Aerial Thermography for Crop Stress Evaluation

Moshe Meron, Ph.D.

MIGAL Galilee Technology Center, PO Box 831 Kiryat Shmona 11016 Israel
meron@migal.org.il

Victor Alchanatis, D.Sc.

Institute of Agricultural Engineering, Volcani Center, ARO, PO Box 6, Bet Dagan 50250, Israel. victor@volcani.agri.gov.il

Yafit Cohen, Ph.D.

Institute of Agricultural Engineering, Volcani Center, ARO, PO Box 6, Bet Dagan 50250, Israel. yafitush@volcani.agri.gov.il

Abstract. *Foliage temperatures measured in proper context with environmental conditions are sensitive indicators of crop water stress. Aerial thermography of the foliage can provide water stress maps of crops, if properly managed. The challenges of aerial thermography for site specific irrigation are in the measurement and extraction of the relevant canopy temperatures from the thermal image; in determination of the lower and upper temperature limits normalized to ambient conditions; in geo-referencing the results; and in providing useful crop related interpretation. This paper discusses the technology involved.*

Keywords. Site specific irrigation, CWSI, Artificial reference surface, bolometer,

Introduction

The classic crop water stress index (CWSI) introduced by (Jackson, Idso et al. 1981; Idso 1982) became the widely accepted standard for crop water status evaluation from canopy temperature. It is defined as the relation between the actual crop canopy and the reference canopy temperatures of a fully transpiring crop under the same ambient conditions:

Eq. 1. $$CWSI = (T_{canopy} - T_{ref}) / (T_{max} - T_{ref})$$

Where *Tcanopy* is the crop temperature, *Tref* is the reference temperature; *Tmax* is the temperature of a non-transpiring leaf. Ample evidence couples CWSI to other plant stress indicators, like leaf and stem water potential or stomatal conductance, for example (Moller, Alchanatis et al. 2007) and others.

The first challenge of aerial thermography for site specific irrigation is the measurement and extraction of the relevant canopy temperature (*Tcanopy*) from the thermal image by separating the foliage temperature from the soil and from other artifacts. Normalization of foliage temperature to ambient conditions is the second step, i.e., to determine the lower (*Tref*) and upper (*Tmax*) boundaries for CWSI calculation. Ultimately, results should be geo- referenced to crop boundaries, divided into management zones, and the end user should be provided with useful crop related interpretation.

This paper discusses the current methods and technologies involved.

