Plant-based sensing for irrigation management in the field

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Abstract

Optimizing irrigation is a challenge for sustainable agriculture. The water status of most annual crops is strongly related to soil water status due to shallow, dense root systems and low hydraulic resistance (Rplant). Such crops can be managed with soil moisture measurements and models of ET. However, trees and vines have characteristics that complicate meteorological and soil-based methods: tall, discontinuous rough canopies and deep, low density and erratic root systems with relatively high hydraulic resistance. The high Rplant leads to a greater dependence of water potential on evaporative demand, and leads to dynamic daily water potentials. Sap flux gauges and meteorological modeling can be used to estimate crop water use though discontinuous canopies and crop level effects on stomatal conductance complicate such models. With uncertainty of root distributions and strong weather response, direct measurement of plant water status is desirable in woody crops like winegrapes that require regulated stress for best grape quality. Methods have been developed to estimate or measure plant stress though few are well-suited to commercial use. Remote sensing of spectral characteristics may relate to water status, but is indirect and has many interferences. Some measure a tissue response to water potential variations, such as visual symptoms of stress or dendrometers (shrink/swell sensors) and turgor gauges on trunk, leaf or fruit. These also are indirect and correlations to tissue properties often change. Other methods measure plant water potential directly: the pressure chamber, stem psychrometer or embedded microtensiometer or microosmometer. The much higher temporal resolution with continuous monitoring of stem potential will raise questions about diurnal patterns of plant growth and function, and if irrigation management at much shorter intervals will be valuable. No single measure or model will provide optimal irrigation management, and the integration of direct and remote sensing with modeling is needed. User-friendly software interfaces are needed to facilitate end-user data interpretation and the final decision-making.

Keywords: water potential, sensors, fruit crops, nut crops, irrigation, drought stress, water use model, sap flow, root distribution, hydraulic resistance, remote sensing, dendrometer

INTRODUCTION

Managing the water status of crops is critical to optimize yield, product quality, profitability and sustainability (in perennial crops). This is especially complex due to the variations in the natural and managed soil and aerial environment interacting with variable genetics, plant management and changing market demands. In zones with limited rainfall, irrigation is a key to managing crop water status. However, precise management is difficult without having appropriate measurements of plant water use, the stress the plants are experiencing, the resulting effects of water stress on plant growth and function to be able to define the optimal regime of water status for each crop and product requirement. How can we measure or estimate these in the field?

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There have been many instruments and methods developed over decades to measure or estimate the water relations of soil and the aerial environment around plants, plant water use, the internal water status of plants, and plant responses to stress. We will briefly examine some of broad issues affecting which measurements are most useful to guide irrigation, and more specifically discuss some more recent plant-based measurement methods. The readers are referred to more extensive reviews this general topic (Jones, 2004, 2007; Fernandez, 2010, 2014; Damm et al., 2018).

Effective irrigation depends on measurement or adequate estimation of water requirements and crop water status that integrates many factors. The key questions are: what is the amount of water used by the plant? What is the water status of the crop? What is the seasonal regime of water status that ensures the desired performance (yield, product quality, sustainability in perennials, etc.)? In cases where water is very limited, the question may be what is the minimal amount of irrigation to support the desired crop performance? Finally, how do we measure the water use and water status so we can manage it?

The goals of irrigation differ with crop genetics or product demands. A common goal is to reduce or eliminate crop stress with the minimal amount of water. This assumes that any significant water deficit will have detrimental effects on crop performance. Another goal, more common in fruit and nut crops, is to impose regulated crop stress to maintain or improve product quality (e.g. winegrape flavor profiles), improve management (e.g. increasing hull split in almonds) as well as to save water and increase crop water use efficiency.

Note that examples presented indicating where a method may not work or may give results difficult to interpret are not meant to invalidate any method or say that it never works well. The examples are to point out the complexity of the plant-water relationships in different species and in different field environments, and stimulate users to fully understand each method and factors that affect them.

CROP TYPE AFFECTS CHOICE OF MEASUREMENT

Crop types can be considered in two general categories: annual crops and woody crops, though there are some exceptions. It is helpful to consider how crop structure, root system characteristics and plant hydraulic resistance can influence the plant water status, its reactions to the environment and which types of measurements are most appropriate.

Crop structure

In general, annual crops are low, continuous canopies, and in mid-season when most irrigation is used, the soil is normally fully covered by vegetation. Woody crops, however generally have tall discontinuous canopies due to the need for alleyways for equipment access. These differences in structure affect the factors that regulate water use. In both cases, radiation is a major driver of water use since it provides the energy. In the low continuous canopies, a heavy boundary layer of air forms except in windy conditions. This is a resistance to the movement of air from the crop to the air. Consequently, increases in stomatal conductance of the crop tend to be countered by decreased VPD as the humidity cannot escape the boundary layer (Figure 1). Thus, a calculated reference water use, the ETo (Allen et al., 1998), is about 90% related to radiation with only minor effects due to variations in VPD or temperature or stomatal conductance (see Jarvis, 1985 and Jones, 2014a for a more detailed account). If radiation is known, then it is a good estimate of ETo is available as long as the wind speed is low.

