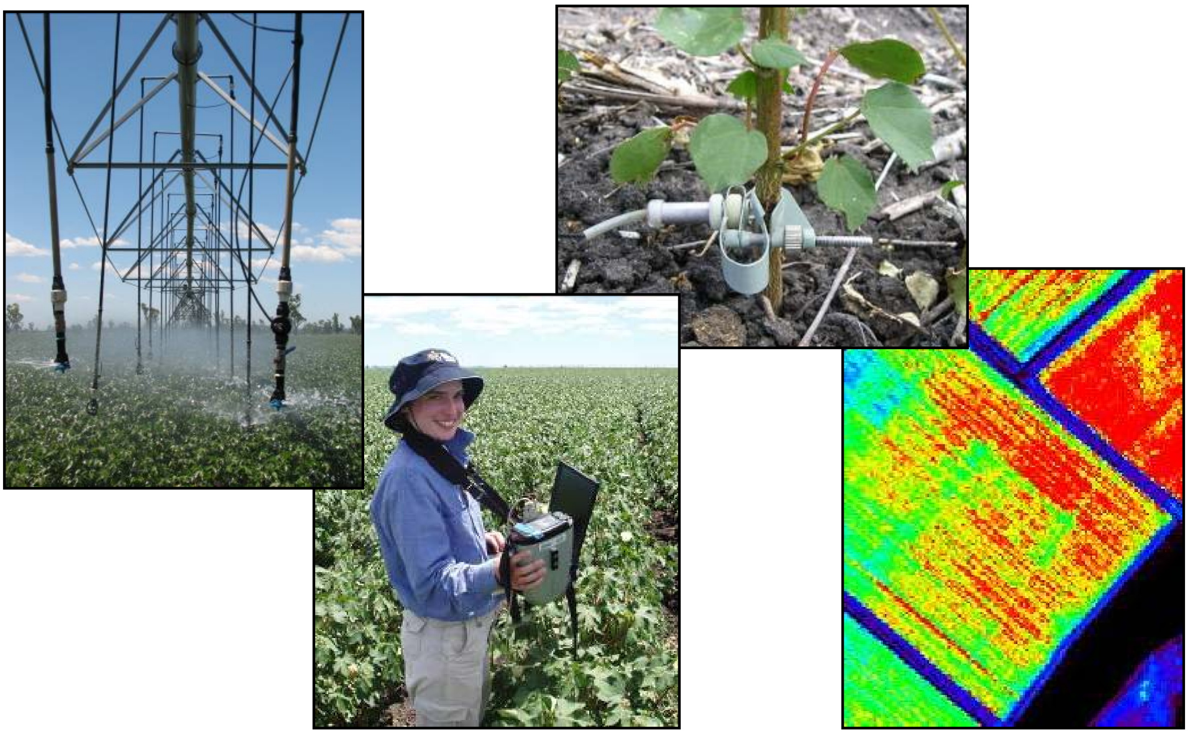
A Grower Guide to Plant Based Sensing for Irrigation Scheduling



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ACRONYMS

β-gauge	Beta gauge
CASI	Compact airborne spectrographic imager
CHPM	Compensated heat pulse method
CWSI	Crop water stress index
DCA	Daily contractual amplitude
DSI	Daily stem increment
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
HRM	Heat ratio method
IR	Infrared
K_c	Crop coefficient
LVDT	Linear variable differential transformer
MDS	Maximum daily shrinkage
NDVI	Net difference vegetation index
RAW	Readily available water
SDS	Stem diameter sensors
SHB	Stem heat balance
T_{air}	Temperature of the air
T_{canopy}	Temperature of the canopy
T_{dry}	Temperature of a non-transpiring (dry) leaf/canopy
T_{nws}	Temperature of non-water stressed leaf/canopy
TD	Thermal dissipation
TDF	Trunk diameter fluctuations
UAV	Unmanned aerial vehicle
VPD	Vapour pressure deficit
Ψ_w	Plant water potential
Ψ_p	Pressure potential (ie. turgor pressure)
Ψ_o	Osmotic (or solute) potential
Ψ_s	Stem water potential
Ψ_l	Leaf water potential

FOREWORD

The adoption and use of plant based measurement sensors in agriculture has increased in recent years as a result of technological advances and a greater focus on the spatial management of crop inputs. For practitioners, there seems to be a never ending array of new tools being released onto the market each season. Similarly, plant monitoring sensors which were originally developed for research applications are increasingly being used for commercial irrigation scheduling. However, the wide range of scheduling tools available, and the reputed benefits of each tool, make it difficult for farmers and researchers to identify the appropriate technology to use for their purpose.

This publication was conceived as a first reference point for individuals who are new to plant based sensing. It is also hoped that the collation of this plant based sensor information will assist farmers and industry advisers to make more informed decisions in relation to the choice and use of plant based sensing technology for irrigation scheduling. Chapter 1 provides a brief introduction to the measurement options for scheduling irrigation and the benefits associated with plant based approaches. The main types of plant based sensing involve either contact sensing of the plant or non-contact sensing. Chapter 2 discusses the main contact methods of plant sensing while Chapter 3 highlights the non-contact proximal and remote plant sensing methods.

Each sensing method is discussed in the same way to enable easy comparisons. A brief overview is provided followed by details on the method of operation, maintenance requirements, typical purchase costs, and the advantages and disadvantages of the method for commercial irrigation scheduling. Contact information for manufacturers and/or dealers is also provided at the end of each section. However, all information in relation to specific products and costs should be regarded as indicative only as the products, costs and suppliers are constantly changing.

We hope you find this publication useful. Happy sensing.

Simon White
Steven Raine

1. IRRIGATION SCHEDULING

The process of irrigation scheduling involves both the identification of the time to apply the water and the volume of water required to be applied. Volumetric inefficiencies in irrigation result largely from irrigating too often or applying too much water at each irrigation. Agronomic inadequacies occur when the plants are inappropriately stressed due to either insufficient water being applied frequently enough or excessive water application resulting in waterlogging or increasing the incidence of disease. The first step in improving both volumetric efficiencies and agronomic water productivity is knowing how much water to apply and when to apply it.

The plant response to irrigation is a function of the plant water status. Plant water status is influenced by a range of factors including the soil water potential (ie. the energy required to remove water from the soil), the interface (i.e. resistance and area) between the soil and plant roots, hydraulic conductivity within the plant and the evaporative demand (i.e. atmospheric conditions) to which the plant is exposed. Hence, methods commonly used to schedule commercial irrigations commonly involve measuring either (a) atmospheric conditions (b) soil moisture or (c) plant stress.

1.1 Atmospheric Measurements and Water Balance Techniques

Atmospheric techniques for irrigation scheduling are widely used to estimate crop water requirements over whole seasons. They are also used to provide a first estimate of appropriate irrigation schedules where infield soil or plant measurements are not undertaken. In these methods, the daily crop water use (termed the "crop evapotranspiration" or ET_c) is calculated using a crop coefficient (K_c) and a reference evapotranspiration (ET_o) obtained from atmospheric measurements as:

$$ET_c = K_c * ET_o \tag{1.1}$$

Details on the identification of appropriate crop coefficients and the calculation of the reference evapotranspiration can be found in "FAO56: Crop Evapotranspiration –

Guidelines for computing crop water requirements" (Allen et al. 1998).

Not all of the water held within a soil is able to be extracted by plants. An estimate of the volume of soil water that is accessible to the plant without imposing an unacceptable level of crop stress is required to identify appropriate irrigation intervals and application volumes. The acceptable level of crop stress will vary between crops and even within a season depending on the crop management target. For example, lettuce crops have a smaller water potential stress limit compared to lucerne crops. Similarly, it is often desirable to impose a relatively large moisture stress prior to flowering in perennial tree crops but a smaller stress during fruit filling periods. Hence, the maximum acceptable crop stress value should be viewed as a management variable that is determined by the grower.

The volume of soil water able to be readily utilised by the crop (termed the "readily available water" or *RAW*) may be estimated from texture-based soil water characteristic data (Table 2.1) and the maximum acceptable crop stress. The active crop rooting volume may be used to convert the tabulated *RAW* (in mm/m) into a volume appropriate to the individual plant or unit crop area. The irrigation interval may then be calculated from the ET_c and *RAW* values using:

$$\textit{Irrigation interval}\text{ (in days)} = \textit{RAW}\text{ (mm)} \;/\; ET_c\text{ (mm/day)} \qquad (1.2)$$

Table 2.1: Effect of soil texture on readily available water

Soil Texture	**Readily Available Water (mm_{water} per m_{soil}) between field capacity and;**				
Crop Stress Level	***-20 kPa***	***-40 kPa***	***-60 kPa***	***-100 kPa***	***-200 kPa***
Sandy	30	35	35	40	45
Loamy Sand	45	50	55	60	65
Sandy Loam	45	60	65	70	85
Loam	45	65	75	85	105
Sandy Clay Loam	40	60	70	80	100
Clay Loam	30	55	65	80	105
Light Clay	27	46	57	70	90
Medium Clay	24	43	55	65	83
Heavy Clay	21	40	53	60	81

Irrigation schedules developed using atmospheric measurements are widely used. However, there are a number of limitations, particularly as the spatial scale of discrimination required for management decreases. For example, while the crop coefficient can be adjusted for a range of factors (e.g. crop age, canopy cover) appropriate values for different crop cultivars and management conditions (e.g. deficit irrigation, partial root zone drying) are not normally available. Similarly, the soil water characteristic data commonly used for estimating the soil water volumes is often based only on the soil textural properties. However, the readily available water content of a particular soil will also be strongly influenced by the soil structure and organic matter content. Hence, the cultivation and crop management history of the soil will affect the readily available water content. Estimates of rooting volume are also commonly based on a small sample of point measures which may not adequately reflect the variation observed in the field. The technique is also not suited for differential (i.e. variable rate) irrigation at small spatial scales as the atmospheric measurements are normally obtained from a single local weather station and assumed constant over the surrounding area.

1.2 Soil Moisture Monitoring

Soil moisture monitoring is widely used for scheduling irrigations and involves measurements of either soil water potential (i.e. tension) or soil water content. Most soil moisture monitoring involves a single point measurement of soil moisture within the plant root zone. These measurements are useful in understanding the changes in soil moisture within the root zone and relating these observed changes to both the volume of irrigation water applied and the extraction of water by the plant. It is also possible to identify the time to irrigate and, with either trial and error or infield sensor calibration, the volume of water to apply.

A major limitation with using soil moisture monitoring for irrigation scheduling is that plant water uptake and stress does not only respond to the soil water content or potential. A range of other factors including atmospheric conditions (ie. radiation intensity), nutrient availability, root zone salinity, incidence of pests or disease and previous crop stress history all impact plant water uptake. Another limitation is that most soil moisture measurements are often only taken at a single point. The accuracy and appropriateness of the irrigation schedule developed using this data is therefore reliant on the selection of representative monitoring sites within each management zone and/or is based on the assumption that the field is homogeneous in terms of both soil characteristics (i.e. moisture content and water holding capacity) and crop characteristics (i.e. growth and rooting depth). To improve confidence when using soil moisture monitoring devices, growers often deploy multiple sensors at different depths within the root zone and/or a range of locations within the fields. Detailed information on equipment and methods of soil moisture monitoring including case studies is available in "Soil Water Monitoring: An Information Package" (Charlesworth, 2005).

1.3 Plant Based Monitoring

Measurement of plant water stress has been a topical issue for a number of years and there are now a range of plant sensing tools available for both research and commercial crop irrigation scheduling. Plant based sensors can be broadly classified into either contact or non-contact sensors. Contact sensors are those that are physically mounted so that they are in direct contact with the plant. By their nature, contact sensors normally provide single plant or point source data. Non-contact sensors are further divided into either proximal (i.e. near to the crop) or remote (i.e. aerial and satellite based data acquisition) sensors depending on how close to the crop the sensor is located. Proximal sensors can be either hand-held, fixed or vehicle mounted.