Methods

Measurement and extraction of the relevant canopy temperatures

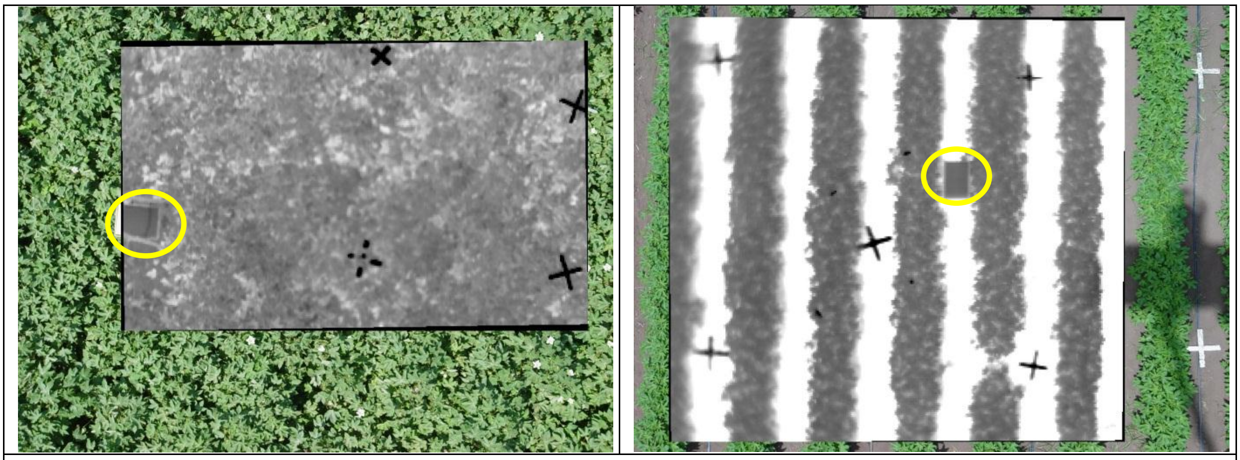

Figure 1. Thermal image overlaid on color picture of fully covered (left) and 0.56 m row width of 0.96 m row spacing (58% cover, right) drip irrigated cotton canopies. Crosses are alignment references, WARS marked with circle. Temperature scale: 19^{o}C (black) to 24.5 ^{o}C (white).

Surface temperatures are never uniform from their nature, even on a single cotton leaf, moreover on a canopy. The examples of seemingly uniform or partially covered cotton canopies (Figure 1.) raise the question:

Where is the relevant *Tcanopy* in the image to use it in the CWSI equation ?

Pixel histograms and statistical filtering can assist in the evaluation. (Meron, Tsipris et al. 2010a)

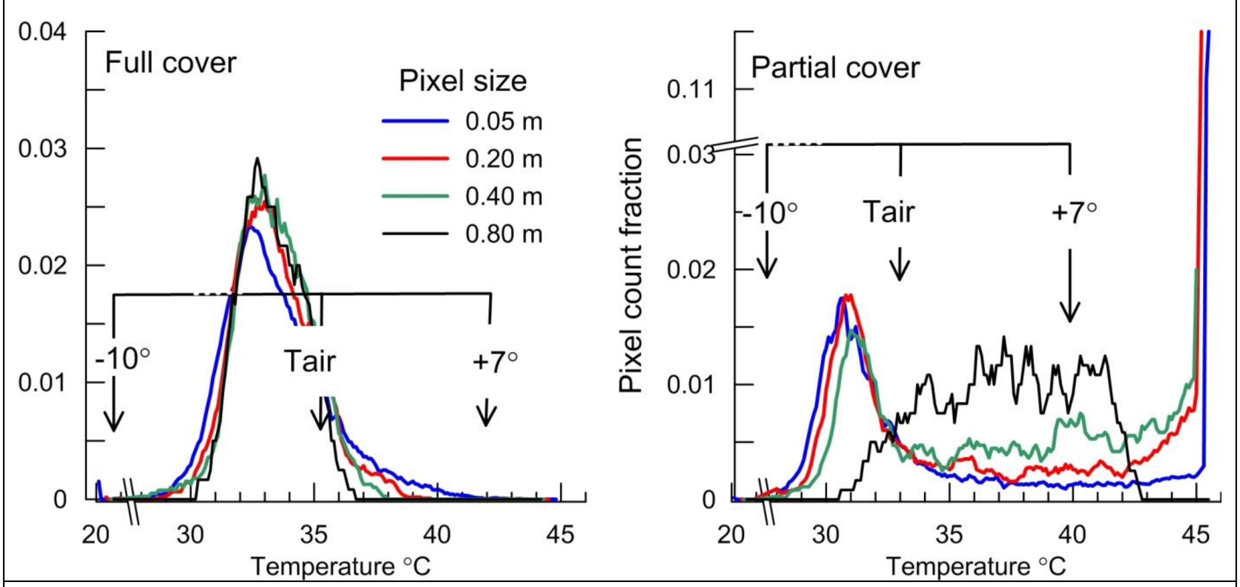

Figure 2. Pixel temperature histograms of fully (left) and 56% covered (right) drip irrigated cotton canopies. Filtering temperatures (Tair-10, Tair, and Tair+7) are marked with black arrows. Axes are broken to allow display of the relevant ranges.

