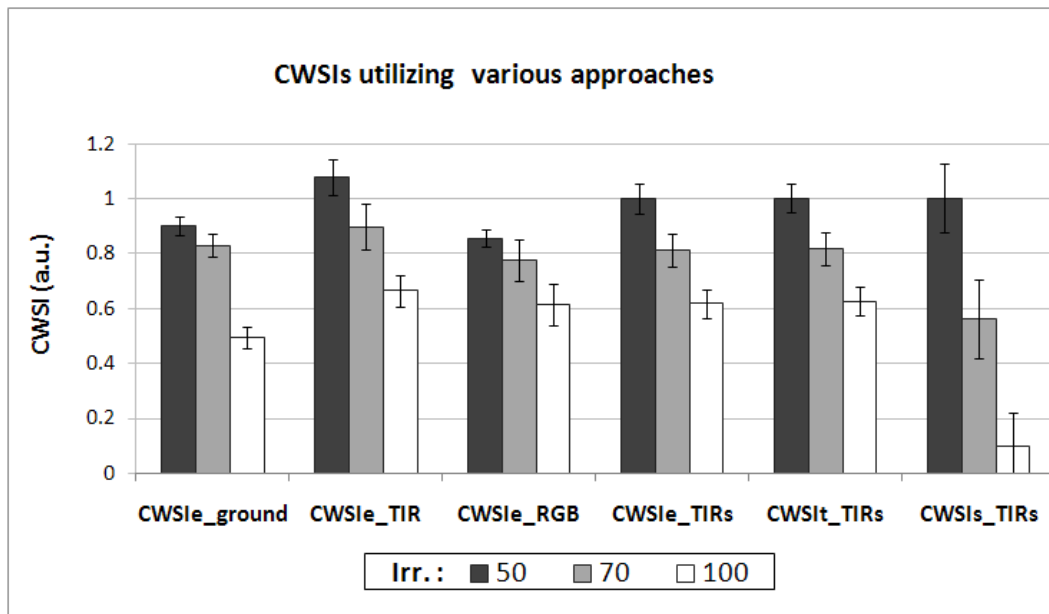
Figure 2. Mean CWSIs values utilizing different approaches described in table 1. Error bars are confidence interval at *p*=0.05. Irrigation treatments (Irr.: 50, 70, and 100) are percentage from commercial application quota.

   Most aerial CWSI values are higher than the CWSI that was calculated using the ground-based image (CWSIe_ground). Only CWSIe_RGB and CWSIs-TIRs for 70% and 100% irrigation treatment did not follow the same pattern of behavior. This can be explained by the coarser spatial resolution of the aerial images causing mixed pixels. Temperature recorded in a single pixel of a 35 cm resolution probably reflects information of canopy as well of soil. This is expressed by apparent higher canopy temperature. The soil fraction becomes prominent especially in the 50% irrigation treatment, where canopy density is low. The unmixing procedure minimized the mixture effect and lower CWSI values were obtained for the 50% and 70% irrigation treatments (CWSIe-RGB). However, this correction was less effective for 100% irrigation treatment (Figure 2).
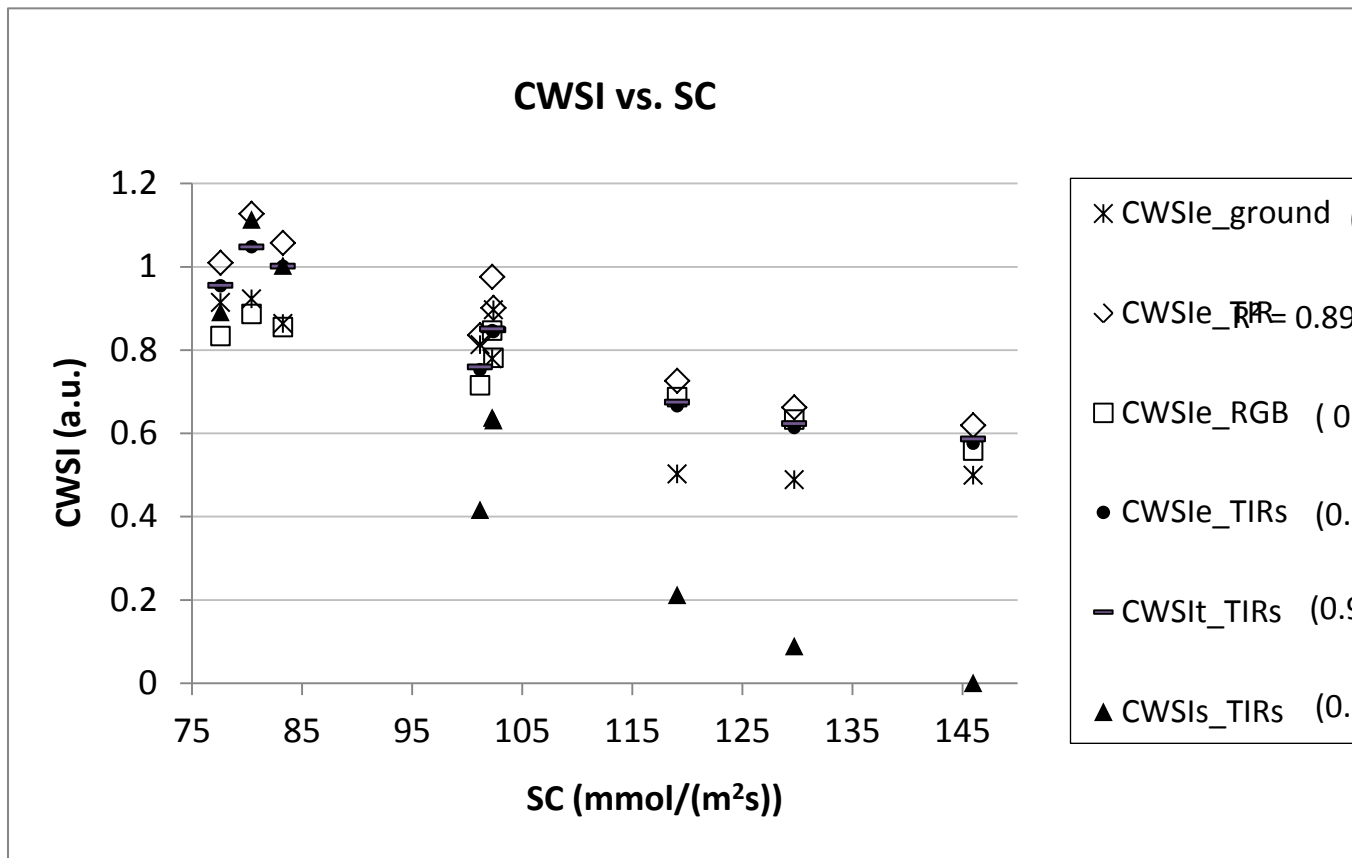

