CROP WATER STRESS MAPPING FOR SITE SPECIFIC IRRIGATION BY THERMAL IMAGERY AND ARTIFICIAL REFERENCE SURFACES

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ABSTRACT

Variable rate irrigation machines or solid set systems have become technically feasible; however, crop water status mapping is necessary as a blueprint to match irrigation quantities to site-specific crop water demands. Remote thermal sensing can provide these maps in sufficient detail and at a timely delivery. In a set of aerial and ground scans at the Hula Valley, Israel, digital crop water stress maps were generated using geo-referenced high-resolution thermal imagery and artificial reference surfaces.

Canopy-related pixels were separated from the soil by air temperature-related upper and lower thresholds, and canopy temperatures were calculated from the coldest 33% of the pixel histogram. Wetted artificial surfaces provided reference temperatures for crop water stress index (CWSI) normalization to ambient conditions. Cotton leaf water potentials related linearly to CWSI values with R^2= 0.816, n=56. Aerial scans of cotton-, process tomatoes-, and peanut field-generated crop stress level maps corresponded well both with ground-based observations by the farm operators and irrigation history. Numeric quantification of stress levels was provided to support sectioning decisions in spatially variable irrigation scheduling.

Keywords: Cotton, Peanut, Process tomato, CWSI, Leaf water potential

Abbreviations: CWSI - Crop Water Stress Index; LWP - Leaf Water Potential; ETp - Potential Evapo-Transpiration

INTRODUCTION

Site-specific irrigation may be defined as matching water application in time and quantity to actual crop needs at the smallest manageable scale, to achieve the desired crop responses. As variable rate water application technology is already available, field scale application will depend on the ability to map the variability of the crop water status (Camp, Sadler et al. 2006). Point-sensing soil or crop water status devices, using wireless communication, are abundant and can be connected to the irrigation machines for real time control e.g. (Peters and Evett 2004; Kim, Evans et al. 2007). However applying them in numbers sufficient to match spatial variability (Or 1995; Schmitz and Kuyper 1998; Schmitz and Sourell 2000), will be cost prohibitive with current technology. Remote thermal imagery is a viable alternative to point measurements, since the canopy temperature of the whole field can be measured at once and a map of the plant water status distribution in the field can be produced.

Evaluation of relevant crop temperatures by pattern recognition of sunlit leaves (Leinonen and Jones 2004; Cohen, Alchanatis et al. 2005), may approximate the theoretical "big leaf" temperature for heat balance calculations. However, this method is limited to very fine pixel resolution, and requires exact co-registration of the thermal image with the visible, limiting practicality of aerial surveys. Histogram processing of image frames, taken at pixel size less than half width of the visible fraction in a partially covered canopy, enables separation of canopy from soil temperatures, as these are different portions of the histogram distribution (Meron 1987). The 33% coldest fraction of the remaining canopy related pixels can be used as the representative "cold" crop temperature for water stress evaluation, as demonstrated in (Meron, Tsipris et al. 2003). More detailed evidence to support this procedure is in preparation.

The widely accepted crop water stress index (CWSI) concept (Jackson, Idso et al. 1981) is defined as a fraction of the canopy temperature between an upper (dry) and a lower (wet) reference under ambient conditions. The relation between ambient conditions and a variety of baselines and references have been investigated along the years. Empirical well watered base lines (Idso 1982) introduced initially with CWSI were found later to be excessively related to specific conditions. Natural surfaces like well watered crop temperature (Gardner, Nielsen et al. 1992; Gardner, Nielsen et al. 1992) behave as good indicators, but need dedicated maintenance, considering production scale implementation. Wetted and greased foliage (Jones 1999) reference temperatures are mainly micro scale methods. Wetted artificial reference surfaces constructed of manmade materials (Meron, Tsipris et al. 2003) are well defined, reproducible and reliable indicators of ambient conditions, with some limitations at non-turbulent wind velocities.

The area covered by a thermal survey system is defined by swath width (multiple of sensor array width and pixel size) and velocity. Pixels are limited to the largest size that will enable separation of soil temperatures and detection fractions of canopy temperature, usually smaller than half of the covered crop row width. Acquisition velocity is limited by shutter speed, defining pixel sharpness. Cooled imagers are fast and sharp, but expensive. Bolometric thermal imagers are more widely used, being more affordable. However, their acquisition speeds of 1/140 to 1/200 sec are too slow to freeze motion. Aerial or ground surveys with bolometric cameras must slow down to eliminate blur, or be able to handle blurred images and the enlargement of the pixel size because of pixel "smear" in the movement direction.