Thermal images from Figure 1 were converted from the original 0.025 m footprints to pixel sizes of 0.05, 0.10, 0.20, 0.40 and 0.80 m/pixel, by averaging four neighboring pixels into one larger pixel size, simulating decreasing resolution of image acquisition. Pixel histograms of both images are shown in Figure 2. The thermal image histogram of a fully covered, uniformly irrigated cotton crop (Figure 2, left) shows Gaussian pixel distribution, in all pixel sizes. In partial canopy cover (Figure 2, right) the Gaussian curve of the colder, foliage related pixels, and the hotter, soil related pixels are discernable up to 0.20 m pixel size. Pixels of 0.80 m size are inherently mixed between soil and foliage, being larger than the 0.58 m cotton canopy width. Large, but smaller than row width, 0.40 m pixels are divided between pure foliage (within the Gaussian distribution) and mixed pixels.

Statistical filtering based on ambient temperature may be applied to eliminate soil and mixed pixels in sparse canopy / partial cover histograms, assuming that leaf temperatures do not exceed *Tair* +7 (Irmak, Haman and Bastug 2000), and pixels below *Tair* -10 are artifacts; example shown in Figure 2. Surface temperature of the colder part of the canopy (*Tcanopy*) can be defined from the filtered data by weighted average of pixels temperature up to predefined thresholds (Figure 3.). In case of full canopy cover filtering and pixel size bear minor effects and filtered or simple population averages are similar. In partial canopy cover filtering and minimizing pixel size are essential to get meaningful data. As a rule of thumb, the optimal pixel size is half of the foliage width in row crops. Setting *Tcanopy* to 25%-50% coldest pixel range is essential in sparse canopies. Choosing threshold levels between 25% to 50% is a matter of preference and standardization.

In digital aerial photography pixel size is the capacity limiting factor, as the swath width is the product of the number of image pixels by the pixel size. Efforts to extract crop temperatures from mixed pixels (Moran, T.R. Clarke et al. 1994) reached limited success so far. Thermal imagers are limited in pixel count, so economic efficiency and thermal survey accuracy must be optimized to achieve meaningful results.