In contrast the tall rough structure of an orchard or vineyard leads to more turbulent air flow which greatly reduces boundary layers and couples the crop to the bulk air. This imposes the ambient air on the leaves so VPD becomes important to water use (Butler, 1976; Dragoni et al. 2005; Villalobos et al., 2013). For the same reasons stomatal conductance, and its response to VPD, are much more important though stomatal closure in response to increased VPD may tend to counter the effect of VPD (Jones et al., 1985). Thus for tall rough crops, radiation, VPD and stomatal conductance are important and should be measured or estimated. Additionally, other factors not directly related to water, such as crop load, may affect water use in woody crops (Naor, 2006; Naor et al., 1997, 2013) via their effects on stomatal conductance.

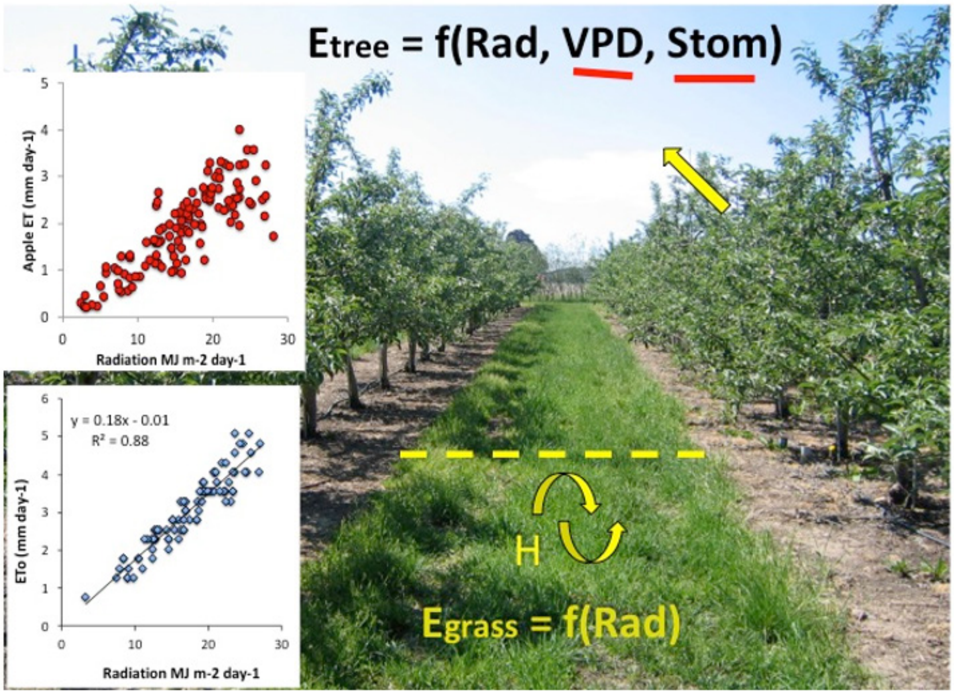

Figure 1. Differences in factors affecting wate loss by low versus tall crops. Note the low grass or calculated ETo is driven greatly by radiation while tree E also depends on VPD and bulk air VPD.

Root system characteristics

Annual crops tend to have quite dense root systems that are relatively shallow. The roots explore the soil well and have high root length density expressed as root length per volume of soil. So, the placement of a soil moisture sensor in a representative location is not very difficult. In contrast, woody crops tend to have large root systems that can extend significant distances horizontally and vertically; but they generally have low to very low root length density (Atkinson, 1980). Deeper root systems also tend to encounter and respond to soil structure and resource variations with deeper soil horizons. This makes locating soil moisture sensors much more difficult as deep rooting plants may access water from varying depths. This is especially true in grapevines since vines have no inherent structure; the roots are opportunistic and grow wherever the conditions are best. In very arid zones the roots may concentrate under the drippers allowing easier locating of soil sensors. So soil moisture monitoring is much more variable in woody crops.

Additionally, low root length density can lead to localized drying of the soil in the narrow rhizosphere around the roots as high transpirative flux through only a few roots requires a large amount of water uptake per root. This then leads to an additional resistance through the dry soil around the root system. A preliminary estimate was made of the volume of soil in the rhizosphere of the roots of an apple tree, assuming normal spacing, 1 m soil depth, an average root length density for apple, and 1 mm of rhizosphere soil (Ortas, 1997 estimated 0.5 mm for sorghum). The results suggest that only 2-4% of the available soil volume allotted per tree is in the rhizosphere which could support only about 3-4 h at most of mid-day transpiration without replacement. This is consistent with Atkinson's (1980) contention that very likely there is mid-day localized drying around the roots with species of very low root length density even with good bulk soil moisture.