Plant based sensors have also been classified (Remorini and Massai 2003) according to whether they measure a direct physiological indicator (e.g. plant water status) or an indirect physiological plant response induced by changes in plant water status (e.g. leaf temperature, plant organ diameter or growth). Plant water status sensors measure either the plant water content (e.g. stem micro-variation sensors, dendrometers, leaf thickness sensors) or the plant water potential within the root, stem or leaf (e.g. pressure chamber and psychrometer). Plant response sensors include those which measure a change in the plant that is related to the change in water status and include tools such as sap-flow sensors, porometers (ie. measures stomatal conductance) and thermal infrared guns (ie. measures canopy temperature).

1.4 Advantages and Limitations of Plant Based Sensing

Depending on the crop, plants can exert a significant degree of control over their water status by manipulating their response to the soil moisture availability and the imposed evaporative demand. Hence, plant based sensors which either directly measure plant water status or the response of the plant to the imposed conditions have an advantage over other methods of scheduling as they provide an integrated measure of the plant's response to both the soil moisture availability and evaporative conditions.

Plants can commonly control evapotranspiration losses at diurnal time scales by varying leaf angle relative to the incident radiation (i.e. sunlight) and/or by a change in stomatal aperture. Over longer periods, plants will respond to soil moisture and evaporative demand by changing their rate of leaf extension or moderating their rooting depth and/or density. These physiological changes in response to atmospheric conditions and soil-water may be either an advantage or limitation for plant based sensing techniques depending on the purpose of monitoring and the characteristic being measured.

For plant sensing to be successful, the measurand needs to respond to changes in the available soil moisture and/or the atmospheric evaporative conditions. For example, under periods of moisture stress or high evaporative demand, a reduction in stomatal aperture results in a reduction in transpiration and hence, an increase in canopy temperature. This change may be measured using a canopy temperature sensor and presented as a crop water stress index value. However, in some plants, measurements of tissue water content may not be a reliable indicator of irrigation stress because autonomous stomatal control may be used to maintain the same tissue water content under a wide range of environmental conditions.

A significant current limitation in the application of plant based sensors for commercial irrigation scheduling is that these techniques do not provide a direct measure of the irrigation volume required to be applied. Hence, plant based sensing is commonly used in conjunction with soil moisture measurement equipment and/or a water balance approach.

2. CONTACT METHODS OF PLANT BASED SENSING

2.1 Introduction to Plant Water Status

The response of a plant to the combined effects of soil moisture availability, evaporative demand, internal hydraulic resistance and resistance/uptake capacity of the plant/root interface is principally measured in terms of the plant water status. The plant water status can be determined by measuring either the tissue water status (ie. potential or content) or the plant's response to a change in tissue water status. Wilting is an extreme example of a plant response to a decrease in plant/cell water content and plant water potential.

It could be argued that the best plant based measurement to use is one which directly measures plant water content relative to a well watered control. However, plants have evolved response mechanisms which reduce the impact of plant water loss and maintain tissue water content. In these cases, measurements of plant water content may not adequately identify the effect of increasing evaporative demand and/or increasing soil moisture deficit. Plant water potential is a direct measure of the energy status of the water within the plant and reflects both the soil-water availability and atmospheric conditions.

The potential energy of water (ie. water potential) is affected by the influence of gravity, matric properties, osmotic gradients and applied pressures. The matric potential is due to the adsorptive forces binding water to a matrix. In plants, the influence of gravitational and matric potentials are negligible and often ignored. Osmotic potential gradients are created by differences in solute concentrations and results in water moving across membranes (e.g. in roots) from regions of high potential (i.e. soil) to regions of low potential (i.e. plant tissues) in an attempt to reach equilibrium. Osmotic (or solute) potential (Ψ_o) is always negative due to the presence of solutes (pure water has a Ψ_o of zero). In plants, differences in pressure potential (Ψ_p) are created by the action of water evaporating from the leaves and are related to the turgor pressure. Hence, the plant's total water potential (Ψ_w) can be calculated as:

$$\Psi_w = \Psi_o + \Psi_p \qquad (2.1)$$

2.2 Measuring Plant Water Status

2.2.1 Pressure Chamber

Quick Overview

Pressure chambers (e.g. Scholander pressure chamber) are devices used to measure plant water potential (i.e. how much tension/suction force is being exerted by the plant on its water supply due to evaporative demand and soil moisture availability). To measure plant water potential, a plant sample (e.g. stem or leaf) is placed into a chamber and a pressure applied until moisture is exuded from the plant material. The pressure at which moisture is extruded from the plant material is termed the "end point" and the water potential of the plant material is reported as the negative of the end point pressure applied to the chamber.

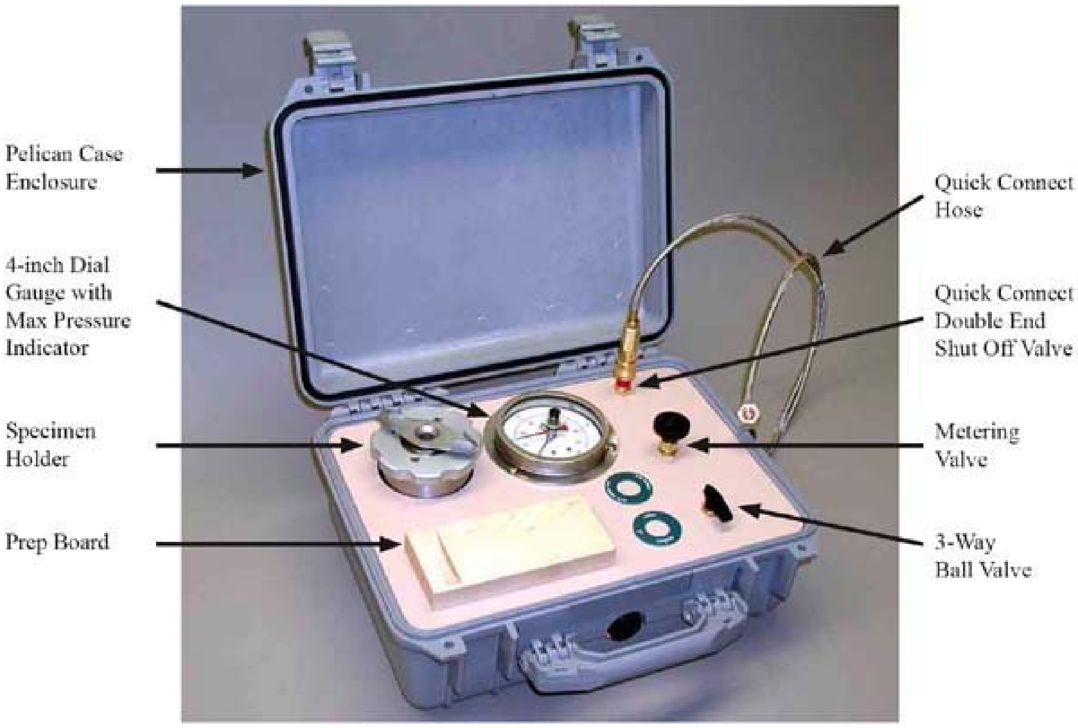

Figure 2.1: Portable pressure chamber and console
(Source: http://www.ictinternational.com.au/PortablePWSC.htm)

Method of Operation

The evaporative demand and the soil moisture availability apply a tension on the water present within the plant. When a leaf (or shoot) is cut from the plant, the tension causes water within the plant to be drawn inwards from the cut end. The leaf (or shoot) should be placed in the pressure chamber and sealed with a rubber insert so that only the cut end is external to the chamber. Pressure is then slowly applied to the chamber until the water within the petiole (or shoot) is pushed out to the cut surface. When water is visible on the cut surface, this is defined as the end point and the pressure applied is recorded. As the pressure required to reach the end point is the inverse of the internal tension being exerted on the water within the leaf (or shoot), the value of plant water potential (Ψ_w) is expressed as a negative value. An increase in the applied chamber pressure required to reach the end point means a greater level of tension (i.e. decrease in Ψ_w) is being exerted on the plant due to a larger moisture stress and/or evaporative demand being present. Water potential is normally reported in measurement units of -Bar or -MPa (Note: 1 Bar = 0.1 MPa = 100 kPa).

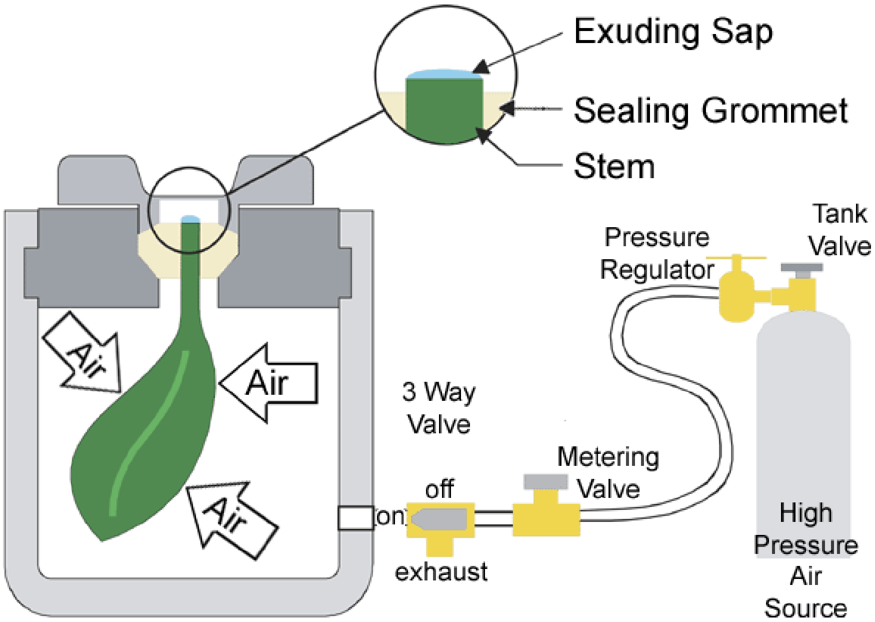

Figure 2.2: Operation of a pressure chamber to measure plant water status
(Source: http://www.ictinternational.com.au/pwsc.htm).

Plant water potential is a result of soil moisture and evaporative demand and is continually changing throughout the day (diurnal). Hence, plant water potential measures are generally taken at two different times during the day depending on the purpose of measurement. Midday measurements of plant water status (limited to clear days only) will give the lowest leaf water potential (negative value) a plant is exposed to as evaporative demand peaks at or soon after solar noon. Pre-dawn measurements of plant water status enables measurement without the presence of transpiration (water flux) as evaporative demand at pre-dawn is negligible. This measure of plant water status therefore reflects soil moisture condition in close contact with the plant roots which have equilibrated over night.

There are also two measurements methods which can be undertaken. Leaf water potential, measured on a sampled leaf exposed to the atmosphere and stem water potential, measured on a sample leaf which has been covered. As each leaf is different in size, location and orientation, differences will be present in the measured leaf water status. This can be overcome by measurement of stem water potential. Sampling for stem water potential involves covering the leaf for a predetermined period of time with a plastic/foil envelope. This is to ensure water loss is stopped and the leaf water potential equilibrates with the stem (xylem) water potential. Stem Ψ_p is considered a better indicator of plant water status than leaf Ψ_p as it accounts for whole plant evaporative demand (plant water status). To account for differences in leaf and stem water potential due to climatic conditions, baseline values for corresponding weather conditions can be formulated. Baseline values are obtained through measurement after an irrigation event which refills the soil profile.