Economization of thermal mapping depends on the system's capacity to cover area. One of the options to enhance capacity is skip-scanning over swaths and frames and interpolating CWSI values by geo-statistic methods.

MATERIALS AND METHODS

Ground measurements.

Ground-based measurements were performed during the summer of 2007 at a commercial cotton (*Gossypium hirsutum x barbadense* hybrid c.v. Acalpi) field in the Hula Valley of Israel (N33.11, E35.35), in a mediterranean climate. The field was selected as an experimental platform based on its extremely variable soil water-holding characteristics. The cotton was planted and cultivated by conventional methods and was uniformly irrigated with a lateral moving sprinkler system.

A FLIR (Bilerica, MA) model SC2000 radiometric IR scanner, equipped with a 45º FOV lens was mounted on the spraying boom of a TECNOMA (Epernay, France) model "Laser 4000" self propelled, high pass sprayer, about 5.0 m. above crop level, 3 meters left to the center, pointing straight down 180 degrees to zenith (FIGURE 1.). The scanner was remotely controlled by FLIR ThermaCam™ software run on an IBM ThinkPad laptop. A GPS locator (MID-TECH model RX 400p) with 1-3 m. spatial accuracy was mounted on the sprayer and connected to the same laptop. Image capture and GPS acquisition rates were measured every second, and the files were synchronized by the computer clock.

Ten sampling points along an extremely variable water holding capacity row were allocated and marked, and four young, sunlit, fully expanded leaves were sampled for leaf water potentials (LWP) at each location, using a pressure chamber, on every scanning day (Figure 2.), within 15 minutes of the scan. Main stem lengths were recorded weekly until ceasing of growth.

Artificial reference surfaces placed at the side of the field consisted of wet, white, non woven fabric covering a polystyrene float, placed in a 0.4 x 0.3 m. water-filled plastic box, kept constantly wet via wicking water from the bath.

FIGURE 1. IR scanner mounted on high pass sprayer.

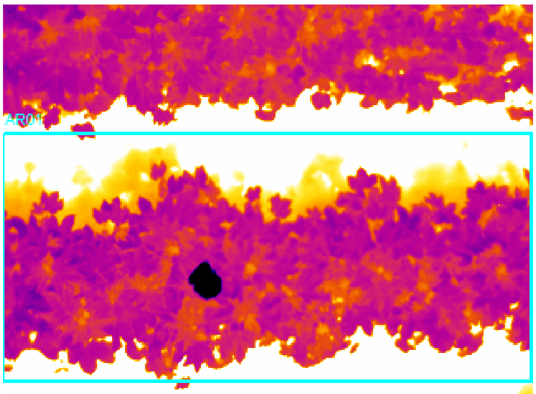


FIGURE 2. False color IR image of a cotton row. a. location marker and plant height measuring stick. b. LWP sampling points

An Apogee (Logan UT) thermal sensor mounted 0.1 m. above the surface recorded ARS temperatures. The sensor was connected to a Campbell Scientific CR10X data logger, together with air temperature, relative humidity, global radiation, and wind velocity sensors at 2 m. elevation. Value averages were recorded in 1-minute intervals.

Six ground surveys were performed throughout the season. Swath widths ranged 1.5 to 4.5 m. Swath densities ranged every 12 to 24 meter distances (1/3 to 1/6 coverage). Survey dates and other details are presented in Table 1.

Table 1. Survey dates, times, coverage, and ambient conditions.

