Principles and Practices of Plant-based Irrigation Management

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SUMMARY. Many consider tools for plant-based irrigation management methods to be the most precise way to manage irrigation in either a research or a commercial settings. Although many types of tools are available, they all measure some aspect of water movement along the soil–plant–atmosphere continuum. This article presents some of the more commonly used tools and the methods involved to properly employ them. In addition, recent literature is reviewed to provide context to the methods themselves and also to highlight each one's specific advantages and disadvantages. Ultimately, there is no clear winner or “best” tool as all have disadvantages, either due to prohibitive cost, the amount of data output, the difficulty of data interpretation, lack of signal resolution, or lack of dynamic ability to provide decision support. Therefore, we conclude that the user should carefully weigh these varied advantages and disadvantages in the context of their production goals before deciding on a given tool for irrigation management.

Irrigation management typically starts with indirect or direct monitoring of the crop or its surrounding environment. The most common indirect methods are the monitoring of soil moisture conditions—either through measurement of soil water content (relative or absolute) or soil water tension. Another common indirect method uses estimates of crop evapotranspiration (ET_c). Direct, plant-based irrigation management methods provide the irrigator with direct knowledge of the plant's hydration state or water status.

When used correctly, direct, plant-based methods can be leveraged to schedule irrigation events more precisely, thus maximizing water conservation.

For plant-based irrigation management to be effective, several requirements must be met. First, the measurements must be sensitive and consistent indicators of plant water status. In other words, the sensors or methods should accurately identify when a plant is well watered or experiencing a water deficit. Second, plant-based measurements should accurately reflect the amount of water in the soil profile. Thus, the data provided by the plant-based measurement tools should be well correlated to soil water availability. Finally, plant-based measurements should be highly correlated to other physiological processes of importance, such as vegetative and reproductive growth and, in some cases, crop quality.

In this article, we review some of the major plant-based irrigation management tools, the principles behind them, and their associated methodology. The interpretation of the data along with the advantages and disadvantages of each tool are discussed in

the context of their practical utility for both researchers and commercial producers. First, however, it is necessary to briefly review the physiology behind water movement through plants.

Water potential

Water is an essential plant component, constituting the majority of the fresh weight of plant cells. Most morphological and physiological characteristics of land plants are adaptations for maintaining a high internal water status. The term “water status,” although somewhat vague, is commonly used to discuss the hydration states of plants (and also soils). Generally, well-watered plants and field capacity soils are said to have a “high” water status, and drought conditions lead to a “low” water status.

The water status of plants and soils is often defined in terms of water potential (ψ). The ψ refers to the chemical potential of water, or the ability of the water to do work, and it is expressed in pressure units (bars or megapascals). Water moves spontaneously down a chemical potential gradient (from high to low), releasing energy (and doing work) along the way. In layperson's terms, this concept is often restated as the mnemonic “water flows downhill.”

The ψ of pure water at standard temperature and pressure is given a value of zero. The total ψ of a system (plant or soil) is made up of several components, although the detailed discussion of each is beyond the scope of this article. Briefly, the addition of solutes always lowers the total ψ of the system, so it would be negative. The application of pressure (if it is positive) to the system can raise the ψ , such as in turgid plant cells. In contrast, if the pressure is negative (i.e., tension) in the system, it would further lower the ψ , such as in the plant xylem. Ultimately, as the plant or soil becomes “drier,” the ψ value becomes more negative (lower). If they become “wetter,” the ψ becomes less negative (higher). However, the total

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Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.1	bar	MPa	10
2.54	inch(es)	cm	0.3937
1	ppm	$\mu\text{L}\cdot\text{L}^{-1}$	1

ψ of plants and soils will never be positive under most conditions. Importantly, ψ can be used to evaluate movement in both plants and soils.

Water movement through the soil—plant—atmosphere continuum

Water flows from the soil through the plant and out into the atmosphere along what is known as the soil-plant-atmosphere-continuum (SPAC). Accordingly, most plant-based irrigation methods are correlated to detect some aspect of the SPAC. Plants are directly connected to the atmosphere through tiny microscopic pores located on the undersides of leaves called stomates (or stomata; Fig. 1). Stomata are microscopic epidermal structures on plant leaves that consist of two guard cells around a pore. Carbon dioxide (CO_2) diffuses into the stomatal cavity from outside of the leaf to be used during photosynthesis, whereas water (H_2O) vapor diffuses out through stomata in the process known as transpiration.

