# 2.4 Plant water status measurement

Dr Guy Roth
formerly Cotton CRC, Narrabri

Dr Rose Brodrick
CSIRO Plant Industry, Narrabri

Dr Phil Goyne
formerly QLD DPI&F, Warwick

Dr Warren Conaty
CSIRO Plant Industry, Narrabri

## Key points

Plant based measurements

- are effective at monitoring the water status of a crop.
- some techniques are not practical to schedule irrigations due to difficulties in accurate data collection and the requirement for some of the techniques to be undertaken on clear, sunny days at solar noon due to the high frequency of clouds at solar noon in Australia
- many techniques are useful for on-farm trials where researchers are involved.
- Developments in technology have shown potential for cost-effective plant based sensing for irrigation scheduling in Australian crops.

Plant based measurements arguably provide the most precise measure of plant water status for scheduling irrigations as they provided the integrated response of the plant to soil moisture availability and atmospheric influences. There are a range of plant sensing tools that can be used for both research and commercial crop irrigation scheduling. Satellites, airborne imaging systems and hand held instruments are frequently proposed as tools to measure crop stress caused by water, soil compaction, lack of nutrients, diseases and mites. In practice, however, there are a number of practical difficulties in using plant-based sensing for irrigation scheduling.

Many tools that in the past have only been practical for research purposes are now becoming accessible for commercial use. The development of cheap, wireless and remote sensors has renewed interest in the application of plant based sensing techniques for irrigation scheduling. This chapter briefly outlines those most commonly used plant based measurements for research purposes and irrigation scheduling. For a comprehensive review of different plant based sensing technologies see White and Raine (2008).

## Plant Spectral Sensors

Plant spectral sensors operate on the principal that when electromagnetic radiation (for example light) is reflected from a surface, the properties of the surface will influence the properties (for example wavelength) of the reflected radiation. This principal can be applied to crops by looking at the reflectance from the crop canopy, which will be influenced by factors such as water stress and nutrition. Figure 2.4.1 shows the spectral reflectance of a cotton crop near Wee Waa as measured by a portable spectro-radiometer.

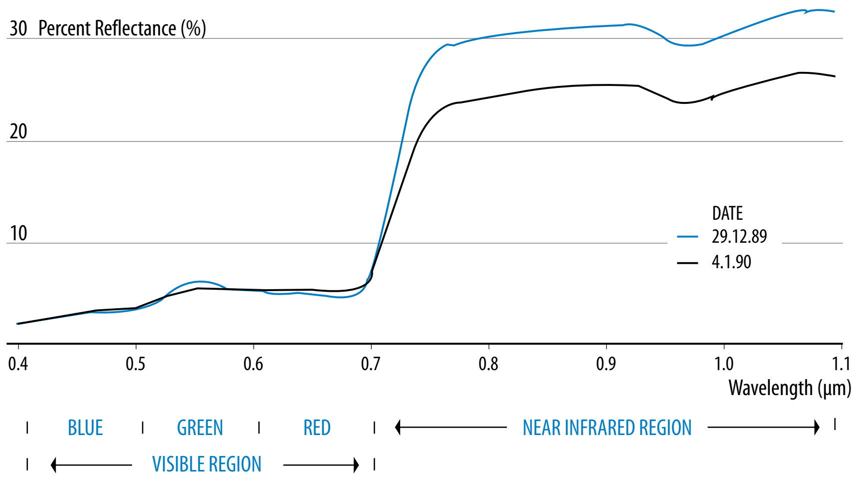
Studies have been conducted to investigate how the onset of water stress influences crop temperature and reflectance in the green, red, near infrared and thermal infrared wavelengths of the electromagnetic spectrum. These studies show that electromagnetic reflectance can be used to provide details on the spatial distribution of plant growth and development through the use of vegetation indices.

Vegetation indices are algebraic combinations of the measured canopy reflectance from different wavelength bands and are especially useful for the analysis of reflectance data. Numerous indices have been developed, most of which involve the red (0.6- 0.7 µm), near infra-red (0.7- 0.9 µm), short-wave infrared (0.8- 1.0 µm) and mid-infrared (1.0- 2.5 µm) wavelength bands.

Vegetation indices are typically the ratio of wavelengths reflected from reference and measurement surfaces (for example, leaves). One of the most commonly used vegetation indices is **normalised difference vegetation index (NDVI)**. It is calculated using the red and near infra-red wavelengths, which are the most commonly used wavelengths by remote sensing tools.