Date	Swath width	Coverage	Start time	End time	Air temp.	RH	Wind	Radiation
	m	%	hr	hr	C	%	m/sec	W/m^2
			Ground survey					
18/06	1.5	4%	12:32	13:55	32.4	37.6	4.2	955
2/07	4.5	19%	13:20	14:29	31.0	44.6	3.4	873
8/07	4.5	38%	12:37	14:41	32.5	42.4	3.5	850
23/07	4.5	38%	12:29	13:38	32.3	47.0	3.2	908
2/08	4.5	38%	12:23	13:45	33.4	41.1	2.6	926
29/08	4.5	38%	12:52	13:51	35.4	31.9	3.2	840
			Aerial survey					
20/8	45-50	80-120%	12:18	13:15	34.0	34.8	2.3	920

Crop water stress index was calculated using the following formula:

Equation 1: $$CWSI = \frac{\text{Canopy T - reference}}{\text{Air T} + 5^{\circ} \text{ - reference}}$$

Where: Canopy T is the mean temperature of the 33% coldest pixels after discarding pixels hotter than 7 ºC from the air; reference is the wet ARS temperature and Air T is air temperature at the time of image acquisition.

Images were processed in Visual Basic 5, using OLE automation functions provided in the ThermaCam™ package. In the first stage, the pixels outside of the temperature (T) limit described by Eq. 2 were discarded, assuming that those

Equation 2: $$(T_{air} - 10) < T_{pixel} < (T_{air} + 7)$$

temperatures were not canopy-related, and the histogram was recalculated. The average weight of the coldest 33% pixels was designated as the canopy temperature and CWSI was subsequently calculated. Each CWSI frame was assigned to the corresponding GPS location. Maps were generated by geo-statistic interpolation of the CWSI points using built-in functions of ArcView 9.2 Spatial Analyst extension.

Crop cover was determined by dividing the number of plant related pixels by the total pixels per square meter.

Aerial survey.

Aerial survey was conducted over several field crops in the Hula Valley, Israel, on August 20 2007; see ambient conditions in TABLE 1. The radiometric imager (FLIR SC2000), equipped with a 45° FOV lens was mounted looking straight down over an opening in the aircraft floor, and the GPS antenna was mounted under the front windshield. Image and GPS location acquisition arrangements were similar to the setup in ground surveys. Flights were directed by the visible wheel paths of the lateral moves in sprinkler-irrigated fields, and by flag bearers on the ground in drip irrigated fields. Flight altitude was 45-50 meters above ground, adhering to Israeli ceilings for agricultural aerial applications, with resulting swath widths of 45- 50 meters. Ground pixel sizes obtained were about 0.15 m across flight direction, but due to the "smear" caused by the slow shutter speed, pixel size increased to 0.3 m along the path.

Images were divided during processing to six equal sub-frames of 2 rows and 3 columns, covering about 250 m^2 crop area, and CWSI was evaluated for each sub-frame. Center location of each sub-frame was calculated from GPS center point and azimuth data (Figure 3.). Water stress maps were generated as described in the ground surveys.

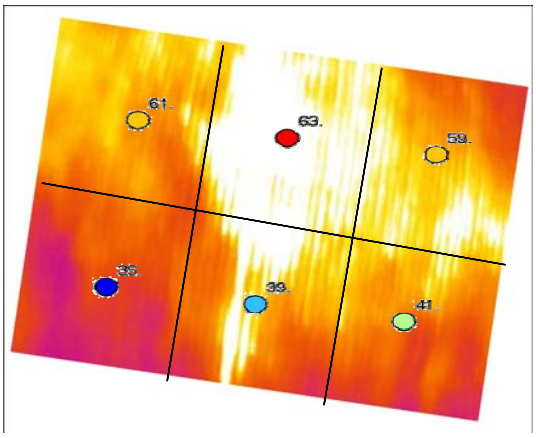


FIGURE 3. Ground referenced thermal image, showing image division and CWSI points.

RESULTS AND DISCUSSION

Ground measurements

First scan (June 18) was performed before commencement of irrigation following winter rains. Overview of the test area showing LWP sampling point locations overlaid on the June 18 CWSI map, is shown in Figure 5a. The wide diversity of crop stress conditions indicates the variability of soil water holding capacities in this field.