The hydraulic and biochemical mechanisms that govern the stomatal opening and closing are influenced by many environmental factors, including changes in temperature, light intensity, atmospheric CO_2 concentration, air humidity, and soil moisture content (Bertolino et al., 2019). In general, however, stomata gradually open in the morning as the sun rises, and at $\approx 50\%$ of full sunlight, they are fully

open, although there is variation among shade vs. sun-adapted plants. When the sun sets in the evening, stomata close, and typically little water is lost from plants at night, although this is an area of active research.

While stomata are open, water vapor passively diffuses out of the leaf. This is due to the large ψ gradient between the inside of the leaf and the atmosphere. Inside the leaf the ψ is relatively high (e.g., -0.8 MPa), while the ψ of the atmosphere is typically orders of magnitude lower (e.g., -100 MPa). This difference creates a steep gradient that drives transpiration and water loss from the leaf. A beneficial side effect of transpiration is its cooling effect on the leaf (due to the latent heat of vaporization) that can be leveraged to schedule irrigation.

Stomatal closure in response to drought is a complex process regulated by a network of hydraulic and hormonal signaling pathways, the discussion of which is beyond the scope of this paper. In general, stomatal closure in response to water deficit is a mechanism to prevent embolism of the vascular system and complete desiccation of the plant (Martin-StPaul et al., 2017). However, closure of stomata to prevent embolism bears the trade-off of potential detrimental impacts on plant growth and productivity, as well as leaf temperature regulation. Ultimately, stomatal closure reduces leaf gas exchange that can be

detected and used as a signal to schedule irrigation.

The water that is lost from the inside of the leaf through the substomatal cavity must be replaced by water from the cells that surround the cavity. Water movement out of those cells lowers their ψ , establishing a ψ gradient that extends to the roots. The water lost from those cells must be replaced by water from other nearby leaf cells, and ultimately by water drawn up through the leaf xylem. Indeed, the vascular system in higher plants evolved to provide distant above-ground organs with a consistent water supply. The velocity of water transport through the plant shoot can also be measured and used as a proxy for transpiration to ultimately schedule irrigation. Shoots are connected to the roots through the entire vascular system, and so water is subsequently drawn up from the roots to replace the water that was lost from the leaf. Finally, the water that is lost from the roots is replaced by the soil water. To maintain water flux from the soil into the roots, root tissues must maintain a ψ that is lower than that of the soil, and must necessarily remain in physical contact with the soil water solution.

Plant-based methods

PRESSURE CHAMBER. The most widely used tool used for plant-based irrigation management is the pressure chamber (Fig. 2A), introduced by Scholander et al. (1965). In practice, its measurement of plant ψ is considered to be the gold standard measure of plant water status (Santesteban et al., 2019). As such, it is often used as a reference value against which other emerging technologies (e.g., several of those outlined later in the article) are calibrated (King et al., 2020).

The pressure chamber has become so ubiquitous among plant scientists and commercial practitioners alike that detailed descriptions of the methodology used are often omitted. This has led to some disagreement among users regarding proper methodology. However, years of research have detailed the various errors that can arise from improper sampling and measurement, ultimately refining the proper techniques. Several determinations are available for use in irrigation management: predawn water potential, midday leaf

Fig. 1. Cross-section of typical leaf showing tissues and structures including stoma (Wikipedia, 2021).

Fig. 2. Examples of various plant-based methods in use: pressure chamber (A), infrared gas analyzer [IRGA (B)], IR thermometer [IRT (C)], and sap flow (D). These are merely examples of instruments; others of similar types are available (photos A–C by A.D. Levin; photo D courtesy of L.E. Williams).

water potential, and midday stem water potential.

As the name suggests, predawn leaf water potential (ψ_{pd}) determinations require leaf samples taken before sunrise, whereas midday leaf (ψ_{leaf}) and midday stem (ψ_{stem}) water potential measurements require leaf samples taken just after solar noon. These time points are critical because they represent the steady-state moments when leaf transpiration is either minimal (predawn) or maximal (midday). In other words, water flux out of the leaf is at a steady state, and the leaf's water status is not rapidly changing during each time point.