Accuracy and repeatability of measurements is a function of consistence in measurement procedure and uniformity in size, shape, orientation, age and position of leaves sampled. Measurement of stem water potential overcomes errors associated with individual leaf conditions. The most common problems encountered when using a pressure chamber is a difficulty in detecting the true end point resulting from bubbling and/or the appearance of non-xylem water at the cut surface. This can be minimised by avoiding perforation or damage to the leaf sample and avoiding over squeezing the petiole through the rubber sealing gasket. A moderate level of operator experience is required to minimise these problems and improve end point repeatability.

Hand pump chambers are also available which are more suited to field studies as they do away with the need for a pressurized nitrogen tank. However, in choosing one of these systems ensure that the range of pressure achieved with the hand pump is sufficient for the purpose and check that there is an adequately level of pressure control to the chamber during pumping.

Maintenance

Maintenance of pressure chambers is generally regarded as minimal. Lubrication of the joints and seals along with a visual assessment of pipe and connector condition should be undertaken regularly.

Cost

Basic pressure chambers typically range from $5000 to $7000. Additional components are normally priced separately and commonly include the eye lens, extra sealing gaskets, insertion tool and portable tank. A volume reducer may also need to be considered depending on the model purchased and the size of sample being measured. The main consumable costs are associated with re-filling the nitrogen cylinder and the purchase of stem water potential bags.

Advantages and Disadvantages for Commercial Irrigation Scheduling

The most common method of measuring plant water status involves the use of pressure chambers. Pressure chambers are widely used for research applications but chambers are also commonly used in commercial irrigation scheduling services to complement soil moisture monitoring. The main advantage over point source soil moisture monitoring is that plant water potential measures account for soil moisture availability throughout the whole root system as well as the evaporative conditions imposed on the plant. Use of a pressure chamber also enables replicate measurements/samples to be taken across a field. The main limitations for commercial irrigation scheduling are associated with the labour and time required for measurement, limitations in the timing of measurements due to diurnal fluctuations and environmental (e.g. effects of cloudy days) constraints. Some level of experience is required for proficiency and repeated accuracy. The operation of high pressure apparatus is potentially dangerous when used by inexperienced operators. There is also no ability to automate the measurements and the leaves need to be destructively sampled.

Manufacturer/Distributors of Commercial Products

Manufacturer/Distributor	Contact Details	Further Information
PMS Instruments Co.	1725 Geary Street SE Albany OR 97322 USA Ph: (541) 704-2388	www.pmsinstrument.com
Skye Instruments Ltd *Distributor:* ANRI instruments and controls Pty Ltd	21, Ddole enterprise Park Llandrindod Wells, Powys LD1 6DF UK Ph: +44 1597 824811 Unit 29, 756-758 Burwood Hwy, Ferntree Gully VIC 3167 Ph: +61 (03) 9543 2664	www.skyeinstruments.com

SoilMoisture Equipment Corp. *Distributor:* ICT International.	801 S.Kellogg Ave. Goleta, CA 93117 Ph: 805-964-3525 P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.soilmoisture.com www.ictinternational.com.au
Eijkelkamp Agrisearch Equipment *Distributor:* Aqualab Scientific Pty Limited	Niverheidsssstraat 30, PO Box 4, Giesbeek, ZG 6987, The Netherlands Ph: +31 31388 0200 36/10 Gladstone Road, PO Box 419 Castle Hill NSW 2154 Ph: +61 (02) 9894 4511	www.eijkelkamp.com www.aqualab.com.au

2.2.2 Psychrometer, Dew Point Hygrometer and Osmometer

Quick Overview

These instruments are used to measure the relative humidity (i.e. water vapour potential) of the atmosphere equilibrated with plant tissue in a closed chamber. The main difference between each instrument is the method of measuring the water vapour potential in the air chamber. These instruments can be used on either plant tissue samples or installed in situ on stems and leaves in the field. In each case, the plant tissue sample is required to equilibrate with the air volume within a sample chamber. Hence, measurement of the equilibrated water potential in the sample chamber provides a measure of the plant water potential.

Figure 2.3: C-52 sample chamber
(Source: http://www.wescor.com/environmental/index.html)

Method of Operation

A sample of selected tissue (commonly a leaf disc or punch) is placed in a small sealed container insulated to ensure temperature stability. The tissue sample and the surrounding air are allowed to equilibrate and the water potential of the air is then measured. Plant tissue samples may be either intact, abraded or cut to ensure equilibrium and response rates. The loss in water to the atmosphere from the tissue sample in the curvet is normally considered insignificant. However, consideration of the cut surface to area ratio for the tissue sample may be required if collecting only small samples.

There are a variety of sensor techniques used to detect the water potential of the air in the chamber. In the wet bulb psychometric method, the temperature of a wet thermocouple varies according to the evaporative cooling effect and the relative humidity of the air in the sample chamber. Since the thermocouple is wet and the tissue sample has a water potential below zero, a water potential gradient (i.e. vapour pressure deficit) exists between the thermocouple, the surrounding air and the plant tissue sample, causing a movement of water away from the surface of the thermocouple in the form of evaporation. The resultant change in temperature due to evaporative cooling is assumed to be linearly related to the water potential of the sample for a constant chamber temperature. A correction factor is applied to the measured output to convert the reading at a given temperature back to a standard measure at 25^{o}C. An alternative method of measuring the water potential is the chilled mirror dew point technique. This method relies on measurement of the relative humidity in the closed sample chamber. A mirror within the chamber is chilled. As the mirror cools, a dew point sensor detects when moisture condenses on the surface and an infrared temperature sensor measures the temperature at which the dew point is reached.

Figure 2.4: WP4 Dewpoint Meter
(Source: http://www.decagon.com/environmental/wp4)

Osmometers use a reference droplet of standard solution with known concentration. Depending on the water potential gradient between the reference droplet and sample tissue there is a measured change in temperature of the reference droplet. Hygrometers can be used to measure either leaf or stem water status. Stem hygrometers involve clamping the instrument to the stem of the sampled plant. A small cut is made to expose the sapwood and a thermocouple in the sample chamber is placed in contact with the exposed sapwood. A second thermocouple in the sample chamber is used to measure the chamber air temperature. A third thermocouple is imbedded in the sample chamber body to measure the instrument temperature and provide temperature compensation correction. Stem water potential measurement is achieved using either a psychrometric (wet bulb) or hydrometric (dew point) measurement.

Figure 2.5: L-52 Leaf Hygrometer
(Source: http://www.wescor.com/environmental/index.phtml)

Figure 2.6: Stem Hygrometer
(Source: http://www.ictinternational.com.au/stemhygrometer.htm)

Cost

Prices vary significantly across the range of different devices and between suppliers. The WP4 distributed by ICT costs approximately $11500. The Wescor Dewpoint meters are approximately $4000 and vapour pressure osmometers are approximately $9000. The

Wescor C-52 sample chamber is about $900 and individual Wescor leaf hygrometers/psychrometers cost around $400 each.

Advantages and Disadvantages for Commercial Irrigation Scheduling

These instruments are considered a valuable, thermodynamically based measure of water status which with some particular devices (stem hygrometers) are able to be automated for continual logging on a single plant. However devices which require a leaf disc and leaf hygrometers are able to take multiple samples but are labour intensive and time consuming. Also there is timing limitations in sampling times due to diurnal fluctuations and environmental constraints (consideration for cloudy days).

Other measures of plant potential which are typically research focused and/or laboratory based include:

1. Cryoscopic osmometer - measures the thawing point of a sample of sap, hence only measures osmotic (solute) potential.
2. Pressure probe - measures the pressure exerted by sap from an individual cell to compress air in a sealed capillary tube or measures the pressure exerted to push sap back into a cell once punctured with a fine micro-capillary tube, hence only measures turgor pressure (pressure potential).

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	Contact Details	Further information
Decagon Devices Inc	950 NE Nelson Court Pullman WA 99163 Ph: +1 509-332-2756	www.decagon.com/
Wescor Inc	PO Box 361 Logan, UT 84323-0361 USA Ph: (435) 753-6756	www.wescor.com
ICT International	PO Box 503 Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.ictinternational.com.au

2.2.3 Measurements of Tissue Water Content

There are a range of sensors which function to indirectly measure the water content of either leaf, fruit or stem plant tissues. Sensors include dendrometers, stem micro-variation (diameter) sensors, linear variable differential transformer gauges, Beta gauges, leaf thickness sensors and the direct measure of relative water content. A key advantage for many of these measurements is that they are non-destructive and can be conducted in situ on growing plants. All these sensors measure changes related to the plant water content rather than the water potential and hence, only provide an indirect measure of plant water status. However, previous research work has found good relationships between plant water content measures (e.g. stem diameter) and water potential measurements (e.g. in the leaf or stem) and that these measures can reliably infer plant water potential status. However, there is a need to accounting for the lag time between changes in the water potential and content.

Tissue water content sensors typically measure changes in the structure of a plant component (e.g. leaf, stem, fruit or plant height). Under non-limited water conditions, a daily fluctuation in plant water status will occur with a return to a constant or base level reached overnight as an equilibrium between the plant and soil-water potential is reached. Under soil moisture limiting conditions and/or as evaporative demand increases, the daily fluctuations in plant water status increase in amplitude as the plant can no longer meet the evaporative demand.

2.2.3.1 Dendrometers

Quick Overview

Dendrometers have primarily been used for growth measurements for tree and forestry applications. These can be broadly grouped into contact dendrometers (calliper style devices that measure trunk diameter and diameter tapes which measure the girth or circumference of the trunk) as well as non-contact /optical dendrometers (optical callipers, optical forks and rangefinder dendrometers). Dendrometers devices of much high resolution using linear variable differential transformers (LVDTs), also know as strain gauges are able to measure in the micron scale growth response as well as diurnal change in stem and fruit size related to changes in tissue water content. Main measurement methods can be categories as girth (circumference dendrometers), stem or leaf diameter (diameter dendrometers), stem radius (radius dendrometers), fruit and vegetable dendrometers and vertical dendrometers for measuring the vertical change in a section of a plant stem. The measurement and continuous recording of the diameter of stems and fruits is sometimes also referred to as the micromorphic method. The comments below refer only to dendrometers of high resolution which measure diurnal changes in tissue water contact and are collectively referred to as stem diameter (or microvariation) sensors or strain gauges.

Figure 2.7: Dendrometer measuring stem diameter fluctuations

Method of Operation

Stem diameter (or micro-variation) sensors measure the daily diurnal change in stem diameter. These sensors measure the change in tissue water status which is occurring within the plant as transpiration increases after sunrise and subsequently decreases at the end of the day. Root originated sap (water) is transport within the plant through the xylem. The xylem is neighboured by associated living cells (cambium and phloem). Stem shrinkage is the result of water loss and turgor in these living cells as a result of redistribution of water in response to the imposed water potential gradients.

The water potential in the xylem decreases due to an increase in transpiration after sunrise. This results in a radial flux between the xylem and the surrounding living cells. A water flux as a result of the imposed potential developing causes movement of water out of the living cells into the xylem and inturn causes tissue water loss and a reduction in cell volume and hence, a trunk diameter contraction. The majority of plant tissue acts as a reservoir which can shrink due to a redistribution of water responding to the water potential gradients and water transport resistances within the plant (Molz and Klepper, 1973). As translocation decreases in the late afternoon, there is a re-hydration of the living cells and swelling of the trunk occurs into the night.

There is a close association between the stem water potential and that of the amplitude of daily change in stem diameter contraction. Under water limiting conditions, there is an increase in the water potential gradient and a resulting increase in water movement out of the living cells and an increase in the stem diameter contraction.