Pre-visual detection of water stress using handheld radiometers, vehicle mounted, airborne or satellite imagery to determine vegetation indices has been proposed as a more accurate way to time irrigations. Unfortunately, this is easier said than done as these instruments have so far been more successful for other applications such as measuring leaf area, detecting diseases and measuring spatial variability in fields.

Figure 2.4.1. The spectral reflectance of a cotton crop




Source: Roth 2002

# Crop canopy temperatures and irrigation scheduling

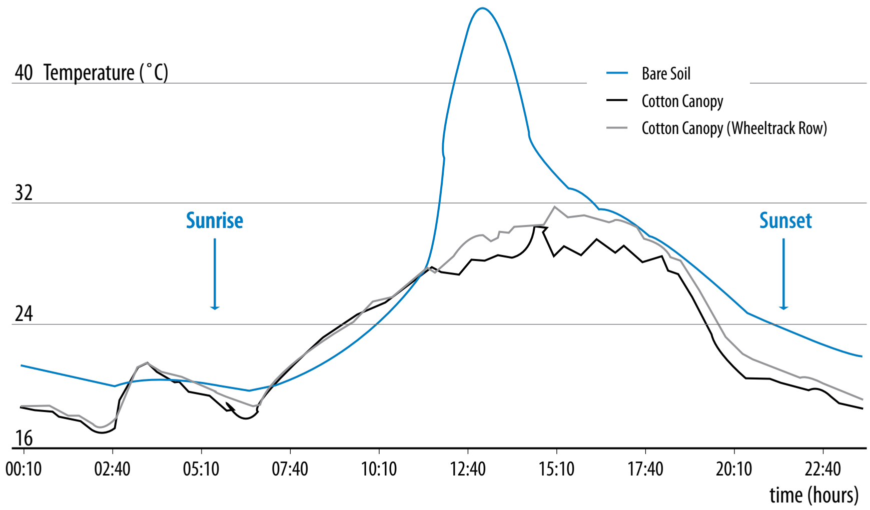
Compared to well-watered plants, water stressed plants exhibit elevated canopy temperatures. Plant leaves open their stomata to admit carbon dioxide for photosynthesis and at the same time, due to vapour pressure deficits, water vapour flows out of the leaf which cools the leaf surface. When soil water becomes limiting, transpiration decreases, thus reducing the leaf cooling effect and causing the crop temperature to rise. This occurs as a result of both reduced water availability and stomatal closure which is the plants water conservation mechanism. This is why when you touch the leaves of a well watered crop in sunlight on a hot sunny day they are cool, whereas a piece of green cardboard would feel hot.

All objects emit energy, or radiation, that is measured as their temperature. For crop canopies the temperature is usually measured with a thermal infrared thermometer (IRT). The advent of increasingly affordable and reliable IRTs and remote sensing imagery has stimulated research into plant based stress detection, through the monitoring of crop canopy temperatures.

Measurements of crop temperature can be taken using handheld or vehicle mounted devices, wireless fixed sensors, or thermal imaging cameras. Readings need to take ambient conditions into account, and errors can occur if background (soil) temperatures are being measured in the field of view of the instrument. There can be variations in temperature depending on the part of canopy being measured and the angle of measurement.

In addition, canopy temperature can vary during the day in response to both increased solar radiation and ambient temperature. Figure 2.4.2 shows the variation in canopy temperature measured by Roth (2002) over a day in a cotton crop, with differences between the temperature of the canopy measured in a compacted area (wheel-track row) compared with a non-compacted area of the crop. Data interpretation can be difficult as both water stress and ambient conditions (air temperature, radiation, humidity, wind speed etc) influence changes in canopy temperature and there are a number of approaches to interpreting canopy temperature measurements to identify crop stress to determine irrigation requirements.

Figure 2.4.2. Diurnal change in canopy temperature




## Stress degree day method

Wiegand and Namken (1966) proposed that the difference between leaf temperature and air temperature ($T_L$-$T_a$) could be used for irrigation scheduling. This idea was adopted by Idso et al. (1977) and Jackson et al. (1977), who suggested the difference between canopy temperature ($T_c$) and air temperature ($T_a$) obtained about an hour after solar noon could be used for irrigation scheduling. This method is known as the "stress degree day" concept and assumes environmental factors such as vapour pressure deficit, net radiation and wind would be manifested in the canopy temperature.