Leaf water potentials correlated linearly (R^2 = 0.816) to CWSI (Figure 4.) over the full crop stress range. The scatter is considerable in the well-watered part, down to -1.6 MPa LWP or CWSI 0.4; however, the stressed range above CWSI 0.4 is clearly discernible from the well-watered range

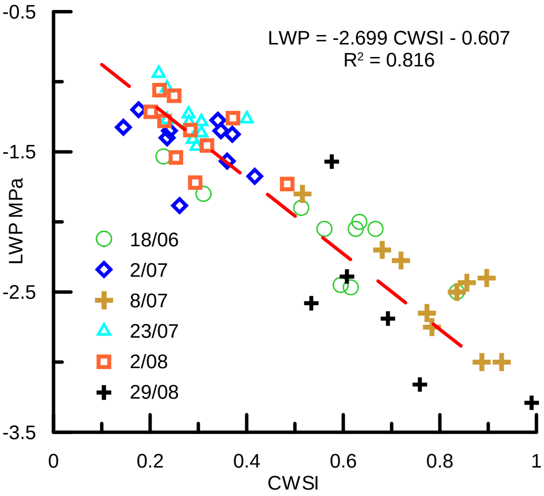


FIGURE 4. Relation of cotton CWSI to leaf water potentials in 6 scanning days, at the monitored field, Hula Valley 2007.