Daily contractual amplitude (DCA), maximum daily shrinkage (MDS) or Trunk Daily Fluctuations (TDF) is the diurnal change in stem diameter measured as the difference between the night time maximum to the following days minimum. Under constant weather conditions and a limiting water situation both an increase in DCA and decrease in growth rate will occur.

Leaf thickness sensors are also commercially available and use similar technology as the stem diameter dendrometers.

Maintenance

Sensors generally have minimal maintenance requirements. Some manufacturers recommend checking annually to ensure that all parts are moving freely and to remove dirt and dust from sensor surfaces.

Cost

Individual sensors start from less than $1000 each. However, the price varies with the level of sophistication in the hardware employed (number and type of sensors, logging and communication requirements) and the software required to manage and interpret the data.

Advantages and Disadvantages for Commercial Irrigation Scheduling

As plant water status is controlled to some degree by stomatal aperture and other mechanisms, the sensitivity in using a plant water status indicator may be limited in application amongst isohydric plants which have an ability to maintain their plant water status as evaporative demand and/or soil moisture availability becomes limited.

Logging dendrometers devices are advantages for irrigation scheduling due to the non destructive measurement method and continual measurement capability. The value in there use will be dependant on the ability for calibration, either to other physiological destructive measurements such as plant water potential, desired crop response and/or researched threshold values for irrigation scheduling. Limitations in the use of such devices can be attributed to them being a point based measurement device and adequate representation of the field is required. Also a degree of complexity in measurement data as a guide to irrigation scheduling may exist due to possible plant conditioning effects and hysteresis. The application of such sensors outside of mature tree crops may also be limited without an account of changes in plant stem diameter due to growth through the crop growing season (further discussed in section 2.3.3).

A disadvantage in the use of leaf thickness sensors is that they may be considered a less sensitive measure than leaf water content or daily stem variation as a fraction of leaf shrinkage is in the plane of the leaves (not the direction of the sensor). Relative water content of leaves is a low cost and relatively simple method of plant sensing but does require post field measurements which may limit its application for in commercial irrigation scheduling.

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	Contact Details	Further information
Phytech Ltd. *Distributor:* Isis Phytomonitoring	Yad Mordechai 79145, Israel Ph: +972-8-6715175 sam@isisphyto.com.au	www.phytech.co.il www.isisphyto.com.au
Dynamax, Inc *Distributor:* ICT International.	10808 Fallstone #350, Houston, Tx. 77099 Ph: 281 5624 5100 P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.dynamax.com/ www.ictinternational.com.au
Agro-technologies	Parc d'activites du Roubian 13150 Tarascon, France contact@agro-technologies.com	www.agro-technologies.com/ang/index
Ecomatik	22 Muenchner Street D-85221 Dachau/Munich, Germany Ph: ++49 (0) 8131 260 738 info@ecomatik.de	www.ecomatik.de

2.2.3.2 Relative water content (or relative turgidity)

Quick Overview

Relative water content is calculated as the ratio of the leaf water content when sampled compared to the water content of the same leaf sample when re-hydrated (ie. well watered). Samples are cut from a leaf using a hole cutter, weighed, hydrated and re-weighed.

Method of Operation

Leaf discs from predetermined position on the leaf and plant are sampled in the field and placed in closed weighting bottles. After weighing, the discs are re-hydrated for a pre-determined period of time in distilled water before being blotted dry of excess moisture and re-weighed (turgid weight). The discs are then oven-dried to obtain a dry weight and relative water content is calculated using the equation:

$$\text{Relative water content} = \frac{(\text{sampled leaf weight} - \text{dry leaf weight})}{(\text{turgid leaf weight} - \text{dry leaf weight})} * 100 \qquad (2.2)$$

Cost

This is a low cost option as the leaf sampling device used can be home made. Modified paper hole punchers and other spring loaded punching devices have been used with success. Small sealable containers are required to store leaf discs between sampling and weighing. A high resolution (preferably ±0.001 g) balance for weighing the leaf discs after sampling, re-hydration and oven drying is also required.

Advantages and Disadvantages for Commercial Irrigation Scheduling

Although this is a low cost option for direct leaf water content measures, there is large sample variation. Hence, there is a need to use a large number of samples and to ensure consistency in the leaf age and size of leaf disc selected as well as sampling location on the leaf. As this is a measure of plant water content and not water potential there also needs to be consideration of the plant's ability to maintain water content under limiting soil moisture availability and/or increased evaporative demand (especially in isohydric plants such as cotton). This technique is not considered practical for irrigation scheduling under commercial conditions.

2.2.3.3 β gauges (Leaf thickness sensors)

Quick Overview

β (Beta) or thickness gauges are used to measure the thickness of leaves based on the attenuation of beta particles. Non-destructive measures of leaf water content can be made by using a calibration equation relating attenuation with a range of known leaf water contents.

Method of Operation

The Beta gauge consists of two main components; a radiation isotope which provides the source of beta particles and a radiation detector to measure the level of beta particles being received. As the density of the leaf (and presence of moisture) changes, there is a corresponding change in the quantity of radiation allowed to pass through the leaf and hence a change in the level of radiation measured on the opposite side of the leaf with the detector.

Calibration of a Beta gauge is achieved by measuring similar leaves with a range of known relative water contents which were manually measured. Re-sampling in the same canopy location on leaves of the same age and regular re-calibration will reduce problems associated with growth and variability in leaf material.

Maintenance

Beta gauges are virtually maintenance free as there are no moving parts.

Cost

There is a wide range of industrial application sensors available. Costs vary depending on application, logging capabilities and resolution.

Advantages and Disadvantages for Commercial Irrigation Scheduling

Beta gauge measurements have been around for more than 50 years. They have been found to be a reliable way to non-destructively measure relative water content if regularly calibrated as changes in leaf age, structure and composition occurs. Limitations include a requirement for a large number of samples to overcome leaf sampling variation.

The nature of a species' response to water limited conditions and/or extreme evaporative demand (isohydric verses anisohydric) may limit its' commercial use for irrigation scheduling. The main disadvantage is that the instrument uses a radioactive source. In comparison to gamma rays, beta particles do not travel as far and therefore exposure to operators is commonly avoided with shielding around the gauge. Check local legislation for licensing and compliance requirements.

Manufacturer/Distributors and Commercial Products

There is quite an extensive range of beta gauges commercially available on the market. The majority of instruments are for the measurement of materials and coatings (such as steel, plastic, glass and rubber).

2.3 Measures of Plant Response

2.3.1 Sap-flow Sensors

Quick Overview

These sensors measure the velocity of sap flow by monitoring changes in sap temperature when heat is applied to the stem. These measures can be used to calculate plant transpiration rate.

Method of Operation

The three main types of sap flow sensors (heat balance, thermal dissipation, heat pulse) all use heat as a tracer. The following outline of each sensor operation has been adapted from Smith and Allen (1996) and Green, Clothier *et al.* (2003) .

Energy or stem heat balance (SHB) sensors work by measuring heat transfer due to the movement of the sap when the stem is continuously heated. As heat is applied to the stem, the flow of sap is resolved by balance of the fluxes of heat from vertical heat loss by conduction in the stem, radial heat loss by conduction and by heat loss from sap flow. The Dynagage sensor consists of a flexible circumferential heater, a thermopile to measure radial heat loss (away from the stem), and differential thermocouples pairs to measure the temperature difference along the stem.

External influences of temperature changes and moisture intrusion is assumed negligible and minimised by the use of foam/cork insulation and a weather shield over the sensors extending above and below the thermocouples and stem section. Surface selection and preparation must include selection of a straight and even diameter stem without lumps (such as from old branches) and excess loose bark should be removed (sand rough bark back smooth).

It is common practice to apply a silicone-grease based electrical insulating compound on the stem to ensure good contact, minimise moisture ingression, lubricate sensors to enable easy movement during installation, accommodate stem growth and prevent the heater from sticking. However, Dynagage recommends the use of canola release spray instead due to possible choking of the cambium due to the grease being impervious to moisture and air. A further step to prevent water ingression is the addition of a collar on the stem above the sensor sealed with a water proofing compound (e.g. silicone grease or blue-tac). Heat balance sensors can either be stem types- defined where the heat is applied radially around the circumference of the stem or by trunk types- where by the heat is applied to only a segment of the trunk. In the later case the heat and temperature measurements are instrumented through stainless steel or Teflon coated probes installed into the conducting xylem (sapwood). Comprehensive installation instructions are generally provided with the purchase of all commercial sensors.

Figure 2.8: SF-4 - Stem flux relative rate sensor

(Source: www.agrisupportonline.com/store/sensors_pht.htm)

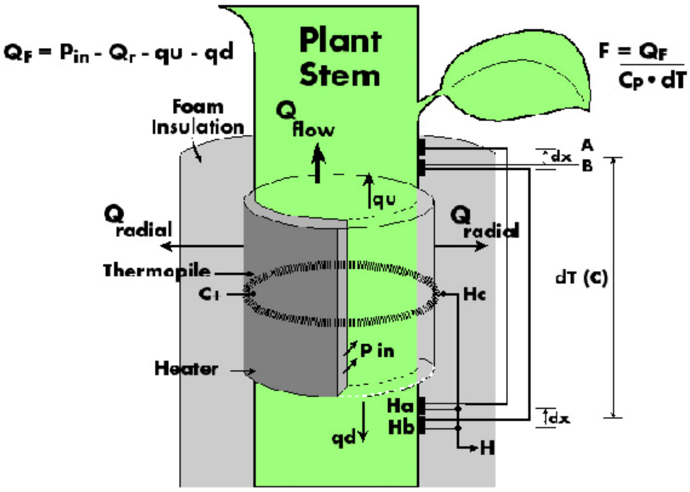

Figure 2.9: Principal of operation for the Dynagage sap flow sensor
(Source: www.ictinternational.com.au/dynagage.htm)

Thermal dissipation (TD) uses an empirical determination (Granier's) from a measure of sapwood temperature upstream of a heater probe inserted into the sapwood and continuously heating. The smaller the temperature difference between the two probes the more rapidly the heat is being dissipated and the higher the sap flow velocity.

Dynagage recommends that two sets of probes should be placed around stems which are 75 to 150 mm in diameter. For stems >150 mm in diameter, four sets of probes should be inserted around the stem. A water poof seal (e.g. plastic putty or pruning wax sealer) is required around the probes, followed by a foam insulation jacket and further thermal insulation using reflective foam bubble wrap. A chlorine bleach (e.g. 10% Chlorox) is also recommended to minimise disease spread between trees.

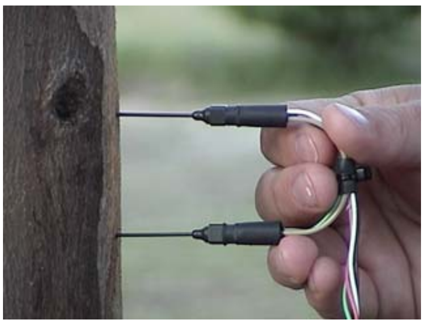

Figure 2.10: Thermal dissipation probe
(Source: www.ictinternational.com.au/tdp.htm)

A modification to the thermal dissipation method developed by Granier (1985) is used by Ecomatik for large (>20 cm diameter) trees. This method uses an additional two thermocouples to measure background temperature gradients by being placed an equal distance, horizontally apposed to the heating probe.