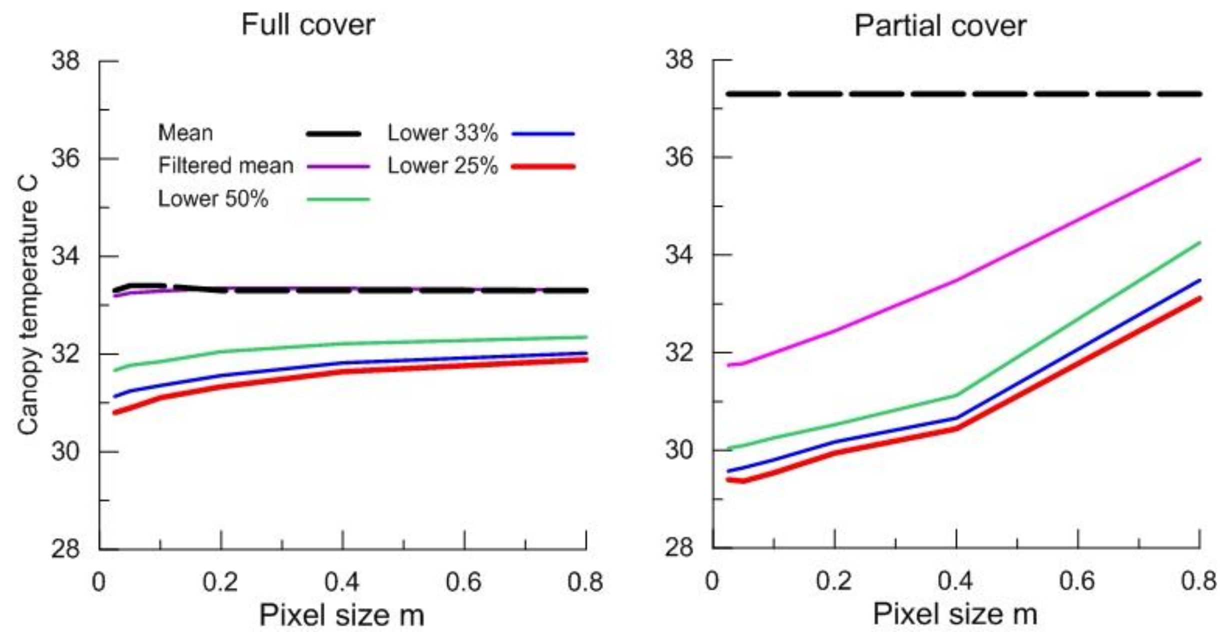

Figure 3. Mean canopy temperature of coldest 25%, 33%, 50% and 100% pixels of drip irrigated cotton after air temperature filtering, and without filtering, as related to pixel size: left-for full crop cover, right- for partial crop cover Ambient temperature was 2°C lower when partial cover images were acquired.

Image interpretation and spatial resolution.

Three principle methods are used for CWSI evaluation from a thermal image, in relation to ambient conditions:

- The "Big Leaf" energy balance paradigm, where the crop canopy is a virtual uniform flat surface receiving even radiation. In reality the surface is not uniform, so in practice the sunlit leaves are selected by superimposition of the thermal over the color image (Alchanatis, Cohen et al. 2006). To acquire "pure" canopy pixels without soil or shaded leaves temperature, the effective ground pixel size is limited to less than the sunlit leaves size. Color images with exact overlap of IR images must be taken simultaneously, quite a difficult task from aerial platforms. A ground based weather station is also necessary.

- The natural reference system, where well watered crop patches are maintained for *Tref* (Clawson, Jackson and Pinter 1989). A seemingly straightforward approach, which requires some efforts involved in patch maintenance. In experimental plots the contrast between irrigation treatments was apparent. At this point of time more development is needed to support practicality of this system in aerial surveys.

- Wet Artificial Reference Surface (WARS) method (Meron, Tsipris and Charitt 2003) (Meron, Tsipris et al. 2010a). Artificial reference surfaces are Styrofoam boards covered with white non-woven viscose cloth, floating in a water filled tray. The viscose cloth is kept wet by wicking water from the tray. A ground station (Figure 4.) measures ambient and WARS temperatures. CWSI is calculated by Eq. 1. using WARS temperatures as *Tref* and *Tair* +5 as *Tmax*.

The WARS method was lately proven as preferable over others tested in Israel (Alchanatis, Cohen et al. 2010) and became currently the de-facto standard in experimental and semi-commercial applications of aerial thermography for crop water stress evaluation there.

Figure 4. Ground station with Tair and WARS sensors.

Image acquisition.

The less expensive but also less accurate uncooled (bolometric) thermal imagers became popular over the more accurate and much more expensive cooled sensor (MCT and QWIP) types. Two main issues are problematic with bolometric imagers in aerial thermography: pixel smear and recalibration. Pixel smear is caused by the slow "shutter speed" (image registration time) of 0.007-0.008 sec of the sensor, over 40 m/sec of the slowest flight speed of a fixed wing aircraft, moving over the ground about 0.3 m with "open shutter". That means smearing the pixel over 0.3 m in the flight direction and blurring the image. Despite this limitation, we obtained meaningful results in aerial crop stress detection (Cohen, Alchanatis et al.; Alchanatis, Cohen et al. 2010) (Meron, Tsipris et al. 2010b). Uncooled radiometric imagers have ± 1°K best accuracy by design. They need periodic recalibration when the outer shell temperatures change. On the ground, in presence of a known reference, this is a tolerable problem. While in flight, recalibration may confuse and invalidate the results. Selection and operation of thermal imagers for aerial thermography must regard this issue and treat it properly. For commercial operations, where capital costs are recoverable, the more expensive cooled imagers would be preferable at comparable image detector size.