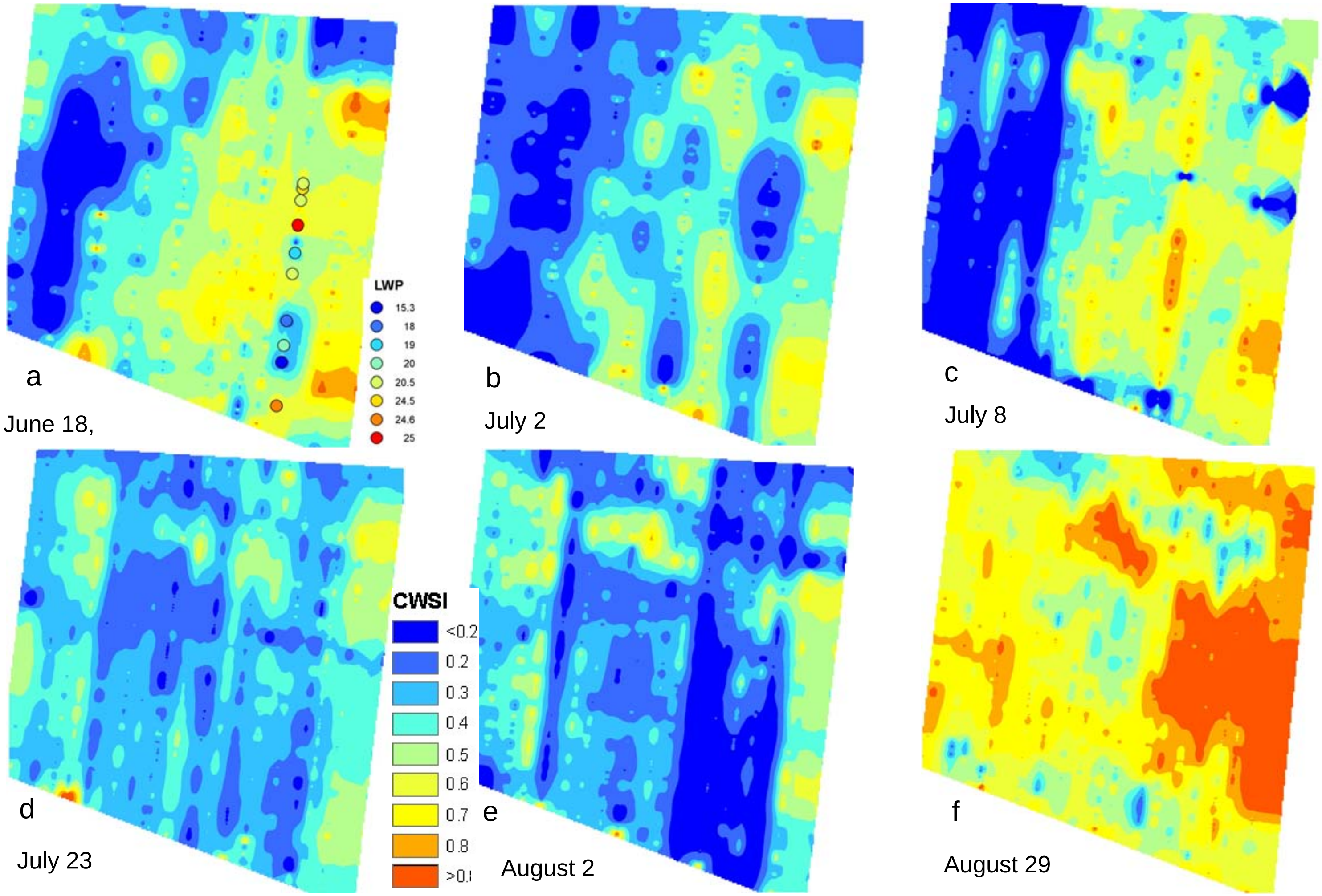


FIGURE 5. Cotton CWSI maps of the monitored field, acquired on six ground survey days in 2007. LWP sampling points, with corresponding values on 18 June are shown in map a.

According to this result, CWSI can replace LWP in cotton water-stress evaluation, at least as a stress / no-stress indicator.

The maps in Figure 5. are the results of six ground surveys. Stress levels on the survey dates are a function of irrigation timing and water quantities applied. (Figure 6.)

The first survey event (Figure 5.a) occurred one day before commencement of irrigation. The cotton consumed water stored in the soil, and stress levels developed according to the native water holding capacities in various sections of the field. The diversity of stress levels is also illustrated by the variances in the ten testing points (Figure 7.), where crop height, crop cover and LWP measured on this date showed close correlation. Plants growing in the light soil consumed all the available water, (right side of the map) and remained small and deeply stressed, while the other plants (left side) flourished in higher water capacity soils.

The second survey (Figure 5. b) was performed following the second irrigation, and the third (5.c) right before the third irrigation was applied. Looking at ETp and water applied during the first two irrigations (Figure 6. arrows 1 and 2) the soil water deficit is evident and maps 4 b. and 4 c. show that clearly, mainly in the light soil.

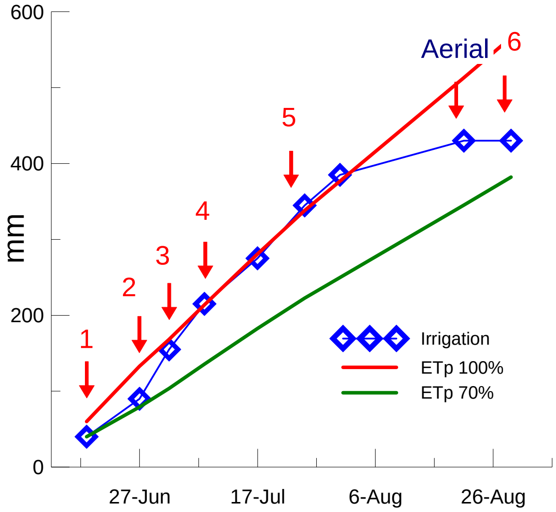


FIGURE 6. Full and 70% ETp, irrigation and survey events (red arrows) in the monitored field at the Hula Valley 2007.

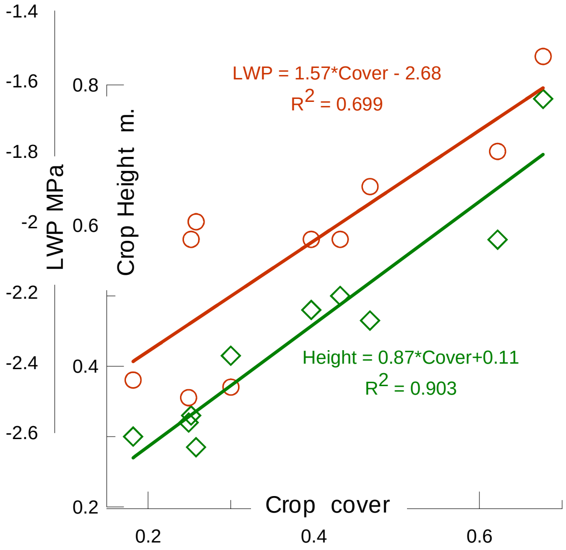


FIGURE 7. Relations between crop cover, crop height, and LWP on 18 June 2007, before first irrigation in the monitored field.