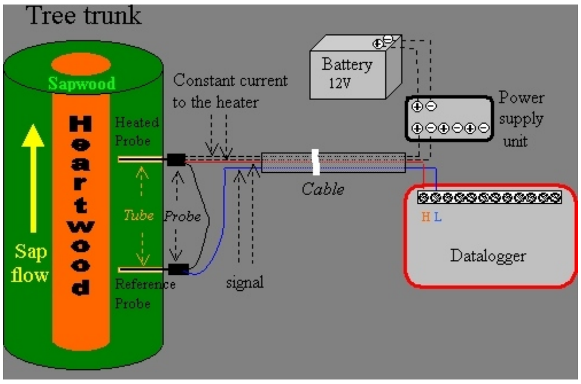

Figure 2.11: Schematic of Granier's thermal dissipation sap flow sensors
(Source: www.plantsensors.com/)

Heat pulse sensors apply a short pulse of heat and measures the corresponding velocity of heat pulse in the stem sap. A single heating probe (heat-pulse probe) is inserted into the sap wood and a temperature (miniature thermistors) probe is placed upsteam and another downstream of the sap flow from the heater probe at pre-determined distances. The distance between the heat-pulse probe and the downstream thermistor probe is set at an unequal (nominally twice) distance between the heat-pulse probe and the upstream thermistor. Once a short pulse of heating is applied via the heat-pulse probe there is dissipation of heat through conduction away from the heat-pulse probe. However, due to the upward movement of sap there is a shift in the maximum heat pulse (signature) from the heat-pulse probe towards the downstream thermistor probe. The time taken to move the peak heat pulse half way between the two thermistors (equal temperature readings) is recorded. This is then replicated a number of times around the circumference of the stem (typically four times, by division of the stem into four quadrates).

Each set of probes around the circumference are inserted at different radial depths to account for differences in sap flow with radial depth. Due to the evasive nature of probe insertion there is a limited period of reliable instrumentation before removal and reinsertion at a different local/stem has to be made. This is due to the wound reaction of the plant and an increasing reduction in localised sap flow around the probes position over time. Past information or an assessment of reaction time/ impact of 'wounding' on estimated transpiration rates should be conducted and known.

Physical blockages in sap flow also occur from the probe insertion which needs to be accounted for in calibration (correction for wounding). Probe misalignment can also cause considerable error and should be minimised through correct installation procedures. A post measurement correction factor for small misalignments can also be undertaken with the use of over-length probes placed in the probe holes and a measurement of the spacing between and angle of each probe protruding is undertaken. This method is commonly referred to the compensated heat-pulse theory. This is based on the use of two thermistor probes. A probe placed both upstream and downstream of the sap flow enables a distinction to be made between the effect of convection (i.e. heat transfer due to the movement of sap) and conduction (i.e. the loss of heat into surround tissue). The use of a downstream thermistor compensates for the effect of conduction.

A modification to the (compensated) heat-pulse method (CHPM) is the T-max heat-pulse method where by only one temperature sensor is placed at distance downstream of the heating probe. Sap flow is then determined by the time lag for the measured temperature rise to peak at the downstream temperature sensor. An addition modification to the CHPM is the heat ratio method (HRM) used by ICT International. This utilises a temperature probe upstream and downstream of a heat-pulse probe. By measuring the ratio of heat transported to the two symmetrically placed temperature sensors, the magnitude and direction of water flux can be calculated.

Correct placement of temperature sensor probes and heating probe is aided by the use of a drilling jig which can be temporarily fixed to the stem to ensure correct hole alignment and spacing.

Sap flow has also been measured by deuterium tracing (using an isotope as a tracer instead of heat). This is not as common as the heat methods and is suggested as not having practical applications for commercial irrigation scheduling and/or real time and continual monitoring.

Table 2.1: Summary of sap flow sensors

Manufacturer	Sensor name	Method	Size Range
Dynagage	Microsensors	SHB	2 – 7 mm
Dynagage	Stem Gages	SHB	8 – 32 mm
Dynagage	Trunk Gages	SHB	32 – 165 mm
Phytech	SF-4M SF-5M	SHB	1 – 5 mm 4 – 10 mm
Phytech	SF-8M	-	>15 mm
ICT	HRM sapflow sensor	HRM	>10 mm
Dynagage	Digital Dynagage	SHB	2 – 150 mm
Dynagage	Thermal Dissipation Probe	TD	>125 mm
Ecomatik	SF-G SF-L	TD	>50 mm >200 mm

Maintenance

Refer to individual manufacturer's instructions on maintenance requirements as these vary for each model. The type of sensor used is dependant on the plant species being measured. Dynagage recommends cleaning stem heat balance sensors every two weeks or weekly in plants having rapid growth.

Cost

Due to the range and differences in devices available it is advised individual manufacturers and distributors be contacted in regards to particular devices and any additional equipment required.

Advantages and Disadvantages for Commercial Irrigation Scheduling

The use of systems such as the Dynamax sap flow logger-irrigation controller has enabled automation and real time control of irrigation scheduling based on an estimate of whole plant transpiration rates. In comparison the use of porometers to achieve this (at a same level of resolution) is complicated by factors such as: scaling from leaf sample areas to canopy water use, consideration of canopy dynamics and non-autonomous measurement resulting in limiting sampling times with greatly increased labour requirements, technical difficulty and cost. However, these sensors only provide an estimate of transpiration and hence water use is limited by point based measures being made on a per plant basis with a sap flow sensor. Therefore an appropriate sample size (number of plants) must be measured to ensure a representative estimate is achieved.

It has been noted that sap flow sensors reliability to predict transpiration is dependant on validation in the species of interest, especially if there is not thermal heterogeneity of the stem. This occurs in species where there is non-uniformity in sap-conducting elements.

Stem heat balance sap flow sensors are able to measure sap flow in both woody and herbaceous species, as well as on small tree branches. The limitation to this is the narrow stem diameter variation which each sensor can tolerate and therefore a number of sensors may be required when monitoring plants which are still actively expanding their stem diameter. Thermal dissipation and heat-pulse sensors in comparison are only suitable for measurements on woody stems due to the requirement to drill and insert the heating and temperature sensing probes. As a result of the evasive insertion of the probes there is a probe induced effect resulting from wounding (namely blockage of the plants vascular system) and hence to calculate volumetric rates of sap flow requires a correction factor. This correction coefficient/factor can be derived either empirically or calculated from known correction factors for the species being measured.

Wound reactions associated with probe installation are a problem for commercial irrigation scheduling as these will require the removal of the probes and installation on neighbouring representative plants at regular intervals.

Manufacturer/Distributors of Commercial Products

Manufacturer/Distributor	Contact Details	Further Information
Dynamax, Inc *Distributor:* ICT International	10808 Fallstone #350, Houston, Tx. 77099 Ph: (281) 564-5100 P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.dynamax.com/ www.ictinternational.com.au
Phytech Ltd. *Distributor:* Isis Phytomonitoring.	Yad Mordechai 79145, Israel Ph: +972-8-6715175 sam@isisphyto.com.au	www.phytech.co.il www.isisphyto.com.au
Ecomatik	22 Muenchner Street D-85221 Dachau/Munich, Germany Ph: ++49 (0)8131 260 738 info@ecomatik.de	www.ecomatik.de

2.3.2 Stomatal Conductance (Porometers)

Quick Overview

Porometers are used to measure the ability of a leaf to lose gases (namely CO_2 and water vapour) by diffusion in particular through leaf stomata. Porometers are used to attain a measure of the stomatal conductance of leaves (i.e. the rate of CO_2 or water vapour is lost from the leaf stomata).

Figure 2.12: AP4 Porometer
(Source: http://www.delta-t.co.uk/groups.html?group2005092332162)

Method of Operation

There are four different types of porometer:

Mass flow porometers - Air is forced through a leaf and the flow rate of air through the leaf is measured. This method is generally regarded as inaccurate due to the physiological disturbance it causes to the leaf and stomatal aperture and is not used in commercial systems.

Null balance porometers - A constant humidity in the chamber containing the leaf is achieved by changing the rate of dry air flow through the chamber. A stirring fan is used to overcome boundary layer resistance. The rate of applied air is measured and along with the known leaf area within the chamber is used to calculate a resistance value which can then be converted into a measure of stomatal conductance (i.e. reciprocal of resistance).

Dynamic diffusion porometers - Dry air is pumped over a leaf sample which is sealed within a small cuvette until a pre-set humidity level (close to the ambient humidity) is reached. The time is then measured for the humidity within the cuvette to change to a second pre-set value of humidity. This value is then compared to readings obtained with a calibration plate of known conductance to account for ambient temperature and pressure and to calculate conductance.

Steady state porometers – These systems measure the vapour pressure and vapour flux of the leaf surface. A fixed diffusion path within the chamber is used to measure the vapour pressure. Flux and gradient can be calculated from the vapour pressure measurements and the known diffusion path. Steady state porometers which monitor the time required to reach equilibrium by changing the rate of air flow through the chamber are similar to the null balance systems although they measure the time taken to reach a steady state.

Most of the porometers used commercially are either dynamic or steady state systems. Porometers only measure conductance on one side of the leaf. However, plants have stomata on both the adaxial (top) and abaxial (bottom) sides of the leaf. As there is generally a greater number of stomata on the abaxial side of the leaf, the bottom side is normally measured. A single measurement may take between 15 and 60 seconds depending on the conductivity of the leaf.

Re-calibration of dynamic porometers (e.g AP4) in the field is required at the start of each session and when a change in temperature, relative humidity or sensor head cuvette occurs. Re-calibration involves the use of a porous plate/s (thin perforated moulded polypropylene) with six groups of holes. Each group of holes has a known conductance. Water vapour is provided to the back of the plate with dampened paper. The sensor head is then clamped onto the calibration plate and readings taken for each of the six groups of holes for recalibration.

There is some debate over which porometer operating method is most appropriate. The higher accuracy achievable with steady state porometers at higher diffusion conductance is compromised by an increase in complexity, the need for a cycling/stirred chamber which may influence the leaf samples water loss, and difficulty in re-calibration which needs to be conducted under controlled conditions. Dynamic porometers by comparison are less complex, do not need a stirred chamber and can be re-calibrated in the field. However, non-stirred dynamic diffusion porometers could cause a change in measurement conductance due to the influence of the chamber if the sample is left for too long in the chamber before it reaches the second pre-set humidity value. They also measure a smaller sample area and may require more samples to be measured for adequate accuracy.

Maintenance

Deposits of plant material and dust accumulate around the seals and sensor head requiring regular cleaning. Avoid the use of solvents and chemicals as they may damage the seals and relative humidity sensors. Ensure that the seals and sensors are completely dry before use. Batteries should be replaced annually.

Cost

Prices range from $9000 to $14000.

Advantages and Disadvantages for Commercial Irrigation Scheduling

Porometers have primarily been used as a research tool and there has not been widespread use of porometers for commercial irrigation scheduling. Porometers enable a measure of leaf's stomatal conductance and this measure can be used to estimate whole plant water use if the whole leaf area is measured. However, this estimate of whole plant water use is not considered as accurate as measures obtained using sap flow sensing due to complications with the scaling from leaf sample areas to canopy water use and canopy dynamics. As porometers measure stomatal conductance and not plant water status (be it water content or potential) these instruments are not suitable for anisohydric plants (e.g. cotton) that show limited stomatal response even under conditions of limiting soil moisture and high evaporative demand.

The main limitations with porometers for commercial irrigation scheduling are the high labour requirements, the time required for measurements and the requirement for specific measurement timing due to diurnal fluctuations and environmental constraints (consideration for cloudy days). Considerable user experience is also required for measurement accuracy. The need for calibration and the large number of leaf samples required to adequately represent the field reduce the potential to use these instruments for commercial irrigation scheduling.