Hydraulic resistances

Water movement in plants is generally modeled as an Ohm's Law analogy with voltage/water potential gradients, current/transpiration flux, and hydraulic resistance to the flux. A high hydraulic resistance will cause a strong change in the potential gradient with increasing transpirative flux. The importance of plant hydraulic resistance is that it determines how strong a water potential gradient is needed to support a given flux of transpiration through the plant (see Jones, 2014b for detailed discussion). Most annual crops have quite low hydraulic resistances so at a normal full mid-day transpiration rate, the water potential of the top only decreases mildly compared to night (Landsberg et al., 1975; Koide, 1985; Figure 2). So plant water status in low-resistance crops is primarily controlled by soil water status.

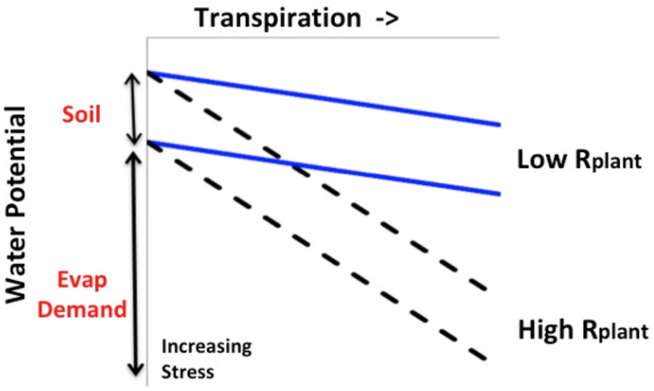

Figure 2. Diagram of the relationship between leaf or stem water potential and transpiration in plants with high and low hydraulic resistance.

In contrast, woody crops, such as apple trees more so than vines, have higher hydraulic resistances, generally due to the larger distance of water movement from soil to upper leaves as well as smaller vessels in the xylem. These higher resistances lead to stronger water potential gradients from soil to leaf during the day giving a strong effect of weather on daily water potential patterns. This means that plant water status of high-resistance plants is dependent on both soil water status and aerial evaporative demand.

It should be noted that this is not strictly and annual versus perennial effect as wheat is a high resistance crop that behaves similarly to apples (Jones, 1978). Also in the literature there are many levels of resistance in plants and their rhizospheres, and it is likely that such resistances may change with development, environment, and patterns of root growth.

IMPLICATIONS FOR CHOICE OF MEASUREMENT METHODS

For all these reasons many external environmental measurements (soil, weather parameters, remote sensing) fairly effective in low resistance crops do not estimate the crop water use and water status particularly well in high resistance crops. This is a significant problem if the grower is attempting to impose a regulated stress for improving product quality or for other management purposes such as limiting excessive canopy growth or increasing the uniformity of hull split in almonds. This has led to the increasing interest in plant-based sensing of water status to guide irrigation especially in fruit and nut crops.

Currently, a small percentage of the more technologically-advanced fruit and nut growers use direct plant measurement such as sap flow or the old manual pressure chamber, or buy the service, to monitor crop stress and modify irrigation to try to ensure that the desired stress regime is generally achieved. However, both high temporal and spatial sampling are required due to the dynamic nature of water use and stress and the natural variation in soils and microclimates. Therefore, efficient plant sensing to provide greater temporal and spatial sampling of physiologically relevant processes has been a goal.

PLANT-BASED METHODS TO MEASURE OR ESTIMATE PLANT WATER USE, GROWTH AND WATER STATUS IN THE FIELD

There are several processes amenable to plant sensing in the field (research-only tools are not considered here): crop water use, expansion or growth of plant organs, and plant water status.

Crop water use

The most common approaches for estimating water use (i.e. evapotranspiration (ET) have been to estimate a soil water balance or to meteorologically estimate and model water use (eddy covariance, surface renewal), or combinations of methods. These methods measure the environment around the crop, but not the crop directly. Although some measurements, such as soil moisture or weather measurements, can be done at the plant scale, we will focus on practical measurements of the plant itself.

The most direct are the sap flow gauges that estimate flow through the main stem(s) of the plant. They are based on measuring the application and transport of heat as an indicator of sap movement in the xylem. There are several techniques, but they all require some assumptions such as an effect of wounding when heat pulse sensors are installed, isothermal conditions for external temperature measurements, sampled location in the trunk is representative radially, etc. (Vandegehuchte and Steppe, 2013). These assumptions may be accurate and allow accurate assessments of transpiration without calibration. But these assumptions are difficult to be sure of without direct calibration by whole plant gas exchange or similar method (Dragoni et al., 2005; Intrigliolo et al., 2008; Pérez-Priego et al., 2010; Pasqualotto et al., 2019).