Beginning with the third irrigation, the water quantities were upwardly adjusted to reach 100% ETp (Figure 6. arrows 3 to 5). The fourth survey (Figure 5.d), right before the fourth irrigation, shows the expected moderate stress levels. In survey 5, before the fifth irrigation, the plants in the light soil appear less stressed than in the higher capacity soils. This contradiction can be explained, as light soil plants were smaller, with only partial crop cover. Their water consumption was closer to 70% ETp than to the irrigation quantities scheduled by 100% ETp, so by full ETp application they were over irrigated. The last ground survey (Figure 5.f) was taken after considerable stress was developed by reduced irrigation before defoliation. The stress is evident in the entire field, but it was more enhanced in the light soils.

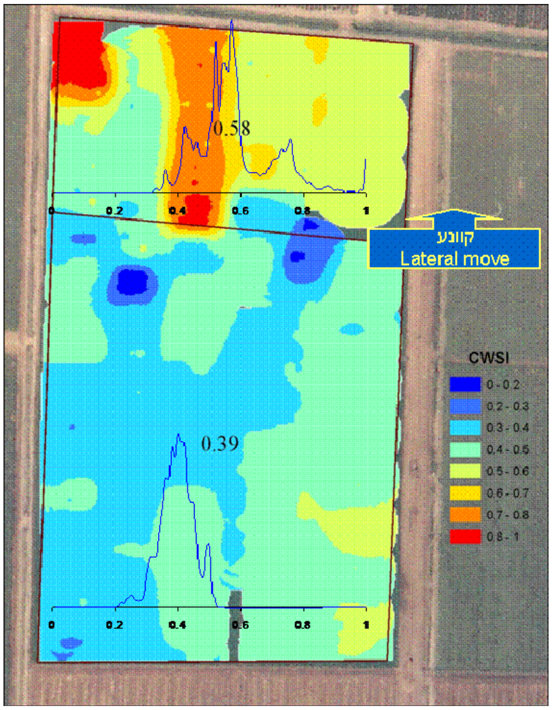


FIGURE 9. Water stress map of a peanut field during irrigation, 20 Aug. 2007. Mean CWSI values and CWSI histograms are indicated before and behind the irrigation advance.

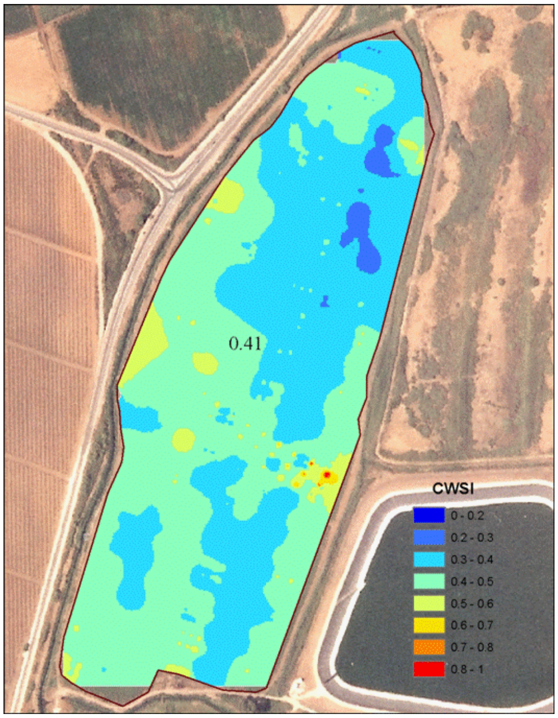


FIGURE 10. Water stress map of a drip irrigated process tomato field on 20 August 2007.

Aerial survey.

The August 20, 2007 aerial survey included two later moves, one center pivot, and one drip irrigated field. The peanut field (Figure 9.) was scanned while irrigation was running, with lateral move position indicated. Mean CWSI levels and CWSI distribution histograms, calculated from the interpolated grid, are shown in the figure. Stress levels were 0.2 CWSI lower after irrigation, and less scattered. Stress levels in the drip-irrigated process tomato field (Figure 10.) were quite low, but less uniform than expected from such an even water distribution system. Apparently, other factors, beyond water distribution uniformity, contributed to crop stress variability in the field.