Geo-referencing and information presentation

Thermal images are small in size and to mosaic an exactly referenced ortho-thermogram (like an orthophoto) requires advanced photogrammetric methods, and specialized airborne equipment (Yalon 2011). Image frames are recorded by GPS location of the aircraft and the deviations of the aircraft position from azimuth and plane are corrected by inclinometers. Such ortho-thermograms enable to pinpoint various events and effects on the ground like clogged / broken emitters, or over / under watered trees in an orchard (Cohen, Alchanatis et al. 2011). Large area mapping of CWSI is done by post processing the thermogram.

Another approach is creating a less detailed, but still usable CWSI map of the field by simplified methods. Images are registered by the center point of the frame from the aircraft GPS location with azimuth correction only. The frame is broken up to smaller sub-frames, and their calculated CWSI values are assigned to each sub-frame's center points. Maps are generated by spatial interpolation of the CWSI points (Figure 5.).

While both methods provide visual presentation of the crop water status, a more practical presentation is needed for irrigation management purposes. Since irrigation management zones are defined by watering units, such as a center pivot segment, or similar, painting the zones in color scale from well watered to stressed status will assist decisions in a glance. In case leaf water potential (LWP) is more familiar to the

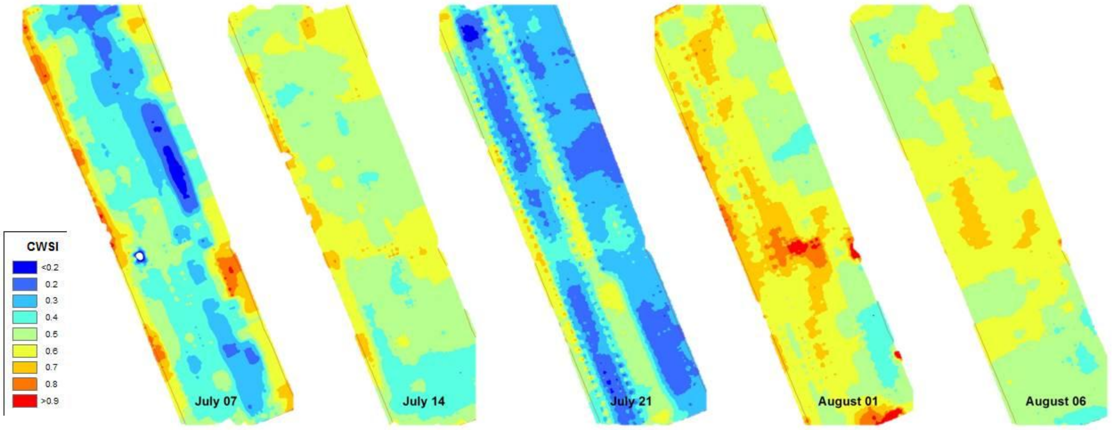

Figure 5. CWSI maps bi-weekly sequence of a drip irrigated cotton field generated by the simple interpolation method. (Unpublished data by Meron *et.al*. 2008.)