Figure 3. CWSI and SC correlation based on mean values of replicates (R^2 values in brackets).

   Extracted canopy temperature based on fused RGB and TIR images highly depends on the accuracy of co-registration between the two types of images. That

may be the cause of the lower correlation of CWSIe_ground and CWSIe_RGB (after applying unmixing procedure) with SC, as compared to the approaches based on TIR images solely (Figure 3, R^2 values in legend). Alignment and co-registration are influential factors while applying the unmixing procedure. They contribute to successful separation between 'vegetation' and 'soil' including all meaningful variation from sunlit to shadowed entities. It could be assumed that CWSIe_ground would be better correlated with SC than CWSIe_RGB (aerial unmixed CWSI) due to its higher spatial resolution. However, a series of high resolution images captures more details such as the slight movements of leaves resulted of the time interval between thermal and RGB image acquisition (30 sec' approximately). This causes a difference in the leaves' position within the images FOV, the RGB and the thermal, which related to the same unit area identified by the geographical coordinates. Although co-registration of ground-based images (RGB and TIR) can be done more accurately than aerial images, wind may trigger inaccuracies in the process of extraction of canopy pixels. This phenomenon is less significant in coarse image resolution where a mixture occurs within most of the pixel information. Time plays an additional role while considering ground-based versus aerial imaging. The experimental area was covered by 3-4 aerial TIR images that were acquired in a few seconds. To cover the same area, 27 ground-based images were acquired in a time slot of 2-3 hours Therefore, for aerial images, CWSI is calculated using a single value for *Tdry* and *Twet* for all replicates and there is no diurnal dynamic effect. For ground-based images, CWSI includes the diurnal dynamics effect.

Extracting canopy temperature utilizing the statistical approach enables calculation of CWSI based solely on TIR images. The three approaches based on statistically evaluated canopy temperature, CWSIe_TIRs, CWSIt_TIRs and CWSIs_TIRs, exhibit lower values compared to CWSIe_TIR, which is established empirically (Figure 2). Yet, their values were not close to CWSIe_ground values as those when using the unmixing approach (CWSIe_RGB), especially the value for the 50% irrigation treatment. Nevertheless, they were more correlated with SC values (Figure 3, R^2 values in legend), thus may be more accurate in indicating plant water status.

The CWSIe_TIRs, CWSIt_TIRs and CWSIs_TIRs exhibit very high correlation with SC (R^2=0.91), thus can serve as good predictors of the plant water status. Yet, the first two might be less practical from the statistical approach for various reasons. The use of CWSIe_TIRs approach requires an AWRS. Keeping this wet reference in steady state is not practical under daily farming conditions. The use of the CWSIt-TIRs approach, where *Twet* is based on meteorological conditions, may be a good solution. Still, there is no established rule for the maximum distance that can be allowed between the crop plots and the location of the meteorological station. The statistical approach, CWSIs_TIRs, is based solely on the thermal images and there is no need for external data. Yet, this approach assumes that during image acquisition some locations in the field are well-irrigated or over-irrigation. Therefore, it is suitable only for the whole field scale and not for small areas.

Another limitation of the statistical approach is apparent from the CWSI values. Utilizing the CWSIs_TIRs values were lowered mainly in the 70% and 100% irrigation treatments, relatively to all other approaches. Considering only

those approaches based on TIR refine the need for careful examination relating the method of extracting the minimum boundary temperature (*Twet*). The results show that it might be efficient to replace the ground wet reference used for extraction of *Twet*, with a minimum value extracted statistically based on TIR image data, or with the theoretical *Twet*. The combined approaches of delineated canopy temperature statistically with either the theoretical or empirical *Twet* obtained similar results since their values were 23.5º and 23.9º *C* respectively. In comparison, the statistical *Twet* was much higher (30.7º *C*). This strengthens the assumption that this approach is suitable for the whole field scale where there may be areas that are well-irrigated. Despite the relatively large area of the experimental plot in this study, the in-field variability is relatively small since it is under careful experimental management. Additionally, imaging days are planned before irrigation, thus, even with the 100% irrigation treatment; the plants could be under low stress and are not representative of well-irrigated plants required for the extracting of *Twet*.

SUMMARY

This study presents practical information related to the application of CWSI for commercial potato fields. It demonstrated various approaches to calculate CWSI and discussed their efficiency and practical usage. The use of CWSI as an indicator for plant water status was examined, considering aerial fused RGB and TIR information versus TIR information solely. The results display the potential of applying CWSI based on aerial TIR data as a tool for monitoring crop water status. These findings should be further investigated using additional dates, locations, and crops.

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