A crop stress map of the cotton field where the ground monitoring took place (Figure 11. next page) was scanned one day before the final irrigation. The western part of the filed, where irrigation cycle begins, is more stressed – about 0.2 CWSI higher – then the eastern part. Stress levels developed gradually with each irrigation cycle, with earlier irrigations more stressed then recent, and this trend is evident in the map. Aerial CWSI map section (red polygon) comparable to ground scans is less detailed than the ground maps of this field (Figure 5.), as aerial scan resolution was much coarser than ground scan. After the final irrigation in the center-pivot cotton field, (Figure 12. next page) the overall high stress levels still differed by 0.14 CWSI between the earlier and more recent irrigation dates.

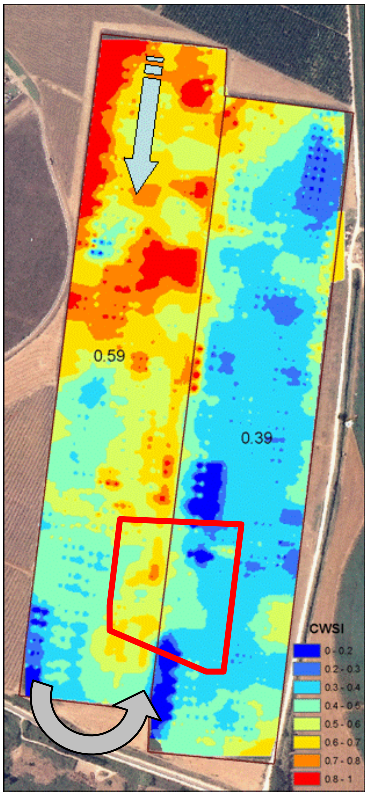
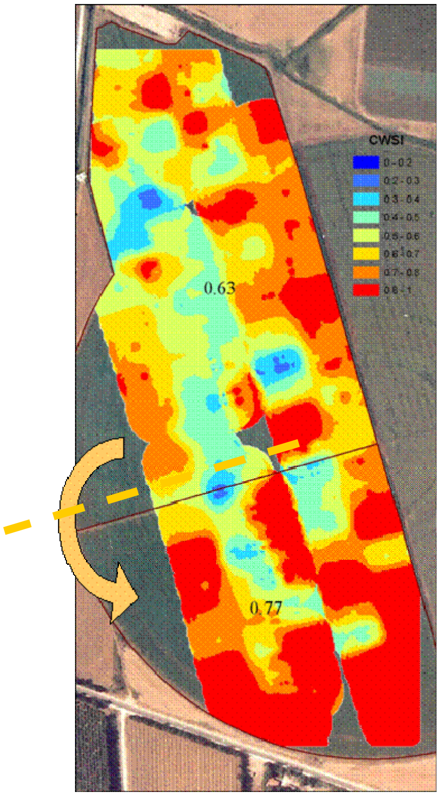


FIGURE 11. Water-stress map of a cotton field **before** last irrigation. Arrows indicate lateral move position and pivoting directions. Numbers are mean CWSI levels for the field parts. Red polygon marks the monitored part of the field



. FIGURE 12□. Water stress map of a center pivot irrigated cotton field **after** last irrigation. Dotted line and arrow indicate final pivot position and turning direction.

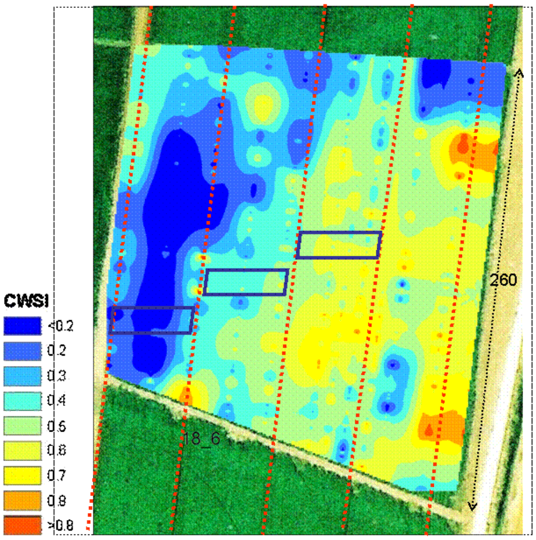


FIGURE 13. Management zones in a per-span controlled variable rate lateral move irrigator. Dotted lines are wheel paths.

Applications in irrigation management

Site-specific irrigation.