Manufacturer/Distributors of Commercial Products

Manufacturer/Distributor	Contact Details	Further Information
Decagon Devices, Inc *Distributor:* ICT International.	950 NE Nelson Court Pullman, WA 99163 Ph: (509) 332-2756 P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.decagon.com www.ictinternational.com.au
Delta-T Devices Ltd *Distributor:* Measurement Engineering Australia	128 Low Road, Burwell, Cambridge, UK Ph: (+44 1638 742922) 41 Vine St, Magill, S.A. 5072 Ph: (08) 8332 9044	www.delta-t.co.uk/ www.mea.com.au
PP Systems *Distributor:* McVan Instruments Pty Ltd	110 Haverhill Road, Suite 301 Amesbury, MA 01913 USQ Ph: +1 (978) 834 0505 58 Geddes Street, PO Box 298 Mulgrave, VIC 3170 Australia Ph: +61 (03) 9582 7333	www.ppsystems.com www.mcvan.com
Eijkelkamp Agrisearch Equipment *Distributor:* Aqualab Scientific Pty Limited	Niverheidssstraat 30, PO Box 4, Giesbeek, ZG 6987, The Netherlands Ph: +31 31388 0200 36/10 Gladstone Road, PO Box 419 Castle Hill NSW 2154 Ph: +61 (02) 9894 4511	www.eijkelkamp.com www.aqualab.com.au

2.3.3 Plant Growth Rate

Only sensors capable of 'real time' measurements (i.e. continually logging) of plant growth rate have been included in this section. A range of other plant growth rate measurements (e.g portable leaf area and chlorophyll meters) exist but are commonly used for long term agronomic monitoring of crop performance rather than for commercial irrigation scheduling. Plant growth rate sensors which are suitable for irrigation scheduling include auxanometers and stem or fruit diameter sensors (i.e. dendrometers).

Quick Overview

Auxanometers are devices used to measure plant height and the extension in plant high over time. This is achieved with a clip like device being connected to the apical (i.e. top most) shoot and measures the change in plant height or growth relative to a fixed reference point. Dendrometers (see section 2.2.3) are devices used for measuring the change in girth of fruit or stems over time.

Method of Operation

Auxanometers use a clamp or similar device clipped onto the growing point of the plant and is attached to a logger by a thin line which is under a small degree of tension. As the plant increases in height, the line is retracted or metered by the logger and the height and/or change in height is recorded.

Dendrometers or stem micro-variation sensors are also able to be used to measure plant growth rates. The increase in stem diameter between the afternoon minimum and the following morning maximum is the result of cell hydration and growth. Daily stem increment (DSI) is the increase in stem diameter between consecutive morning maximum values and constitutes growth. To use these measurements for irrigation scheduling, the user needs to have some understanding of the expected growth patterns under well water conditions and the influence of variations in environmental (i.e. weather) conditions on the growth rate. The same measurement principles apply for fruit diameter or dendrometer sensors which measure fruit diameter changes over time. Daily increases in fruit diameter are plotted as growth over time and this is used as a guide for irrigation scheduling and meeting market requirements. Knowledge of the fruit's characteristic growth rate function and fruit dynamics (active fruit filling) is required to assess individual fruits growth performance against climatic conditions and imposed soil moisture conditions. The use of plant height extension, stem and/or fruit diameter expansion for commercial irrigation scheduling, requires all others factors which will impact on the measured growth rate to be considered.

Maintenance

These devices generally involve mechanical components (e.g. joints, bearings and springs) which deteriorate under field operating conditions if not regularly maintained. Prior to installation each season, moving parts should be checked and lubricated. Measurement sensors should be re-calibrated. The units should be inspected at least weekly during the measurement season.

Cost

Dendrometer devices commonly range from $400 to $4000 per unit depending on the nature and size of the sensor. Manufacturers or distributors should be contacted directly to clarify the particular devices available for specific crops and any additional data management or communication requirements.

Advantages and Disadvantages for Commercial Irrigation Scheduling

Logging auxanometer and dendrometer systems provide a non-destructive continual measurement capability which is useful for irrigation scheduling. The value in using auxanometers is dependant on the ability to assess the performance of the plant being instrumented against either an idealised crop growth response curve and/or researched threshold values for irrigation scheduling based on stem elongation (plant height) rates. The major limitation in the use of such devices is their point based measurement and the need for adequate representation of the field. Also a degree of complexity in measurement data as a guide to irrigation scheduling may exist due to possible plant conditioning effects and hysteresis. The application of stem diameter sensors outside of mature tree crops and auxanometer and fruit diameter sensors may also be limited without consideration of the plant growth rates against idealised extension rates during the cropping cycle. Auxanometers will require re-positioning on the apical shoot and fruit diameter sensors will require re-installation on later maturity fruit over time.

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	Contact Details	Further information
Phytech Ltd. *Distributor:* Isis Phytomonitoring	Yad Mordechai 79145, Israel Ph: +972-8-6715175 sam@isisphyto.com.au	www.phytech.co.il www.isisphyto.com.au
Dynamax, Inc *Distributor:* ICT International.	10808 Fallstone #350, Houston, Tx. 77099 Ph: 281 5624 5100 P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.dynamax.com/ www.ictinternational.com.au
Agro-technologies	Parc d'activites du Roubian 13150 Tarascon, France contact@agro-technologies.com	www.agro-technologies.com/ang/index
Ecomatik	22 Muenchner Street D-85221 Dachau/Munich, Germany Ph: ++49 (0) 8131 260 738 info@ecomatik.de	www.ecomatik.de

3. NON-CONTACT METHODS OF PLANT BASED SENSING

3.1 Site Specific Crop Management and Irrigation

Technological advances in recent years have seen a variety of precision agriculture applications become widely accepted on commercial farms. These include machine and tractor guidance systems, yield monitors and the advent of variable rate applicators for fertiliser and pesticide application. Irrigation has also seen advances with an increased awareness of spatial and temporal variability in both water application and crop water requirements within fields. This has focused attention on the limitations of point source measurements (e.g. soil moisture and contact methods of plant based sensing) and created interest in the use of non-contact plant sensors for site specific irrigation scheduling.

Non-contact plant sensors typically measure the reflectance of electromagnetic radiation (both visible and non-visible wavelengths) from crop surfaces. These platforms have been used for various applications including identification of fertiliser deficiencies and weed or disease infestations in crops. However, non-contact sensing has also been used to detect crop water stress and schedule irrigations (Alderfasi and Nielsen 2001; Kustas, French *et al.* 2003; Roerink *et al.* 1997).

Non-contact plant sensors may be mounted on a platform which may be proximal (e.g. hand held or ground rig device) or remote (e.g. an aircraft or satellite based) from the crop. Proximal and remotely sensed methods of plant monitoring enable the identification of variations in crop water stress and crop water requirements within fields. This combined with the advent of enhanced computer processing capacity (data management, computation and control) and the ability for real-time irrigation control allows for the irrigation application to be varied both across the field and at different times to maximise the economic potential of each management unit within the field. This can yield significant benefits in terms of improved water use efficiency, agronomic crop management, critical irrigation timing/management and reduced off-field environmental impacts.

Many proximal and remote sensing tools which were previously only used by researchers are now accessible for commercial use. The number of product suppliers is increasing and the cost of these products has also been decreasing making these technologies more affordable for routine use.

3.2 Plant Spectral Responses

Electromagnetic radiation transmitted by the sun onto the earth's surface is absorbed, transmitted or reflected off all surfaces (including the crop canopy and soil). However, the electromagnetic waves which are reflected from the various surfaces differ in length and frequency due to the characteristics of the surface material. It is this difference in reflectance (called the "spectral response") that is measured and can be used to infer crop stress and water requirements.

All matter radiates a range of electromagnetic energy/radiation. The electromagnetic spectrum is divided into a range of wavelength regions from gamma rays through to radio waves. Of this spectrum, the visible region is only between 400 to 700 nm wavelengths and includes the blue, green and red colour bands. Other common wavelengths used in agricultural spatial science are the near infrared (NIR, 700–1100 nm) and thermal infrared (3000–15000 nm) bands. The term "panchromatic" refers to a remote sensing device which detects electromagnetic energy in only one very broad band, which includes the visible region.

The spectral response of vegetation is influenced by pigmentation, leaf internal structure and moisture content. Green plants obtain their appearance due to the chlorophyll present in their leaves. It absorbs the red (0.63-0.69 um) and blue (0.40-0.52 um) wavelength bands while reflecting the green portion of the spectrum (0.52-0.60 um). However, the reflectance is much higher in the near infra-red band (Lamb 2000).

Platforms which have been used to capture spectral reflectance data include hand held devices, tractor or machine mounted devices, balloons, unmanned aerial vehicles, planes and satellites. For each of these various sensor platforms, different sensors exist which vary in their ability to acquire spectral reflectance data based on their spectral, spatial, temporal and radiometric resolution. Spectral resolution is the width and number of wavelength regions (or bands) in the electromagnetic spectrum that the sensor measures. Spatial resolution refers to the size of area (i.e. pixel) from which a spectral value can be obtained and therefore defines the smallest feature which can be detected. Spatial resolution is expressed in terms of pixel size. Temporal resolution refers to the time it takes to obtain a new set of data for each site. Radiometric resolution is the degree of change in the spectral response that the sensor is able to measure.

Radiometric sensors for measurement of crop reflectance or spectra can be broadly split into two groups; passive and active. Passive sensors rely solely on the sun as a source of electromagnetic radiation and measure the natural reflectance (i.e. emission) from the surface. Active methods send out their own electromagnetic radiation (commonly light) source and measure the emission reflected back from the surface. Active methods are useful at night and under cloudy conditions.

Both passive and active devices can measure narrow as well as broad wavelength bands within specific electromagnetic regions. In agriculture, these bands are most commonly located within the visible as well as a part of the reflected infrared range (700 to 3000 nm wavelengths). Multispectral scanners/devices simultaneously acquire images of the same scene for at least two different wavelength bands. Hyperspectral devices are those which measure many narrow bands of the electromagnetic spectrum simultaneously. Acquiring spectra data from two or more wavelength bands enables the calculation of radiometric indices which can be used to infer additional information regarding the crop stress and performance.

3.3 Radiometric Sensors

3.3.1 Multispectral Sensors

Quick Overview

Multispectral sensors measure the electromagnetic reflectance from a surface across a number of band widths. A wide range of both active and passive multispectral sensors are available which can be used as handheld devices or mounted on vehicle, aerial or satellite platforms.

Method of Operation

Proximal multispectral units are typically handheld or vehicle mounted. The sensor is connected to a datalogger (often a computer) and pointed at the plant canopy. Comercial units commonly used include the Greenseeker (Ntech Industries Inc) and CropCircle (Holland Scientific Inc). Both of these devices come with logging and GPS capability to enable maps of the field measurements produced. Cropscan Inc also produces a range of radiometric sensors.

Figure 3.1: Handheld multispectral scanner with computer logging in front harness

Figure 3.2: NDVI Greenseeker sensor with logger in backpack.

Active radiometric devices have their own built in light source that produce light at specific wavelengths to overcome differences in solar radiation due to cloud and diurnal changes. For example, CropCircle has a series of modulated polychromatic light-emitting diodes (LED array) which produce a specific wavelength and a silicon photodiode array (i.e. photodetectors) which detect the reflectance within a specific waveband.

There are a wide range of satellite based multispectral sensors from which data can be obtained for agricultural use. In this case, field data is obtained through a local agent and has usually been processed to highlight differences in crop stress using a net difference vegetation index (NDVI). The timing of the data acquisition often has a significant impact on the ability to identify spatial differences in water stress and irrigation requirements.