A recent analysis of sap flow methods (Flo et al., 2019) concluded that "dissipation methods may be more appropriate to assess relative sap flow (e.g., treatment effects within a study) and pulse methods may be more suitable to quantify absolute flows. Nevertheless, all sap flow methods showed high precision, allowing potential correction of the measurements *when a study-specific calibration is performed*." More recent approaches to improving estimates of water flow include combining measures with phenological data and integrating with neural networks (Tu et al., 2019).

Though sap flow systems have some clear limitations, they are easily automated giving excellent temporal sampling, and some have shown to be robust and reliable enough for operation in the field over extended periods of time. Sap flow methods have been successfully used for scheduling irrigation in woody crops (Fernández et al., 2008). Then, irrigation amounts can be controlled by comparing those measurements against similar data from representative plants in other parts of the orchard (Goldhamer and Fereres, 2001). However, these sensors are complex to install correctly, although easy to maintain, variable in accuracy without direct calibration, relatively expensive, and are somewhat difficult in terms of data processing and interpretation. They require highly technical personnel so are not a simple tool for growers. Nonetheless, with highly-skilled management the use of heat balance sap flow in grapes has been used successfully commercially, primarily in a relative sense (Water deficit index = Measured transpiration/(basal Kc * ETref) (Scholasch, 2018).

Monitoring of organs for growth and water status

Other widely-studied plant-based methods for continuous monitoring of the plant related to water are those based on direct measurements of organ dimension variations or more generalized remote sensing of plant size over time. The most common are measurements of the stems, fruit or leaves. In the case of stems and fruit, long-term growth is measured along with diurnal variations. The use of electronic dendrometers (used generally for devices that monitor changes in organ dimensions) for estimating daily variations in organ size and longer term growth to generally estimate plant water status and guide irrigation scheduling has increased. The advantage is that plant organs integrate the plant response to water conditions both in the soil and in the atmosphere though other factors such as crop load or stage of development may also affect the measurements (see Fernández, 2010 for a detailed review).

These techniques allow for non-destructive, automatic and continuous data recording and are easily implemented with data transmission systems for a nearly real-time access to the collected records from a remote computer. Dendrometers (used as a general term) are reasonably robust, generally reliable and relatively easy to install. Drawbacks include the fact that the behavior of these records are influenced by species, plant size, phenological stage, fruit load (Mirás-Avalos et al., 2016) among other disadvantages (Fernández, 2010; Ortuño et al., 2010). Despite these advantages, a number of drawbacks prevent widespread adoption by growers. These include the difficulty to use and to maintain, and the expense of the sensors and the systems needed to collect, interpret and store the data. But ultimately the limitation for estimating plant water status is that they measure an organ response to water status, not the water status itself. Changes in the physical properties of organs (for example, spring wood vs summer wood) will change over the season, as will the correlations to plant water status.

Stem dendrometers tend to be more useful in practice as they are attached to a relatively solid structure and the changes over the season are easily within the range of the sensor. Fruit dendrometers tend to be good to identify early changes in tree stress, but most if not all have limited ranges. For large fruit such as apples, peaches or citrus dendrometers installed at the start of the fruit growth season need to be changed for larger range units in the mid-season. This may not be needed for small fruit like olives or grapes. Fruit dendrometers are more likely to be disturbed by wind or by the wind or residues from speed sprayers.

Another method is monitoring the response of leaf tissue to an applied pressure from a highly sensitive pressure sensor magnetically clamped to a patch of a leaf (called a patch clamp or ZIM-probe, Zimmermman et al., 2008). The measurement is related to leaf turgor pressure though there may be structural resistances from veins and additional development of fibers over the season. This has been reported as an easier to install and easier to use technique than the above-mentioned methods with a potential to be used at field by growers (Fernández, 2014). The probe the measures the pressure (Pp) transfer function through a patch of an intact leaf. This Pp has been shown to be inversely correlated with the turgor pressure (Zimmermman et al., 2008, 2010; Westhoff et al., 2009). Though the equipment is relatively simple, the interpretation of the daily or nightly patterns of maximum Pp value, the turgor recovery phase during the afternoon or the reverse of the Pp curve is rather complex. These values and patterns depend on the plant physiological characteristics and their tolerance or sensitivity to drought stress, which requires a unique interpretation of this technology for each particular case. The usefulness of the patch clamp to detect plant water stress has been studied on several horticultural and fruit crops (Fernández et al., 2011; Rodríguez-Domínguez et al., 2012).

It is related to the leaf water status but it is not clear if the leaf water status is representative of the whole plant water status especially during the day when exposure of any leaf may vary. We have found in apples and grapes that exposed leaves gradually close stomates after 3-5 h and thus change water potentials while stomates on recently exposed leaves remain open (Lakso, 1983; Al-hazmi, 1993). Additionally, leaves may osmotically adjust, changing the turgor-to-total potential relations (Davies and Lakso, 1979; Lakso et al., 1984). The choice of leaves and how they may change affects interpretations requires further testing. It is not clear exactly which leaf to choose, especially in large fruit crop canopies, and how long to monitor before needing to change to a new leaf.