The use of canopy-air differences ($T_c$ – $T_a$) assumes that a well watered crop will transpire at its maxiumum potential rate, resulting in leaf temperatures lower than the air temperature and as soil water availability declines, transpiration declines and leaf temperature rises relative to air temperature. Crops with temperatures above the ambient air temperature are usually stressed.

## Crop water stress index

It is known that vapour pressure deficit (a measure of humidity) and net radiation influence crop temperature. As air becomes drier the vapour pressure deficit increases and the evaporative process becomes more efficient at cooling the plant, which is similar to an evaporative cooler cooling a house.

The Crop Water Stress Index (CWSI) was proposed as a more quantitative and repeatable method for determining crop water status than the stress degree day method. The CWSI is determined by subtracting the air temperature from the crop canopy temperature and comparing the resultant value with that of a well watered crop at the same vapour pressure deficit (VPD).

The crop temperature is measured using an infra-red thermometer, while the air temperature and vapour pressure deficit are measured using dry and wet bulb thermometers, or using formulae to convert relative humidity measurements.

Idso et al. (1981) describes an empirical method for determining the CWSI while Jackson et al. (1981) gives a theoretical explanation of the index. The CWSI value is a measurement of the reduction in transpiration, expressed as a decimal in CWSI units. The CWSI has values ranging from 0 (no stress) up to 1 (maximum stress). A CWSI value between 0.25 - 0.35 would occur when the irrigation is due.

The CWSI is characterized by a lower limit or a "non-water stress baseline", at which the plant is experiencing no stress, and an upper limit where the plant is experiencing severe stress.

Idso (1982) defined non-water-stressed baseline for 26 different species for clear sky conditions and found that these baselines were different for various phenological stages in certain crops. For winter wheat crop, different baselines should be developed for pre and post head stages. Gardner et al. (1992) suggested that baselines are strongly location dependent, and perhaps species and variety dependent.

To determine a non water stressed base line it is a matter of measuring a non stressed crop canopy temperature over a range of VPDs. This can be done by monitoring it as it changes over one day or by taking measurements on different days when the VPD is different around solar noon.

The CWSI is calculated by using the following formula: Where

A is the upper limit of $T_{crop} - T_{air}$,

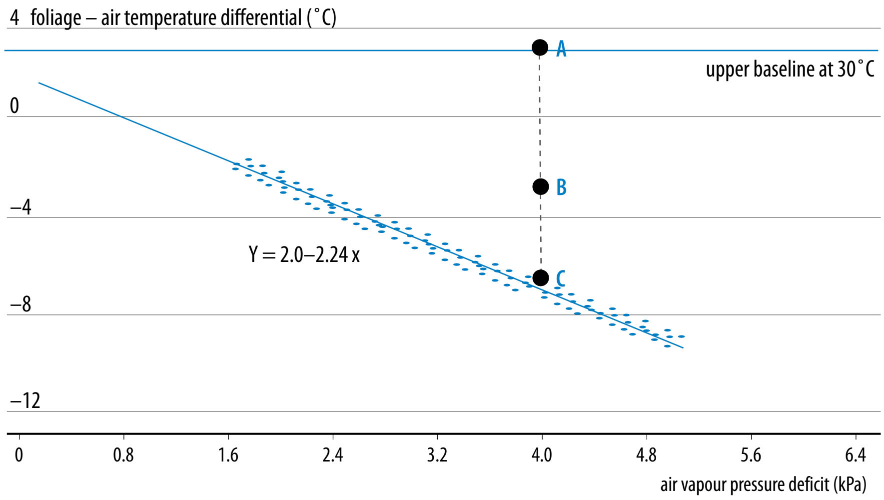
B is the actual measured vale of $T_{crop} - T_{air}$ and

C is value of $T_{crop} - T_{air}$ if the crop were non-stressed (Figure 2.4.3).

$$CWSI = \frac{B - C}{A - C}$$

While in theory this method is very sound and has worked well in irrigation experiments in dry, sunny climates like Arizona, it has not been adopted in Australia. It is more difficult to get baseline data in Australia as the climate is more humid and the VPD range is much less. Furthermore, measurements are required to be taken at peak daily radiation (normally between 12 and 2 pm) on clear cloudless days. Patchy clouds can often build up after midday in Australia and create problems when applying plant based measurement techniques for irrigation scheduling. These combined factors make it is more difficult to collect the data on a routine basis. However, the major limitation to the use of thermal sensing in the past has been the requirement for repeated measurements and the importance of adhering to specific sampling times to calculate the CWSI accurately.