When sampling for all determinations, selected leaves should be mature and fully expanded, with no damage. Leaves for ψ_{pd} measurements should be sampled just before sunrise, before there is any incident light on the leaf because light stimulates stomatal opening and transpiration that may reduce the ψ of the sample. However, Williams (2017) recently reported that still-shaded leaves sampled just after sunrise provide readings nearly identical to those of ψ_{pd} samples. This may extend the sampling window somewhat and provide the operator with the opportunity to take more samples. Ultimately, the total number of samples should be based on expected variability among plots and desired measurement precision.

Midday measurements should be made under clear sky conditions under full sunlight [$>1500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ photosynthetic photon flux density (PPFD)]. Typically, it has been recommended that ψ_{leaf} and ψ_{stem} samples be

taken within an hour of solar noon (when solar elevation is highest), but minimum values are often reached somewhat later when vapor pressure deficit (VPD) is highest (Fig. 3). The timing and duration of the steady-state period are likely strongly influenced by plant water status itself because the response of ψ_{leaf} or ψ_{stem} to VPD depends on how well watered the plant is (Williams and Baeza, 2007). In addition, leaf position on the outside of the

canopy and orientation to the sun may also play a role in the timing and duration of its steady-state transpiration period (Tian and Schreiner, 2021). Therefore, it is recommended that leaves for ψ_{leaf} and ψ_{stem} be sampled between the hours of 1400 and 1600 HR, but this may vary somewhat depending on time zone and/or whether the location is in daylight savings or standard time. Ultimately, best practice is to take repeated measurements

Fig. 3. Diurnal response of midday leaf water potential (ψ_{leaf}) in 'Pinot noir' grapevine before berry ripening (23 July 2020) and during berry ripening (3 Sept. 2020). Data are means $\pm$ 1 SE ($n = 20$). Gray area indicates 95% confidence interval of local smoothing function; 1 MPa = 10 bars.

Fig. 4. Generalized model of the relationship between photosynthetic rate and volumetric water content. The irrigation threshold chosen at 90% maximum predicted photosynthetic rate is shown by the dashed line. Based on research presented by Nambuthiri et al. (2017).

across the midday period within one's system to determine the timing and duration of steady-state values.

For both ψ_{pd} and ψ_{leaf} , leaf samples should be covered with a plastic bag 1 to 2 s before excision from the plant (Williams and Araujo, 2002). However, it is unclear whether this step significantly changes the reading for ψ_{pd} . For example, Turner and Long (1980) show that there were no differences in ψ_{pd} between covered and uncovered leaves of sorghum (*Sorghum bicolor*) and sunflower (*Helianthus annuus*). Nevertheless, it is recommended to always cover the leaf before excision and to keep the leaf covered during pressurization to avoid any pressure-induced heating artifacts (Hsiao, 1990). Furthermore, it is critical to cover the leaf with a plastic bag before excision and during pressurization for ψ_{leaf} measurements, particularly for well-watered plants (Williams, 2017).

Midday stem water potential measurements specifically require enclosing the leaf sample in an opaque bag for at least 10 min before excision and pressurization (Fulton et al., 2001; Levin, 2019). This stops transpiration and allows the ψ_{leaf} to come into equilibrium with that of the stem (Begg and Turner, 1970). This is what gives rise to the somewhat confusing measurement name, even though it also uses leaf samples.

Once the leaf is bagged and excised from the plant, it should be placed into the chamber and pressurized within 30 s (Levin, 2019). The previously cited work demonstrated that samples could be held outside the chamber for up to 60 s with little loss in accuracy, provided they were held in the shade. However, it is impractical to hold samples in the shade considering that measurements must be made in full-sun conditions. Finally, once in the chamber, the sample should be pressurized at a constant rate of $0.025 \text{ MPa}\cdot\text{s}^{-1}$ for maximum accuracy (Naor and Peres, 2001).