Remote sensing of plant growth and water status is a different approach to estimate growth and water status. The sensing are non-contact measurements of plant interaction with electromagnetic radiation of varying wavelengths. This can be done from only a few cms to meters away by hand-held or ground-based systems, by aerial imaging of meters-hectares with planes or drones, and by satellites imaging up to hundreds of hectares. Each has its advantages and disadvantages as resolution changes (Matese et al., 2015) though UAV's with the latest sensors is probably the best combination of resolution and large population sampling.

Of the various measures of growth, generally the best measures are basically estimates of plant or whole crop structure or ground cover. These can be done by lidar or multi- or hyperspectral imaging to identify variations in plant structures spatially. These estimates are often quite accurate. Growth as defined by dimensions can be determined by sequential measurements. The most common spectral indices used in practice, NDVI or PCD (plant cell density), have been related to several plant size components such as leaf area, shoot length, weight of growth, etc. with poor to very good R2 values. Generally, they are best for a range of plant size variation from small to medium as denser growth causes more internal shading which is not seen via the spectral imaging. Another significant difficulty for aerial sensing is in highly manipulated canopies such as grapevines or modern vertical apple orchards with thin vertical canopies where all the leaf area is compressed and from above most plants appear to be similar (Gonzalez-Dugo et al., 2012; Guillén-Climent et al., 2014).

ESTIMATION OF PLANT WATER STATUS

Comments on sampling for plant water status

As discussed the factors that affects plant water potentials are many (Figure 3). This is especially true for crops with high hydraulic resistance present many challenges of variability. The strong dynamic dependence of weather on transpiration and thereby the plant water potentials gives great temporal variability. Besides inherent plant variability, fruit crops also are often planted on more variable soils and slopes than annual crops, particularly grapevines and olives. Ideally, measurements of water status need to have: (1) high sampling rate over time, preferably continuous monitoring, and (2) sampling at a wide range of points spatially, depending on soil or topography. No one technique or method is ideal as they lack either desired temporal or spatial sampling or lack direct measurement of the plant processes or status.

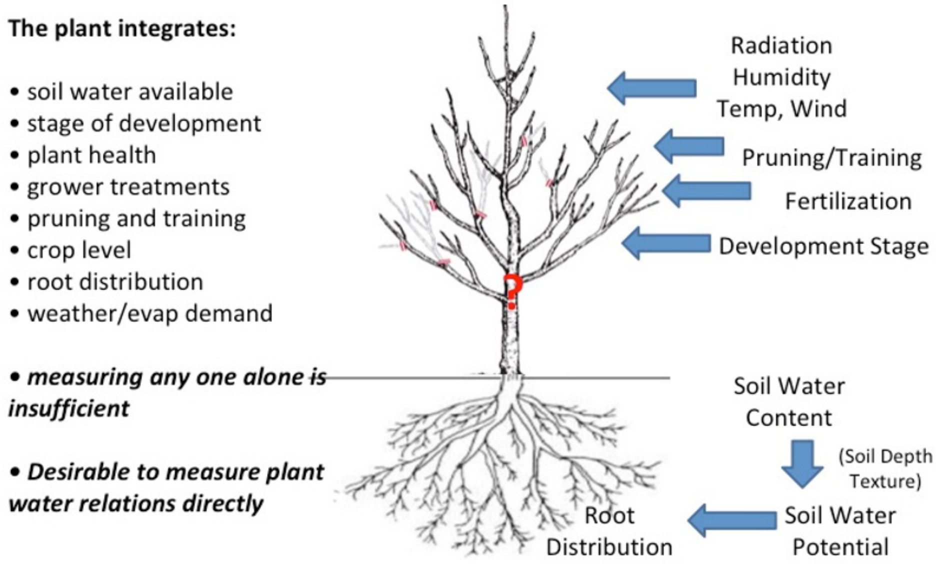

Figure 3. Factors that affect the water status of a plant, especially highly managed crops.

Remote sensing for water stress

Structural estimates of plant size by remote sensing mentioned above have been related to water relations, i.e. plants with more available water will be larger until canopies fill the allotted space. However, many other factors may determine plant size, both natural (e.g. mineral deficiency, soil limitations) or imposed by growers (training, pruning, crop load, etc.). So, caution is needed attributing cause-and-effect to water stress.