Figure 2.4.3. Theoretical relationship between the canopy air-temperature difference and the vapour-pressure deficit



### Relative temperature differences

Canopy temperature variations due to stress are only small (1-3°C) and difficult to separate from variations caused by diurnal and daily changes in radiation. An alternative way to use crop temperatures for irrigation scheduling is, on any one day, to measure the canopy temperature of a well watered crop and use that as a base temperature to compare with other crops on the same day.

Crops with warmer temperatures are likely to be more stressed. Thus, water stress can be assessed by examining differences in canopy temperature between the field in question and a well watered area of the same crop in the near vicinity. This assumes environmental effects are common to all areas on a farm at the measurement time.

Another option, for those growers interested in precision water management techniques, is to use a cropped field as its own reference point and examine the temperature variability within the field.

### BIOTIC – Biologically Identified Optimal Temperature Interactive Console

BIOTIC is an irrigation scheduling tool developed in the U.S.A, based on canopy temperature using a temperature-time humidity threshold system (Upchurch et al., 1996). BIOTIC differs from other temperature-based irrigation scheduling methods as it compares canopy temperature with a biologically based estimate of the optimum temperature of the plant using a three step threshold system.

The first threshold is the species-specific optimum temperature. This optimum temperature or threshold temperature is based on the observation of the thermal dependence of plant metabolic activity and represents the plant's ideal temperature for metabolic and enzymatic function.

The second threshold is a time threshold. This time threshold represents the amount of time that the temperature of a well-watered crop canopy can exceed the temperature threshold, regardless of plant available soil water capacity. This is important, especially in irrigation systems where irrigation cannot be applied at short intervals and large soil water deficits are inevitable.

The final threshold is a limiting relative humidity threshold. The relative humidity threshold is important as under certain environmental conditions, relative humidity can limit transpirational cooling to the point that canopy temperature may exceed the optimum, regardless of soil water. Therefore, temperatures above the optimum under these conditions are not considered in the irrigation scheduling decision-making process.

Under the BIOTIC irrigation scheduling protocol, irrigation is considered appropriate when canopy temperature exceeds the threshold temperature for a period of time in excess of the time threshold when relative humidity is not limiting transpirational cooling (Mahan et al., 2005).

The primary advantage of BIOTIC is that it utilises a plant based biological basis for scheduling irrigation, its simplicity and provision of reliable irrigation scheduling (Mahan et al., 2000). It does not provide information on the amount of water applied in response to an irrigation signal and is designed to provide full irrigation. It can provide irrigation signals at any frequency, however as the interval between detection of water stress and the irrigation event increases, the irrigation signal becomes increasingly complex (Mahan et al., 2000). This is especially important in the context of evaluating the utility and adaptability of BIOTIC to large deficit irrigation scheduling systems such as furrow irrigation.

This system utilises wireless infrared thermometers (IRTs) that continuously measure canopy temperature overcoming many of the limitations in measuring canopy temperature using hand-held IRTs.

The existing thermal optimum approach to irrigation scheduling, BIOTIC, is limited in that it is designed for precision, low volume irrigation application systems. Therefore in its original form, BIOTIC has not been implemented in furrow irrigation systems where large soil moisture deficits occur. Recent research by Warren Conaty (2010) in Australia has identified that this system could be adapted to suit irrigation systems with large soil moisture deficits and is a subject of current research.

### Airborne Thermal Infrared Imagery

It is possible to "photograph" the crop temperature to examine the spatial variation of crop health within and between fields on farms. This can be done from an aircraft or satellite. Problems with satellite imagery in the thermal infrared band include: poor spatial resolution (120 metre pixels), image capture at the wrong time of day (early in the morning – 10.00am, which is not good for stress detection) and the frequency of satellite passes creates problems obtaining images. Airborne imagery can be collected any time and is usually done about 6000-9000 ft above ground level, which results in a pixel resolution of about 3 metres.