LEAF GAS EXCHANGE. Leaf gas exchange can be accurately measured by either an infrared gas analyzer (IRGA) or a porometer. An IRGA measures the concentration of trace gases in an air sample (e.g., CO_2 and H_2O) by detecting the absorption of an emitted IR light source through that sample. Different types of leaf chambers can be attached to a portable IRGA to measure CO_2 and H_2O fluxes from the air that has passed over a leaf surface. When the portable IRGA is paired with a microprocessor, net carbon assimilation (A_{net}) and transpiration (E) are calculated from the mass balance of CO_2 and H_2O between the air entering the sample chamber and the air leaving the chamber (Hunt, 2003). Similarly, a porometer measures

leaf stomatal conductance (g_s) by measuring the difference in relative humidity between incoming and outgoing air. The outgoing air has been enriched with water vapor transpired by the leaf during photosynthesis and is used as a proxy for E . These measurements can then be used to make inferences about the plant physiology and relate A_{net} , E , and g_s rates to other factors, such as soil water content, to inform decisions about irrigation management.

Plant scientists use several commercially available portable IRGAs (Fig. 2B), as well as stationary IRGAs that can be connected to whole-plant chambers and free-air enrichment CO_2 studies (Ainsworth and Long, 2005; Nackley et al., 2018). There has been great development in the commercialization of IRGA for plant science, reducing the size of the devices to equipment that can be carried around to remote locations. However, the expertise needed to operate an IRGA and the cost of these instruments have been noted as limitations to the widespread use of this method for plant physiology-based irrigation (Basiri Jahromi et al., 2020). To reduce the learning curve, detailed peer-reviewed standard operating procedures have been made available to explain the basic methodology (Evans and Santiago, 2014).

TEMPERATURE BASED IRRIGATION. Leaf temperature is inversely proportional with leaf E because the conversion of liquid H_2O into vapor is an endothermic process, absorbing heat energy from the air, resulting in a lower leaf temperature. In agricultural systems, assessing leaf temperature as a proxy for water stress began in the 1960s (Maes and Steppe, 2012) and has recently been popularized because of a proliferation of thermal cameras, infrared thermometers [IRTs (Fig. 2C)], and remote sensing platforms. Many commercial IRTs and thermal cameras are available for plant science, and recently, low-cost do-it-yourself systems have been applied in research and commercial applications (McCauley et al., 2021).

SAP FLOW. Sap flow sensors have been used in many horticultural production systems to provide continuous monitoring of plant transpiration (Nackley et al., 2020; Pearsall et al., 2014; Qiu et al., 2015; Shackel et al., 1992). Sap flow methods calculate the velocity of a short pulse of heat carried

by convection in the transpirational stream (Fig. 2D) (Kirkham, 2014). The velocity of the heat convection is used as a proxy for the plant transpiration rate. The sap flow velocity is diminished when transpiration is reduced—for example, at night and during water-deficit conditions. Therefore, pairing sap flow with environmental measures is an excellent way to optimize irrigation scheduling. For example, sap flow sensors can be correlated with soil moisture levels to determine the soil moisture threshold at which plants close stomata. Similarly, sap flow sensors have been paired with IR thermometers to correlate leaf temperatures with plant transpiration to create a crop water stress index.

CARBON STABLE ISOTOPE RATIO. Of all atmospheric CO₂, 98.9% contains the stable ¹²C isotope, whereas the remaining 1.1% contains the stable ¹³C isotope. Under well-watered conditions, photosynthetic enzymes will favor fixing CO₂ molecules that contain the lighter, more abundant ¹²C isotope (relative to the heavier ¹³C isotope). However, during water deficit, this isotope preference is reduced, and plants will fix a relatively higher proportion of CO₂ the heavier ¹³C isotope. Thus, the C composition of plant tissues that have experienced water deficits will have a relatively higher ratio of ¹³C compared with the atmosphere and can be measured using a mass spectrometer.

Plant water use efficiency (WUE) can be easily calculated at the leaf level by measuring the rate of CO₂ uptake relative to the rate of H₂O loss using an IRGA as described earlier. Fundamentally, the WUE of a plant is a measure of how photosynthesis (which uses CO₂ to build biomass) happens per unit of water lost. Leaf biochemical processes are incredibly dynamic and sensitive to environmental conditions at the time of measurement; therefore, WUE measurements are only useful when considering plant response over short time scales. For integration and understanding of WUE over longer time scales, analyses of stable carbon isotope composition ($\delta^{13}\text{C}$) in numerous plant tissues has proven to be a robust method (Farquhar et al., 1989).