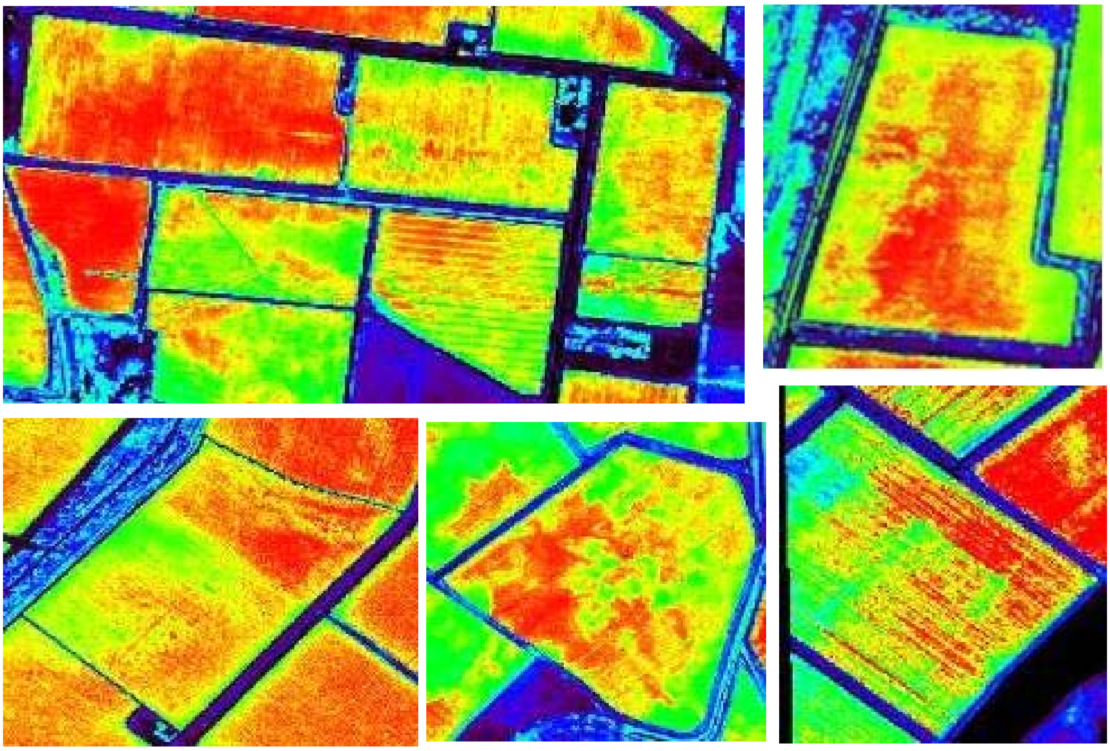

Figure 3.3: Example NDVI images of cotton fields in the Dawson Valley Irrigation Area (2003-04)

Although not widely available for commercial use, low cost passive radiometric sensors have also been developed which involve the modification or addition of specific wavelength filters which can be fitted to cameras. So far these have been principally used in research applications either as handheld devices or mounted on vehicles, balloons and unmanned aerial vehicles (UAVs). Wavelength filters are also currently available for purchase as glasses to enable visual evaluation of turf grass stress.

Table 3.1: Details on selected satellite based multispectral sensors

Satellite / Sensor	Distributor	Measurement Range (nm)	Band widths (nm)	Pixel resolution	Temporal resolution
Landsat 5 / Thematic Mapper (TM)	ACRES GEOIMAGE	450 – 12500	450 – 520 520 – 600 630 – 690 760 – 900 1550 – 1750 2080 – 2350	30 m 30 m 30 m 30 m 30 m 120 m	16 days
Landsat 7 / Enhanced Thematic Mapper (ETM+)	ACRES GEOIMAGE	450 – 2350	450 – 520 520 – 600 630 – 690 760 – 900 1550 – 1750 10400 – 12500 2080 – 2350 520 - 900	30 m 30 m 30 m 30 m 30 m 18 m 60 m 18 m	16 days
ALOS (Advanced Land Observing Satellite) / AVNIR – 2	ACRES	420 - 890	420 -500 520 – 600 610 – 690 760 - 890	10 m	46 days
ALOS / PRISM	ACRES	520 – 770	520 - 770	2.5 m	46 days
Terra / ASTER – VNIR	ACRES	520 – 860	520 – 600 630 – 690 760 – 860	15 m	Order Request
Terra / ASTER – SWIR	ACRES	1600 – 2430	1600 – 1700 2145 – 2185 2185 – 2225 2235 – 2285 2295 – 2365 2360 – 2430	30 m	Order Request
Terra / ASTER – TIR	ACRES	8125 - 11650	8125 – 8475 8475 – 8825 8925 – 9275 10250 – 10950 10950 – 11650	90 m	Order Request
Terra & Aqua / MODIS	ACRES	620 - 14385	36 bands	250 m (bands 1-2) 500 m (bands 3-7) 1 km (bands 8-36)	Daily
NOAA (National Oceanic and Atmospheric Administration) / AVHRR	ACRES	580 – 12500	6 bands	1.1 km	Approx. 14 days
Spot5	CNES	500-1750	4 bands	10 m / 20 m	1-4 days
Spot5 (P)	CNES	480-710		2.5 m / 5 m	1-4 days
IKONOS	GeoEye	445-853	4 bands	4 m	3 days
IKONOS (P)	GeoEye	450-900		1 m	3 days
Quickbird	DigitalGlobe	450-900	4 bands	2.8 m	1-3.5 days
Quickbird (P)	DigitalGlobe			0.7 m	1-3.5 days
EO-1 / Ali sensor	ACRES	400 - 2500	10 / variable		

Maintenance

The sensors generally require regular cleaning, maintenance and re-calibration. However the most common maintenance requirement by the operator is limited to cleaning the device due to dust and other foreign build up over time on the sensor head. Different manufacturers have their own factory servicing & recalibration regime.

Cost

Proximal hand-held sensor systems commonly used for crop sensing are available from approximately $4000. Satellite imagery is available commercially. Unprocessed image scenes (various sizes depending on the satellite platform) start from around $3000 each. Crop vigour images for broadacre farms are currently available for approximately $3000.

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	Contact Details	Further information
Holland Scientific	5011 South 73rd Street, Lincoln, NE 68516. USA	www.hollandscientific.com
NTech Industries, Inc	740 South State Street, Ukiah, CA 95482. USA	www.ntechindustries.com
Cropscan Inc.	1932 Viola Heights Lane NE Rochester, MN 55906 USA Phone: (507)285-9230 Fax: (206) 339-5770 Email: Cropscan@compuserve.com	www.cropscan.com
CTF Solutions	56 Iona Tce, Taringa QLD 4068 Ph: 07 3871 0359 Email: info@ctfsolutions.com.au	www.ctfsolutions.com.au

3.3.2 Hyperspectral Sensors

Quick Overview

Hyperspectral sensors are used to measure the spectral reflectance of an object at a high spectral resolution (across many narrow bands of the electromagnetic spectrum). As with multispectral sensors, these units may be passive or active and are available for platforms ranging from hand-held units to satellite based systems.

Method of Operation

Many of the proximal hyperspectral devices are more appropriate for research rather than commercial purposes due to their requirement for a higher level of user expertise and high cost. The list of commercial satellite based hyperspectral devices are listed in Table 3.2.

Figure 3.4: FieldSpec® HandHeld
(Source: http://www.asdi.com/products-fshh-fshhp.asp)

Table 3.2: Details on selected hyperspectral sensors

Proximal or Remote	Satellite / Sensor	Manufacturer/ Distributor	Measurement Range (nm)	Number of bands/ band widths	Pixel resolution	Temporal resolution
Proximal	FieldSpec 3	ASD	325 – 1075	250 / 3 nm	-	-
	FieldSpec 3Jr	ASD	350 - 1075		-	-
	FieldSpec VNIR	ASD	350 – 1050		-	-
Remote	Hyperion	NASA & USGS / ACRES	400 – 2500	220 / 10 nm	30 m	
	Terra & Aqua / MODIS	NASA / Japan	620 - 14385	36	250 m (bands 1-2) 500 m (bands 3-) 1 km (bands 8-36)	daily

There are few guidelines currently available on the use of hyperspectral devices for commercial irrigation scheduling. A range of commercial proximal and remote hyperspectral sensors are available. Proximal hyperspectral devices are similar in operation to multispectral devices. Passive devices need to be calibrated using a white reference surface which identifies the maximum reflectance value based on the ambient incoming solar radiation. This needs to be conducted periodically during sensing to ensure measurement consistency under conditions of altering solar radiation (ie. as the sun moves during the day or due to cloud intensity). Measures of target reflectance are normally presented as a ratio of the maximum reflectance value and hence, have a value between 0 and 1 for each wave band.

Maintenance

Operator maintenance generally only involves cleaning the sensor head of foreign matter. The sensors should be checked and re-calibrated at regular intervals. Different products have their own factory servicing and calibration requirements. During field operation ensure the device is removed from its case and sufficient time is given for the device to warm up and stabilize with the ambient temperature conditions otherwise 'noise' in the readings may occur.

Cost

Costs vary widely but research quality hand-held hyperspectral units range up to $150,000. Satellite imagery is available commercially with costs starting around $3000.

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	Contact Details	Further information
Analytical Spectral Devices Inc (ASD)	4760 Walnut Street, Suite 105 Boulder CO 80301 USA Ph: +1 303 444 6522	http://www.asdi.com/
LI-COR Inc	4421 Superior Street, Lincoln NE 68504 USA Ph: +1 800 447 3576	http://www.licor.com/
Geophysical Environmental Research Corp.	1 Bennet Common, Millbrook NY 12545 USA	http://www.ger.com
Integrated Spectronics Pty Ltd	PO Box 437, Baulkham Hills NSW Ph: +61 2 8850 0262	http://www.intspec.com/
Oriel Inc	250 Long Beach Blvd, Stratford CT	http://www.newport.com/oriel/Default.aspx

3.3.3 Thermal Sensing

Quick Overview

The crop canopy temperature provides a relative measure of transpiration rate and an indication of crop stress. Non-contact infrared thermometers and cameras measure the radiant energy (i.e. temperature) of an object within the thermal infrared electromagnetic wavebands. Canopy temperature measurements are compared to those obtained from both a non-water stressed and a non-transpiring crop and most commonly expressed as a crop water stress index (CWSI). Baseline values are required to be identified for crops under local conditions.

Method of Operation

Thermometry refers to the use of infrared thermometers (commonly known as IR guns) to take point measurements of canopy temperature. Thermographs are temperature images (or maps) of the crop area which are obtained using a thermal camera. Stomatal conductance is a sensitive crop response and represents the plants main defensive mechanism to reduce water loss from transpiration and maintain water status under limiting soil moisture conditions and/or increased evaporative demand. As stomatal aperture is reduced there is a reduction in transpiration which results in a reduction in evaporative cooling and an increase in canopy temperature. Hence, changes in canopy temperature relative to air temperature and humidity can be used to assess plant water stress.

Figure 3.5: Model 6110.4ZL AGRI-THERM II handheld infrared thermometer
(Source: http://www.everestinterscience.com/products/model6110/6110.4ZL.htm)

Figure 3.6: Using a handheld infrared themometer to measure canopy temperatures

Canopy temperature measurements are most commonly reported in terms of a crop water stress index (CWSI). The canopy temperature is influenced by a number of factors including radiation, air temperature, humidity, evaporative cooling and wind speed. Each of these factors changes diurnally (throughout a day-night cycle) and from day-to-day. However, the main factors are the vapour pressure deficit (VPD), which is related to the air temperature and humidity, and the radiation. The effect of incident radiation differences between different measurements can be overcome by sampling only on clear days and at times close to solar noon (i.e. peak radiation levels). The effect of differences in the VPD is accounted for in the calculation of the CWSI. The CWSI is calculated empirically (Idso *et al*, 1981) as:

$$CWSI = [(T_{canopy}-T_{air}) - (T_{nws} - T_{air})] / [(T_{dry}-T_{air}) - (T_{nws} - T_{air})] \quad (3.1)$$

where T_{canopy} is the canopy temperature, T_{air} is the surrounding air temperature, T_{nws} is the temperature of a non-water stressed canopy and T_{dry} is the temperature of a non-transpiring canopy. The CWSI may also be calculated from an energy balance (Jackson *et al*, 1981).