In addition to scheduling irrigations, thermal imaging has other potential applications including:

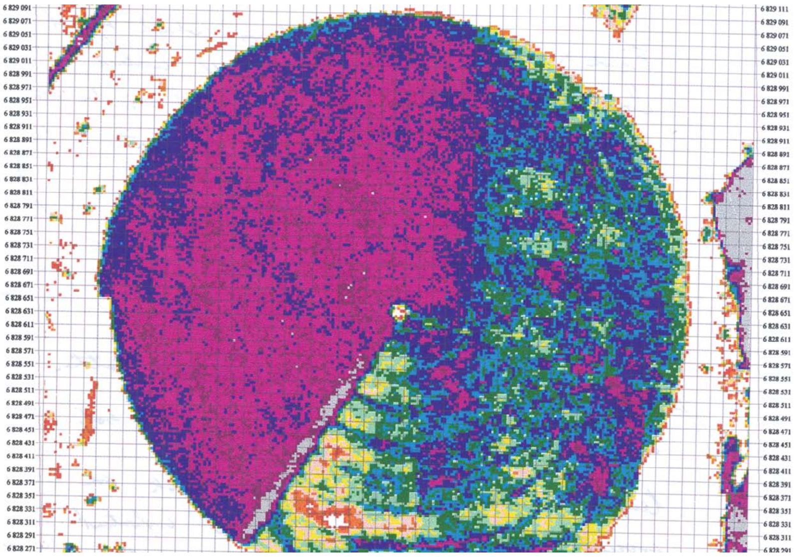
- growers and consultant knowledge of the variability in their fields
- detecting low spots and water logging problems
- early "cut out" detection of highly loaded crops
- early detection of fusarium wilt disease,
- insect monitoring such as mite hotspots, high LAI, etc
- accurate potential yield variation maps
- defoliation information with rank and late maturing crop areas identified for variable rate and product selection,
- hail damage assessment,
- agronomist overview and precision mapping overlay with EM surveys,
- farm maps.
- examination of drip and spray irrigation system distribution.

Figure 2.4.3 shows a well watered cotton crop (28°C – crimson). The higher the temperature, the more stressed the crop, and this is shown by yellow/orange colours.

- The highest crop temperatures between 6 and 7 o'clock are around 31°C (yellow/orange).
- Crimson colours indicate cool crop temperatures and well-watered conditions
- The centre pivot itself can be seen at seven o'clock (grey colour), as the water is the coolest part of the pivot.

An important feature evident in this image is the greater spatial variation in a crop's temperatures as it approaches an irrigation. This image also shows the GPS coordinates which allows any problem points to be accurately located.

Figure 2.4.4. Airborne thermal infrared image of a cotton crop



## Relative Water Content

Relative Water Content (RWC) estimates the water content of sampled leaf tissue relative to the maximum water content it can hold at full turgidity. It is a measure of water deficit in the leaf. It is only used for research purposes with samples processed in controlled conditions. Normal values of RWC range between 98% in turgid and transpiring leaves to about 40% in severely desiccated and dying leaves. In most crop species the typical RWC at about wilting is around 60% to 70%.

Discs are cut from the leaves, to obtain about 5-10 $cm^2$/sample, for no more than two hours at and after solar noon. Each sample is placed in a pre-weighed airtight container and kept cool until it reaches the lab. In the lab containers are weighed to obtain leaf sample weight (W), after which the sample is immediately hydrated by floating on de-ionized water to full turgidity under normal room light and temperature. After 4 hours the samples are taken out of water and dried of any surface moisture and immediately weighed to obtain fully turgid weight (TW). Samples are then oven dried at 800°C for 24h and weighed to determine dry weight (DW).

$$RWC\ (\%) = [(W - DW) \div (TW - DW)] \times 100$$

Where, W = sample fresh weight, TW = sample turgid weight, DW = sample dry weight.

## Pressure Chamber (Pressure Bomb)

The pressure chamber technique for measuring plant water potential has been a standard research technique since the 1960's. It was tried in the Australian cotton industry in the early days, but is no longer used for commercial irrigation scheduling because of problems getting repeatable data due to cloudy weather. It is still used in countries that do not experience clouds such as Israel and California.

Stem parts, leaves, branches or whole plants are placed into the chamber so the cut end protrudes through the specimen holder. Pressure (nitrogen) is applied to the plant part until a drop of sap is observed at the cut end. The pressure required to force a drop of sap from the sample is equivalent to the force with which water is held to plant tissues by forces of adsorption and capillarity. In order to use the pressure bomb as a tool for irrigation scheduling, pressure bomb data have to be correlated with soil water potential data (using a neutron moisture meter and potential evapotranspiration). With this relationship, it is possible to characterize the irrigation scheduling for a specific crop.

Sampling should be done under full sunlight that is cloud free. Under milder or cloudy conditions readings will be less negative and won't give a useful indication of soil moisture. Daytime/solar noon measurements are difficult to interpret and some researchers like to examine pre dawn data to see whether plants are completely recovering from moisture stress overnight. Sampling is easy and generally the uppermost fully expanded leaf petiole is used.