Irrigation machines, pivot or lateral moves, can be sub-sectioned, and controlled section-wise, at a relatively low investment, by already existing technology. Demonstration of potential variable rate, site-specific water application can be seen in Figure 13. on June 18 map before first irrigation. Once such maps are provided, several choices are possible, including pre-irrigation of the stressed sections only, or application of different water quantities according to stress levels. Other related spatial information derived from the same scan, such as crop cover and plant height, or perhaps yield maps or soil tests, may further refine site-specific irrigation management.

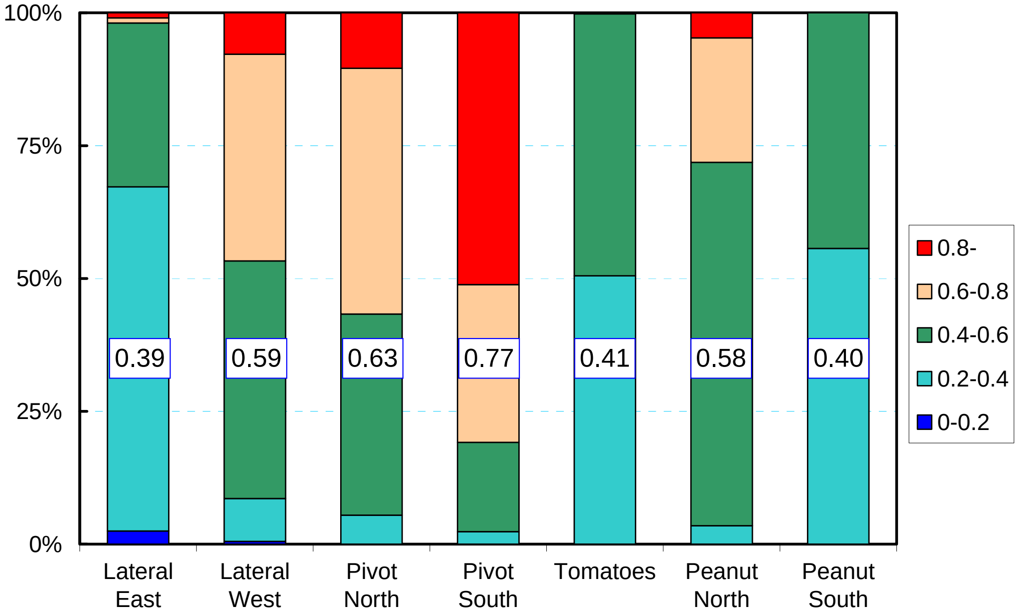


FIGURE 14. Crop stress level (CWSI) distribution and means in the aerial survey fields.

Solid set irrigation. Maps carry important visual information, but they need additional processing to quantify the information in order to act upon it. One of the useful capabilities of digital stress mapping is the numeric reporting of crop-stress level statistics for each management zone (Figure 14.). The grower can assess mean values of crop water status, the distribution of stress levels around the mean, and the extent of water stress extremities in the field at a glance, without studying the maps. This is particularly important in solid set systems, where irrigation is managed in whole units controlled by a single valve. When crop water stress is monitored routinely, short-term changes in stress levels from previous scans can be directly related to changes made in irrigation management. CWSI mean and distribution statistics also enable the scheduling of irrigation to suit drier, wetter or average stress levels. In the long term, stress maps enable reorganization of irrigation zones and valve assignments according to uniformity criteria.

SUMMARY AND CONCLUSIONS

A set of thermal remote sensing surveys were conducted from ground and low flying aerial platforms in the Hula Valley of Israel to provide crop stress maps, a prerequisite of site specific irrigation management. Wetted fabric surfaces were used as wet references, and air temperature +5 °K as dry reference to calculate CWSI. Crop temperatures were evaluated from the thermal image histogram and CWSI was geo-referenced as a single value to GPS readings in the center of the frame. Crop stress maps were generated by geo statistic interpolation. Leaf water potentials of cotton measured at 10 fixed sampling points during the season related linearly (R^2=0.816, n=56) to CWSI at the same spot, and the stressed range was clearly separated from the well-watered range. The CWSI maps corresponded well to irrigation history and information provided by growers. According to the methods tested and developed, thermal imaging can provide the maps needed for site-specific irrigation management.

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