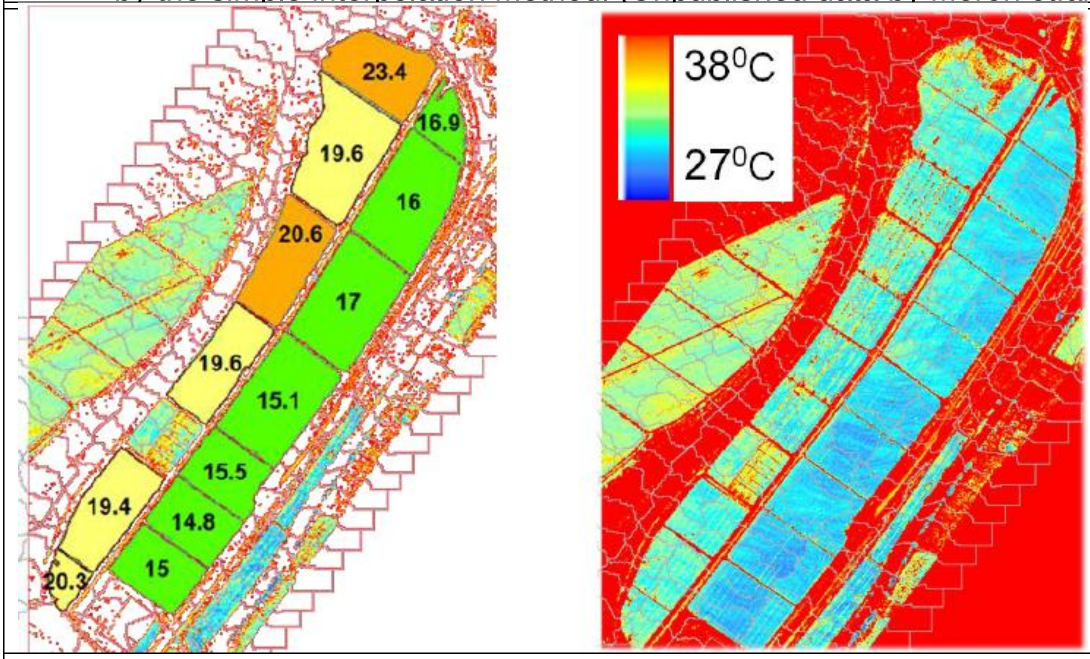

Figure 6. Ortho-thermogram of a cotton field (right) and calculated LWP assigned to irrigation management zones. From (Rosenberg, Cohen and Alchanatis 2011))

growers, CWSI may be converted to LWP according to (Cohen, Alchanatis et al. 2005) as shown in Figure 6.

Irrigation scheduling is based on water balance methods; replenishing water used up by the crop. Crop stress maps provide feedback on the water status of the crop to assess the efficiency of the water application and implement changes. Numeric presentation, assigned to management zones by tabulated or graphic statistics of CWSI (Figure 7.) may better fit irrigation scheduling routines than visuals and maps.

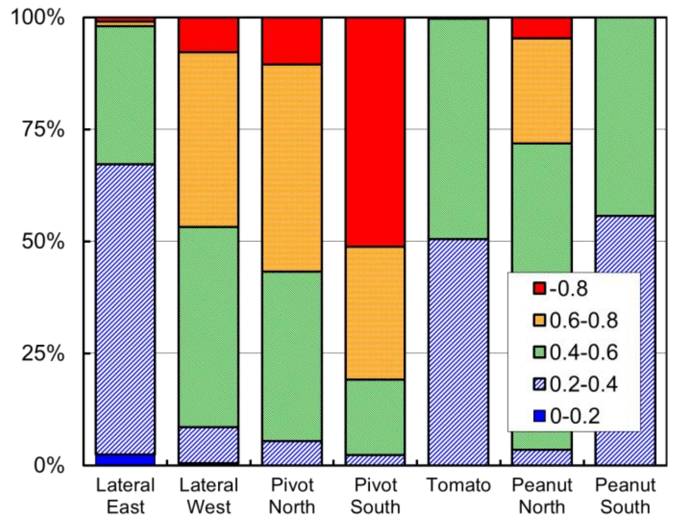

Figure 7. CWSI statistics by management zones (Meron et al 2010)