Delays between petiole removal and measurement can introduce serious errors in the readings obtained due to moisture loss before measurement. The best method is to take the readings in the field. Moisture loss can be minimised by wrapping the leaf in clear plastic 'cling wrap' before excision and placing the leaf still wrapped into the chamber for measurement. Much more consistent results are obtained this way. Some level of experience is required for repeatable results, and the operation of high pressure equipment is potentially dangerous, however maintenance of pressure chambers is minimal and they are simple to operate.

## Thermocouple Psychrometer

Measuring water potential by thermocouple psychometry refers to the measurements of the difference in temperature between an atmosphere and a freely evaporating moist surface. In that atmosphere the psychometer measures small differences in vapour pressure. A thermocouple is formed where wires of two different metals are joined.

If the two junctions are held at different temperatures, an electric current will flow through the circuit. The magnitude of the current is a measure of the difference in temperature between the two junctions. Thermocouple psychometry depends on the principle that water vapour at equilibrium with plant tissue will have the same water potential as the tissue. Water potential of tissue can be measured by measuring the vapour pressure of the chamber in which plant material is sealed.

The plant material is sealed in a small chamber with a thermocouple junction and a drop of water. The chamber quickly saturates with water vapour. Since the water potential of the tissue is more negative than the water potential of the pure drop of water, water vapour moves from the drop into the tissue. As the water evaporates from the junction, the temperature drops. This drop in temperature is compared to a known ambient temperature and vapour pressure calculated.

### Porometer

The loss of water (evaporation) by plant leaves is regulated by the stomata (pores) of the leaves, as absorption of $CO_2$ takes place for photosynthesis. It is an important indicator for the physiological condition of the plant. The opening of the stomata can be interpreted as the resistance against gas diffusion and is measured using the porometer. Measurements of diffusion conductance are therefore important indicators of plant water status and provide a valuable insight into plant growth and adaptation to environmental variables.

### Sap flow sensors

There are three types of sap flow sensors: heat balance, heat pulse and thermal diffusion. The heat balance sensor is placed around the stem and the others require probes to be inserted into the plant stems. These sensors measure the velocity of sap flow by monitoring changes in sap temperature when heat is applied to the stem. The resulting measurements can be related to plant water status as transpiration induces sap flow. These instruments have been mainly restricted to scientific investigations.

## References


Conaty, W. C. (2010) Temperature-time thresholds for irrigation scheduling in precision application and deficit furrow irrigated cotton. PhD Thesis, University of Sydney, New South Wales.

Gardner, B.R. Nielsen, D.C., Shock, C.C. (1992) Infrared thermometry and the crop water stress index. II.

Sampling procedures and interpretation. *Journal of Production Agriculture* 5, 466-475.

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

Idso, S. B. Jackson, R.D. and Reginato, R. J. (1977) Remote sensing of crop yields. *Science* 196, 19-25.

Idso, S. B. Jackson, R.D., Pinter, P.R., Reginato, R. J and Hatfield, J. L. (1981) Normalizing the stress degree day parameter for environmental variability. *Agricultural Meteorology* 24, 45-55.

Jackson, R. D. (1982) Canopy temperature and crop water stress. *Advances in Irrigation* 1, 43-85.

Mahan, J.R., Burke, J.J., Upchurch, D.R., and Wanjura, D.F. (2000) Irrigation scheduling using biologically-based optimal temperature and continuous monitoring of canopy temperature. *Acta Horticulture* 537, 375–379.

Mahan, J.R., Burke, J.J., Wanjura, D.F. and Upchurch, D.R. (2005) Determination of temperature and time thresholds for BIOTIC irrigation of peanut on the southern high plains of Texas. *Irrigation Science* 23, 145–152.

Roth G. (2002) The effect of water stress and soil compaction on cotton canopy relectance and temperature. In Proceedings of 9th *Australasian Remote Sensing Conference*. 20-24 July, 2002.

Upchurch, D.R., Wanjura, D.F., Burke, J.J. and Mahan, J.R. (1996) Biologically-identified optimal temperature interactive console (BIOTIC) for managing irrigation. U.S Patent 5,539,637. Date issued: 23 July.

Wiegand, C. L. and Namken, L.N. (1966) Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature, Agronomy Journal 58:582-586.

White, S. and Raine, S. R. (2008). A grower guide to plant based sensing for irrigation scheduling. National Centre for Engineering in Agriculture Publication 1001574/6, USQ, Toowoomba.