The most common use of remote sensing for estimating water stress is based on thermal imaging at a range of scales from leaf to field using hand-held IR thermometers to satellite imaging (see review by Costa et al., 2013). The basic principle is that water stress regulates the rate of water loss through stomates, thus affecting the leaf energy balance and temperature (Jones, 2011, 2014a, b, 2018). If stomates close, leaves heat up, and this can be measured or imaged easily (Jackson et al., 1981; Idso, 1982). Comparing the canopy temperature to non-stressed and non-transpiring references has been made into the Crop Water Stress Index: CWSI=(Tcrop – T_{nws})/(T_{dry} - T_{nws}), where crop T is related to a non-water-stressed T_{nws} and a non-transpiring T_{dry}.

Inexpensive and-held IR sensors have been used for some time, and can be effective. The measured area is small which allows the user to select the measured tissue, such as a large leaf normal to the sun. This can locate the leaves with the maximum increase in temperature, but the sample is extremely small considering a full field. To improve sampling to large areas, aerial or satellite IR imaging has been considered. Research has demonstrated the existence of variable relations, from none to very good, between the spectral parameters or indices or CWSI obtained either from the analysis of images provided by UAV or satellite, and physiological crop parameters such as stomatal conductance or stem water potential in well-watered and stressed zones (Gonzalez-Dugo et al., 2013, 2015; Rodrigues et al., 2007; Pocas et al., 2015). These relations differed with different fruit species, indicating the need for species-specific calibrations.

There are many difficulties and limitations to the widespread use of thermal imaging. Jones (2018) reviews many. But Briefly some key limitations are related to the many factors that affect the energy balance of the leaf that are not due to water stress. Such as variations in radiation load (both incident radiation and within canopy), wind, humidity, boundary layers related to leaf sizes and shapes, and non-stress factors that affect stomatal conductance (crop level, nutrient status, disease, etc.) (Lakso, 2003; Naor et al., 1997, 2013; Jones, 2018). Aniso-hydric behavior where stomates tend to remain open even with declining water potential (Martinez-Vilalta and Garcia-Forner, 2017), or where significant osmotic adjustment occurs (Lakso et al., 1984) will obviously disrupt the relationship of leaf temperature to water stress. Clearly, thermal imaging is easiest and most useful in consistently clear arid climates as the humid climates cause too much variation primarily in radiation. Since leaf width affects sensible heat transfer, large-leaved genotypes will heat up more than narrow-leaved genotypes, again requiring species-specific calibrations (Lakso, 2014; Fauset et al., 2018).

Additionally, there are many structural and geometric issues. With height, sampling increases but resolution decreases. Especially in discontinuous canopies, this leads to mixed pixels that are so large that each pixel contains images of different things (exposed leaves, shaded leaves, stems, soil, other plants). Thus interpretation is difficult unless the pixel size is smaller than the desired tissue area sample, and determining which pixels to choose is not simple. Even with high resolution, interpreting water stress is particularly difficult with strongly restricted thin vertical canopies, such as grapevines where the projection from above is very narrow and is primarily the youngest, smallest and most ventilated leaves that show the smallest leaf-air temperature differences (Figure 4). Yet trying to view such canopies obliquely to view older leaves introduces many geometric problems. Rapaport et al. (2014) also demonstrated that leaves of different ages and growth rates differed in spectral signatures related to the relative air space in the leaf, adding to the complexity.

The availability of multi- and hyperspectral imaging provided greater opportunities for evaluating different spectral bands and ratios to relate to water stress. Although there have been at least 70 different spectral indices reported, the results relating them to water potentials of different species has been disappointing (Rodriguez-Perez et al., 2007; Gonzalez-Dugo et al., 2013; Ballester et al., 2018). This is again likely due to the number of different processes and structural aspects (e.g. gas exchange, osmotic adjustment, changes in leaf size and angle, etc.) that are affected by stress and how different species have different suites of responses.

Direct measurement of water potential

The pressure chamber – although there are several laboratory methods for measuring the water potential, the only method used significantly in commercial practice to inform irrigation is the traditional Scholander pressure chamber (Scholander et al., 1965; Turner, 1988). Several determinations can be made: exposed or shaded leaves, leaves enclosed in foil bags to equilibrate to the stem potential, fruit water potential, and shoot potentials. If leaves are not bagged, the determination corresponds to the leaf water potential, which has the disadvantage of being affected by environmental conditions of the individual leaf. Generally, due to the resistance in the petiole, the leaf potential will be 0.2-0.4 MPa more negative than the stem if stomata are open.

Figure 4. Remote sensing of plants that are allowed to extend in relation to their growth potential (left) will be better evaluated by remote sensing especially from above than very restricted and pruned vertical canopies (right).

Another modality is the minimum stress pre-dawn leaf water potential, which is measured before or at dawn, when plant water potential is presumably in equilibrium with soil water status due to lack of transpiration. This has been interpreted to be a measure of the effective soil water potential. However, it appears that nocturnal transpiration is more common than originally thought (Forster, 2014). Pre-dawn potentials are correlated to the mid-day water potentials in homogenous soils and uniform weather; but in heterogeneous soils and variable climates they may not. In deep-rooting trees or vines, a deeper soil layer may supply enough water to re-hydrate the plant pre-dawn, but not in mid-day (Ameglio et al., 1999). Thus, it is best interpreted as the “wettest” soil to which the roots are exposed.