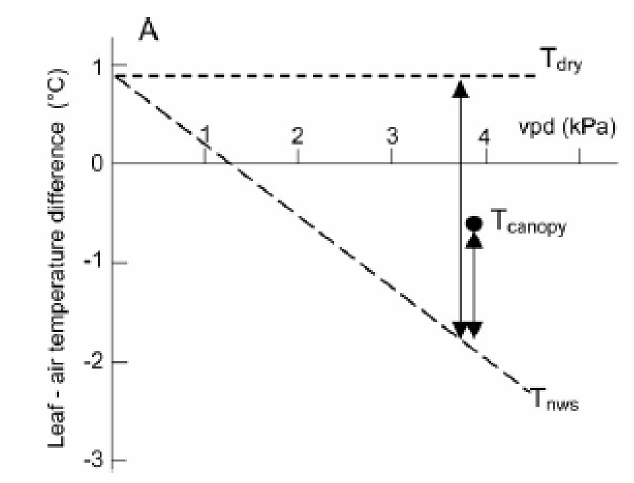

Figure 3.7: Illustration of CWSI noting the upper(T_{dry}) and lower (T_{nws}) baseline temperature values across a range of VPD (represented by dashed lines) and a normalised leaf temperature value (T_{canopy}) found between this range.
(Source: Jones 2004)

The CWSI relates the difference in canopy temperature to a non-water stressed baseline for the same crop and compares this to the range in canopy temperature that could be achieved between a non-watered stressed crop and that of a non-transpiring crop under the same conditions. The canopy temperature is also normalised to the environmental conditions by expressing all values as the difference from air temperature. Hence, a non-water stressed crop will have a CWSI = 0 where as a plant which is not transpiring and under severe water stress will have a CWSI = 1.

Measurements are required to be taken at peak daily radiation and are therefore normally taken between 12 pm (noon) and 2 pm when the crop is under maximum evaporative demand. Measurements should also be taken on clear cloudless days. A measure of air temperature and vapour pressure deficit is also required to calculate the CWSI. Values of air temp and VPD can be acquired from nearby weather stations but ideally should be taken at the same place as the measurements of canopy temperature. Wet and dry bulb thermometer measurements are required and these are sometimes incorporated into commercial thermal sensing models.

Research has demonstrated that there are a range of baseline values for different crop types and that the baselines values are not universal for each crop (Idso, 1982). Due to differences in climate between regions it is advised that a local or specific baseline is developed. This is not difficult and involves sampling wet and dry leaves at a range of VPD conditions (under the same radiation level). However, it is important to ensure that the wet and dry reference leaves are of a similar age and orientation to the incident solar radiation. Common practice involves completely covering one leaf (or target object) with a thin layer of petroleum jelly to provide a non-transpiring dry reference and wetting a similar sized, aged and orientation leaf for the non-water stressed reference. Alternatively, the baseline lower limit (non-water stressed crop) can be obtained by measuring the canopy temperature after the crop has received an irrigation event which has filled (but not waterlogged) the soil profile. Measurements should be taken throughout the day to obtain a range of VPD measurements and hence, a linear regression for baseline leaf temperatures. The upper baseline can be obtained by an alternative method of cutting a leaf and then positioning it back on the plant (i.e. wired in position) and taking measurements once the leaf is no longer transpiring (at least one day later).

All incoming radiant energy on an object is either transmitted, absorbed or reflected. The proportion of each is dependent on the surface characteristics of the object (i.e black, white, reflectant). Only absorbed radiant energy results in a change in the temperature of an object. Infrared guns provide a measure based on the amount of radiation that a black body would be emitting at that temperature. This assumes that a black body absorbs all radiant energy, resulting in no transmittance or reflectance losses. As the proportion of radiant energy which is transmitted, absorbed or reflected can differ between objects, differences in the surface emission characteristics must be accounted for in the temperature measurements. This correction is applied by an emissivity factor which can be adjusted in commercial thermometer guns. Plant material is assumed to absorb only 2% of radiant energy and therefore the setting for emissivity is normally set at 0.98 for agricultural measurements (organic and non-metallic materials). Calibration/testing of the emissivity of a surface can be undertaken by measurement of the surface with the infrared thermometer and comparing the measurements to those taken with a contact thermometer on the same surface. However, this is not normally required for agricultural measurements.

Errors can occur if the thermometry measurement area is greater than the target object. This commonly occurs when background soil is inadvertently included in the sampling area when taking canopy measurements. To ensure this does not occur, ensure that the distance between the instrument and canopy is minimised and the sampling area is well within the bounds of the crop canopy. The instrument focus will also influence the size of sampling area. Some IR thermometers (e.g. Model 6110 and 6130, Everest Interscience Inc) have an intra-optical light sighting system which enables illumination of the area over which the temperature is being measured.

Temperature measurements of the leaf/canopy should be taken from a number of different directions. This ensures that differences in temperature that may exist between alternative sides and orientations of a plant's canopy are taken into account. Given the direction of solar movement, measurements should also be taken facing south as well as facing north to account for variance in canopy measurements from inter-canopy shading. Where a high measurement variance is observed, the number of readings should be increased.

Maintenance

Operator maintenance generally only involves cleaning the sensor head of foreign matter. The sensors should be checked and re-calibrated at regular intervals. Different products have their own factory servicing and calibration requirements.

Cost

Low cost hand-held infrared thermometers can be purchased for as little $300. However, these devices are built primarily for industrial, manufacturing and cold store applications particularly for measurements of friction induced heating in bearings and chilling of fresh produce. These low cost devices commonly lack the resolution and accuracy which is required to assess small changes in canopy temperature. These low cost devices also commonly produce errors associated with temperature changes within the housing during prolonged field measurements due to limited housing insulation.

Purpose built IR thermometers (e.g. Model 6110, Everest Interscience Inc) are available that have features which include in built temperature stability, intra-optical light sighting system for object targeting, real time readout of crop specific CWSI and much high levels of accuracy and resolution. These custom devices can retail closer to $15,000 with the necessary accessories. Top end infrared camera's marketed for uses in scientific environments (including crop temperature studies) can retail in excess of $50 000 and consequently are limited to research purposes only.

Advantages and Disadvantages for Commercial Irrigation Scheduling

The main advantages of both thermometry and thermography for commercial irrigation scheduling can be attributed to the non-contact, real time capacity of these devices. IR cameras enable the capture of temperature distribution data across individual crop canopies as well as across a crop plant population. This also provides the ability to "crop" thermal images to remove non-target temperature measurements. Multi-point measurements using IR thermometers also provide the capacity to map spatial variations. Cost is currently prohibitive for commercial automation of thermal sensor based irrigation systems. However, research systems which autonomously schedule variable rate irrigations are currently being evaluated. The current use of remote sensors platforms (e.g. unmanned aerial vehicles, planes or satellites) for regional irrigation evaluations suggests that commercial applications at the farm and field scales for irrigation scheduling are not far away.

Major limitations to the use of thermal sensing for irrigation scheduling include the requirement for multiple samplings and the effect of sampling time due to diurnal variability. This is a limitation for thermometry and may be an issue in thermography of broadscale cropping systems if remote sensing platforms are not available. The potential usefulness of thermal sensing may be reduced in crops which exhibit a low stomatal response to deficit soil moisture conditions and/or increased evaporative demand. These crops display little stomatal restriction and canopy warming until close to the irrigation threshold value but may display an exponential increase in CWSI once a set loss of plant water status does occur.

It should be noted that infrared thermometers can be harmed by direct solar radiation entering the lens. Hence, never point the gun directly at the sun.

Manufacturer/Distributors of Commercial Products

Manufacture/Distributor	**Contact Details**	**Further information**
Everest Interscience Inc *Distributor:* ICT International	1891 North Oracle Road Tucson, AZ 85705 USA P.O.Box 503, Armidale, NSW 2350 Australia Ph: +61 (02) 6772 6770	www.everestinterscience.com/index.html www.ictinternational.com.au
Apogee Instruments *Distributor:* Campbell Scientific	721 W 1800 N Logan, UT 84321 16 Somer St Hyde Park, Townsville, QLD 4812 Ph: (07) 4772 0444	www.apogee-inst.com/index.htm www.campbellsci.com.au/index.cfm
Flir Systems	10 Business Park Drive, Nottinghill VIC 3168 Ph: (03) 9550 2800	www.flirthermography.com/

4. CONCLUSIONS

There are a wide range of plant based sensing technologies available to identify the onset and severity of plant stress. These technologies can be broadly categorised into those requiring direct contact with the plant and those non-contact sensors that are proximally (e.g. hand-held or machine mounted) or remotely (e.g. airborne, satellite) mounted. The contact sensors provide detailed time-series data for individual plants. This data is useful for understanding diurnal fluctuations and contact sensors lend themselves to being connected into on-site irrigation logging and control equipment. The proximal and remote sensors are more appropriate for collecting spatial data across field, farm or regional levels and hence, are more appropriate for assessing spatial variations in plant stress.

Plant based sensors for irrigation typically measure plant responses that are related to moisture uptake (e.g. plant water status, sap flow), transpiration (e.g. canopy temperature/reflectance) or growth rate. Variations in these measures indicate crop stress which can be used to infer when to apply irrigation. However, plant based sensors do not provide any indication of the volume of irrigation water that is required to be applied. Hence, these techniques should be used in conjunction with either atmospheric or soil moisture measurements to confirm the irrigation requirements. It should also be noted that the level of crop stress observed is a complex function of soil, plant and atmospheric conditions. Hence, the user needs to ensure that the crop stress observed is due to a rootzone soil moisture deficit and not disease, pest or exceptional atmospheric conditions.

Plant based sensing for irrigation requires the identification of well tested/validated crop stress threshold values. Hence, a critical factor in choosing a particular sensor is the level of crop response knowledge that is available under alternative soil moisture and evaporative conditions for the various sensor options. Threshold values for plant based sensors can be developed by (i) correlating the observed sensor outputs with established industry practices (e.g. what are the plant sensor readings when irrigation is applied based on accepted soil-moisture or atmospheric triggers?), (ii) conducting replicated trials where irrigation treatments have been ‘triggered’ over a range of sensor values to identify desirable agronomic crop growth, lint quality, yield or other crop characteristics or (iii) evaluating trends in the sensor data and arbitrarily defining critical levels (i.e. if rate of growth shows a marked slowing then irrigations should be applied). However, care should be taken when assessing the physiological responses (e.g. photosynthetic rate and assimilate production) to water availability as a reduction in the photosynthetic rate may not necessarily inhibit the yield potential of the crop. For example, in the case of deficit irrigation of cotton, mild soil moisture stress may increase yields, reduce water use and increase crop water use efficiency.

It is the plant which is being managed to maximise production and profitability. It is also the plant which is the integrator of the environmental (e.g. soil, weather) conditions and farm management factors. Hence, it is appropriate to monitor plant stress and use this information to target improvements in crop and water management. However, as the range of plant sensing options increases, it will be increasingly important to identify which plant based sensors are appropriate for specific crops and to ensure that the appropriate sensor threshold values for irrigation application are defined.

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