Conclusions

Crop water status mapping by high resolution thermography emerges as a viable tool for site specific irrigation scheduling. Separation of the canopy temperatures from soil and other hot backgrounds needs ample number of "pure", foliage only pixels in the frame, dictating finer spatial resolution than half of the row width in sparse crops. Canopy temperature can be extracted by thresholding the pixel histogram over and under ambient air temperature and averaging the colder fractions of the remaining histogram. Wet artificial reference surfaces or well watered crop patches can be used for cold reference in CWSI evaluation. For hot reference 5°C above ambient temperature is sufficient. While WARSs need ground based instrumentation, natural vegetation surfaces need only air temperature, though the natural method still needs further development. Image acquisition by uncooled thermal scanners in aerial applications must consider pixel smear caused by slow shutter speeds, and radiometric recalibration problems inherent to bolometric sensors. In digital aerial photography image size is a limiting factor, as the swath width is the product of the number of image pixels by the pixel size. Cooled thermal imagers are best suited to aerial thermography but are more expensive, and image sizes smaller. Ortho-thermograms of thermal aerials contain pin-pointed information on crop and irrigation status, but specialized aerial equipment and processing software are necessary. Simpler procedures are available for less detailed but still meaningful crop stress maps based on GPS tagging only.

References

Alchanatis, V., Y. Cohen, S. Cohen, M. Moller, M. Meron, J. Tsipris, et al. (2006). Fusion of IR and multispectral images in the visible range for empirical and model-based mapping of crop water status. ASABE Annual meeting, 2006

Alchanatis, V., Y. Cohen, S. Cohen, M. Moller, M. Sprinstin, M. Meron, et al. (2010). Evaluation of different approaches for estimating and mapping crop water status in cotton with thermal imaging. Precision Agriculture 11: 27 - 41.

Clawson, K. L., R. D. Jackson and P. J. Pinter (1989). Evaluating plant water stress with canopy temperature differences. Agron. J. 81: 858-863.

Cohen, Y., V. Alchanatis, A. Prigojin, A. Levi, V. Soroker and Y. Cohen (2012). Use of aerial thermal imaging to estimate water status of palm trees. Precision Agriculture 13(1): 123-140.

Cohen, Y., V. Alchanatis, M. Meron, Y. Saranga and J. Tsipris (2005). Estimation of leaf water potential by thermal imagery and spatial analysis. Journal of Experimental Botany 56: 1843-1852.

Cohen, Y., V. Alchanatis, A. Levi, S. Ostrovski, R. Brikman, A. Dag, et al. (2011). Aerial thermal imaging for automatic detection of irrigation malfunctions Report submitted to Chief Scientist of the Ministry of Agriculture and Rural Development Number: 458-0524-119 pp. (Hebrew)

Idso, S. B. (1982). Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agricultural and Forest Meteorology 27: 59-70.

Irmak, S., D. Z. Haman and R. Bastug (2000). Determination of crop water stress index for irrigation timing and yield estimation of corn.. Agronomy Journal 92: 1221–1227.

Jackson, R. D., S. B. Idso, R. J. Reginato and P. J. Pinter (1981). Canopy temperature as a crop water stress indicator. Water Resources Research 17: 1133-1138.

Meron, M., J. Tsipris and D. Charitt (2003). Remote mapping of crop water status to assess spatial variability of crop stress. Proceedings of the 4th European Conference on Precision Agriculture. 2003, Berlin, Germany. Ed: J. Stafford and A. Werner. Wageningen Academic Publishers B.V.pp.405-410

Meron, M., J. Tsipris, V. Alchanatis, Y. Cohen and V. Orlov (2010a). Crop water stress mapping for site specific irrigation by thermal imagery and artificial reference surfaces. Precision Agriculture 11: 148-162.

Moller, M., V. Alchanatis, Y. Cohen, M. Meron, J. Tsipris, A. Naor, et al. (2007). Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. Journal of Experimental Botany 58(4): 827-838.

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 Sensing and Environment 46(3): 246-263.

Rosenberg, A., Y. Cohen and V. Alchanatis (2012). Mapping of cotton water status by aerial thermography. Report submitted to the Israeli Cotton Board, (Hebrew)

Yalon, D. (2011). Automatic photogrammetric solution. Geoinformatics. 8: 14-16.