The most generally useful has been the stem water potential (Ψstem) (Naor, 2000; van Leeuwen et al., 2010; Shackel, 2007, 2011). Usually, these determinations are carried out at midday (generally early afternoon), when the maximum degree of stress usually occurs. Stem potentials better integrate the complex hydraulics of the plant, and tend to be more stable. Also shoot tips and fruit equilibrate with the Ψstem, not with Ψleaf. For example, Patakas et al. (2005) found that with decreasing irrigation levels, grapevines reduced transpiration according to the irrigation level, which led to no differences in exposed mid-day exposed leaf potential. However, Ψstem decreased in relation to the irrigation levels and were correlated with decreases in photosynthesis and stomatal conductance.

Although the pressure chamber is acknowledged to give correct readings of water potential and is still the standard method after 55 years, the weaknesses are clear: it is manual only, requires labor which also leads to variability due to operator error or differences, slow procedure, gives very limited sampling over time and space, not scaleable or automateable, and the choice of leaf can affect the reading. Weekly water potential readings are useful, especially in consistent sunny dry regions that allow reasonable extrapolation of the stress on other similar days. However, in more humid and variable climates, measurement on one day may not represent the stress on other days. A simple integration of periodic measurements of water potential have been used to attempt to address this (Myers, 1988). A study of potential integrals and grapevine performance in Chile found the best correlations to berry soluble solids (R^2=0.7), but lower correlations to berry numbers or weight (Zúñiga et al., 2017).

Thus continuous monitoring of stem potential appears to be the best single measure of the dynamics and physiological effects, but also allow integration of stress. Fernandez (2014) has described an ideal sensor for plant water stress. Generally, it should:

- accurately measure a key parameter of plant stress such as water potential;
- be easy to install and maintain; be rugged and reliable;
- cheap to allow many sensors for good spatial sampling;
- monitor stress continuously or at high frequency;
- integrate into wireless networks;
- provide critical data that can be used directly by the grower or feeds into crop models and decision support systems.

1. Stem psychrometry.

An early effort to monitor stem water potential directly was the development of the the stem psychrometer that presses a tiny chamber with a thermocouple against the xylem of a stem (Dixon and Tyree, 1984; Edwards and Dixon, 1995). After equilibration of the air in the chamber with the water potential of the adjacent tissue, the thermocouple is cooled and the dewpoint determines the water potential. This method can provide continuous monitoring of plant stem water potential, can be automated with wireless communications and has given good data for days or a few weeks in some cases. The psychrometer has been very sensitive to work with, but it has provided some unique opportunities for monitoring of field plants in more research settings. However, it is limited for practical season-long monitoring and irrigation management and is rather expensive.

2. Stem tensiometry and osmometry.

Two newer instruments with potential for field use have been developed and are under field testing to monitor stem water potential are a microtensiometer (www.florapulse.com) and a microosmometer (www.saturas.com). They are embedded into or pressed against the xylem in the stem of plants, and work via a direct water connection rather than an air interface used in the stem psychrometer. Both exchange small volumes of water with the plant and measure the pressure differences in the sensor related to that exchange.

The microtensiometer has the same principle as the classic soil tensiometer, but is a very small microelectromechanical (MEMS) device and has a 100-fold range of potentials compared to the soil tensiometer (Pagay et al., 2014; Lakso et al., 2022). The device contains a tiny amount of water that exchanges with the adjacent tissue though a nanoporous exchange surface as the water potential of the xylem changes. The sensor chip is housed in a cylindrical probe that is embedded in the xylem. Continuous measures of stem potential over several months has been obtained with high correlations to standard pressure chamber (Figure 5). Similarly, the xylem tissue equilibrates with the microosmometer that contains a pressure transducer and polymer osmoticum separated from the tissue by a supported reverse osmosis membrane (Meron et al., 2015).

Major advantages of stem potential sensors are that they are direct continuous measures and there is much research and field experience relating Ψstem to plant growth and performance. Both sensors have electronic pressure transducers that can be integrated into wireless Internet of Things (IoT) networks with convenient user interfaces. Although the value of having continuous monitoring of the best physiologically-relevant measure of plant stress is great, there are challenges to making field-rugged sensors. Potential issues with these approaches for practical use include (1) making and maintaining good contact between the sensor and tissue in a dynamic environment and with stem tissues that shrink and swell diurnally and grow over time, (2) determining system rate of response to changing water potentials and correcting for any sensor temperature response, (3) determining and minimizing how different species will react to the wounding necessarily involved with sensor installation, (4) having sensors that will give accurate readings in the field over at least one season in different plant species, and (5) providing the sensor or the data stream from the sensor to growers at competitive prices. These are most adaptable to woody crops though possible in some annuals such as corn after enough stem enlargement.