Advantages and disadvantages

Each plant-based method has a slightly different interpretation, and

each has its own unique set of advantages and disadvantages. The following section highlights the advantages and disadvantages of each method in the context of recent literature.

PREDAWN LEAF WATER POTENTIAL. The main cited advantage of ψ_{pd} is the indirect estimate of soil water availability in the root zone (Medrano et al., 2003). Because plants' ψ is assumed to equilibrate with soil ψ overnight and there is no transpiration, these measurements are typically interpreted as an indirect measure of soil ψ . In addition, it is considered to be less sensitive to variable environmental conditions because plants are not transpiring and there is no light at the time of measurement. There have also been some reports that claim it is a more sensitive indicator of plant water status compared with other pressure chamber measurements (i.e., ψ_{leaf} and ψ_{stem}).

The main disadvantage of ψ_{pd} is that it may not accurately reflect soil water availability. This effect is magnified under heterogeneous soil moisture conditions, both in the field and in containers (Améglio et al., 1999). Plants will typically equilibrate with the wettest portion of the soil profile; thus, ψ_{pd} readings tend to underestimate the maximum water deficit experienced by plants during the day. Another disadvantage of ψ_{pd} that is not often presented is that the response signal is smaller compared with other (midday) pressure chamber determinations (described subsequently) (Williams and Trout, 2005). Indeed, the small signal of the ψ_{pd} measurement often falls within or near the gauge accuracy limit. Thus, if one were relying on ψ_{pd} measurements for irrigation management, a separate gauge with a narrowed range of pressures could be used more effectively. Finally, the last disadvantage is simply the inconvenient measurement time (0400 to 0600 HR).

MIDDAY LEAF WATER POTENTIAL. Of the two daytime ψ measurements, midday leaf water potential (ψ_{leaf}) is the most commonly used (Levin 2019). As with any diagnostic measurements, conditions at the time of measurement must be standardized to ensure appropriate interpretation. Nevertheless, ψ_{leaf} measurements provide a robust indication of whole-plant water status (Levin et al., 2020), although they only provide direct information regarding the ψ of a particular leaf sample. Midday leaf

water potential measurements have the main advantage of being quick and easy, with a single measurement requiring 45 to 90 s to complete. In addition, there is a large body of literature across crops and cropping systems that describes various plant physiological responses at various ψ_{leaf} values. For these reasons, ψ_{leaf} remains one of the most widely used plant-based management tools.

The main disadvantages of ψ_{leaf} measurements are the limited measurement time window (≈ 2 h at solar noon), the sensitivity of ψ_{leaf} in general to the environmental conditions during sampling, and the variability among operators. The short time window necessarily limits the number of determinations that can be made during a measurement campaign and is most often a concern of commercial practitioners compared with researchers. For example, a researcher may wish to make many determinations across replicated treatment plots located in a small area to characterize plant response or trigger an irrigation event. This might typically take ≈ 45 to 60 min because treatment plots are often adjacent to one another, and there is little time lost moving from plot to plot. However, a producer may wish to characterize the ψ_{leaf} of whole production blocks in a commercial farm, where fewer measurements are required per block, but the blocks are disparately located.

ψ_{leaf} is highly influenced by changing environmental conditions. Factors such as angle and intensity of light on the leaf or changing wind speed can influence ψ_{leaf} such that more measurements may be necessary to obtain an accurate average value for the measured unit (e.g., plant, plot, or block). In addition, the position of the leaf within the canopy can strongly influence the reading as well, although this may be more of an issue with assessing large plants such as trees. Finally, because instrument operator is often the largest source of error, it is important to have uniform training across all operators and/or designate operators to the same plots, sites, or fields.