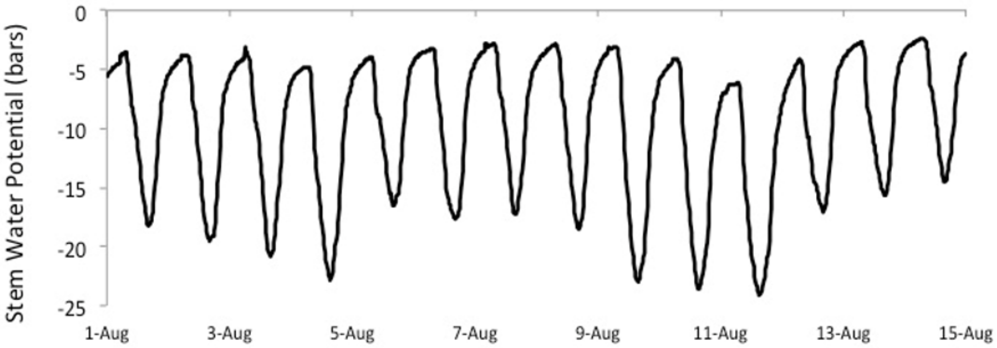

Figure 5. Example of continuous monitoring of stem water potential in an almond tree. Figure courtesy of FloraPulse Co. and K. Shackel.

Assuming continuous stem potential monitoring becomes a practical method, new questions arise. Will the availability of continuous stem water potential measurement lead to more precise irrigation management? There are many reports of shoot and fruit growth with daily or weekly measurements, however, we are not aware of any with diurnal continuous data over a long period. Long-term measurements of fruit, stem or leaf as discussed above have been available with dendrometers, but not in conjunction with equivalently detailed water potential data. Also due to the measurement difficulty, there are only a few reports of diurnal shoot growth rates (Powell, 1976; Landsberg and Jones, 1981; Naor and Wample, 1996; Berman and DeJong, 1997). In apple, grape and peach shoot growth generally increases in mid-to-late afternoon after little to no growth in the morning, giving a strong hysteresis with water potential. This may be related to a delay in the accumulation, then loading and transport of photosynthates from the leaves to the growing organs.

When is the optimal time to measure stem potentials? If the grower needs to regulate vegetative growth or optimize water use efficiency, will the time of the day the irrigation is applied be helpful? The answer may be different in different species, climates and soils. In arid zones with lighter soils and root concentrations under the drippers, timing of water supply is more precise than in the buffered systems in humid climates with extended root systems and heavier soils. In any case, monitoring of stem water potential should be a valuable tool.

Integration of sensing methods

When considering the temporal and spatial variation of plant water status in many crop fields, no single method is adequate to provide the best information for precision irrigation. Direct sensing of plant water status has the great advantage of measuring the final integration of many factors by the plant with outstanding temporal sampling. However, the great disadvantage is that the sample size is necessarily very small due to sensor cost, data analytics, etc. giving poor spatial sampling. Remote sensing has complementary advantages and disadvantages of poor temporal sampling (unless mounted sensors allow continuous observations) as timing of satellite, airplane or drone flights or ground-level sensors are generally quite limited. A solution could be integrating ground and remote sensing: on-the ground installed sensors will provide real time information system continuously collecting data about the dynamic water status in the plant, soil and atmosphere, while remote sensing will allow determining water status at larger scale but with low temporal resolution.

There are current efforts to integrate direct plant measurements by calibrating the remote sensing and soil maps with the direct sensing of stress or growth at points in the field, to allow interpolation in between to develop more detailed management maps. All of these need to be integrated with geospatial Soil-Plant-Atmosphere Continuum models. It is not clear, however, if a general remote spectral method will be found for all crops for many of the reasons discussed earlier. But each crop may need individual calibrations. The optimal resolution for these maps will likely be limited due to the logistics and cost of development of high resolution irrigation zones in commercial use. For example, a large grape grower plans to match the irrigation zones to a Landsat satellite pixel.

CONCLUSIONS

The growth, yield, adaptation and product quality responses to water deficits are very complex and are a manifestation of interactions of crop structure, aerial and soil environment, physiological characteristics of each species and crop management beyond irrigation. As such no individual environmental or plant-based measurement or model will be sufficient to provide all the information for optimal irrigation. The steady progress in plant measurement instrumentation combined with the explosion of new technologies, data analytics and mechanistic models provides new opportunities to gather huge amounts of data. The challenge will be to analyze the data, interpret the information and refine and develop models to generate actionable data for growers. The new results and hypotheses generated by machine learning and AI should not replace but supplement and stimulate more research and knowledge of crop water relations physiology and mechanistic models. The future will be exciting and challenging.

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