MIDDAY STEM WATER POTENTIAL. In general, ψ_{stem} is a sensitive indicator of plant water status (McCutchan and Shackel, 1992), correlates highly to soil water content (Williams and

Trout, 2005) and other measures of plant ψ and gas exchange (Williams and Araujo, 2002), and has a greater ability to discriminate differences among irrigation treatments compared with ψ_{leaf} (Santesteban et al., 2019). Thus, there is increasing acceptance of ψ_{stem} as the preferred determination for plant-based measurements of ψ by both researchers and producers.

One of the primary disadvantages for ψ_{stem} determinations that have been cited is the long equilibration time of prebagged leaf samples (Williams, 2017). Indeed, there has been some disagreement in the literature regarding the length of time required to properly equilibrate the leaf sample for accurate ψ_{stem} determinations. Early studies used leaf samples that were enclosed overnight (Begg and Turner, 1970; McCutchan and Shackel, 1992). Later, Choné et al. (2001) reported no differences in grapevine ψ_{stem} values among equilibration times of 1, 2, and 6 h, thus subsequent studies typically used equilibration times ranging from 1 to 2 h (Naor et al., 2001; Williams and Araujo, 2002). However, Fulton et al. (2001) and recently Levin (2019) demonstrated that 10-min equilibration time was sufficient for ψ_{stem} across several woody perennial fruit crop species [walnut (*Juglans regia*), prune (*Prunus domestica*), almond (*Prunus dulcis*), and grapevine (*Vitis vinifera*)], and Rockwell et al. (2011) found similarly fast equilibration time for red oak (*Quercus rubra*). Furthermore, Hochberg (2020) computed the equilibration time for typical transpiring grapevine leaves to be only 125 s, although those calculations were based on several assumptions, and it is likely that for droughted plants, the equilibration time would be slightly longer. Nevertheless, the literature suggests that 10 min of equilibration time is more than enough for accurate ψ_{stem} determinations, essentially laying to rest the disadvantage of long equilibration time.

GAS EXCHANGE. Fulcher et al. (2012) developed a simple method that uses an IRGA to create irrigation thresholds. In this method, which has been used and modified by other researchers (Basiri Jahromi et al., 2020; Hagen et al., 2014; Nambuthiri et al., 2017), the IRGA is used to measure crop water stress responses by correlating net CO_2 assimilation

over a range of increasingly drier substrate moisture contents (100% to 45% of container capacity). The researchers create water stress conditions by withholding irrigation for ≈ 2 weeks. During the 2-week dry-down period, the researchers use the IRGA to collect midday, single-leaf, gas exchange measurements. To support photosynthetic rates the plant chambers were set equal to maximum ambient light (e.g., $\text{PPFD } 2000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and ambient CO_2 (e.g., 400 ppm). The substrate water content was measured by soil moisture sensors inserted into the pots. The water stress responses were used to establish the irrigation set points. For example, Nambuthiri et al. (2017) set a 10% decrease in maximum photosynthetic rate as the threshold for irrigation (Fig. 4). For boxwood (*Buxus sempervirens*) 10% decrease occurred at $0.28 \text{ cm}\cdot\text{cm}^{-1}$ volumetric water content (VWC), and for deutzia (*Deutzia gracilis*) the irrigation threshold was set to $0.33 \text{ cm}\cdot\text{cm}^{-1}$ VWC (Nambuthiri et al., 2017). The irrigation valves were then programmed to be controlled by the soil moisture sensors that could trigger sprinkler irrigation to refill the container to VWC capacity when the VWC reached the moisture level corresponding to the physiological threshold.

Compared with IRGAs, porometers are significantly less expensive and more portable, thus they may be an attractive tool for users who are only interested in basic gas exchange measurements for survey work and irrigation scheduling. Although they do not directly measure photosynthesis (i.e., A_{net}) like an IRGA, the g_s measurement provided by the porometer remains highly valuable—and easily interpretable. First, from a physiological perspective, g_s is highly correlated to A_{net} (Fig. 5) and has also been shown to be highly correlated to daily plant water use (Williams et al., 2012). Because stomata are highly sensitive to drought, g_s measurements have been used effectively to define threshold values (Lovisolo et al., 2010), and drought response differences across cultivars (Levin et al., 2019).

TEMPERATURE-BASED METHODS. Similar to the IRGA-based irrigation management, leaf temperature-based methods correlate plant physiological responses to decreasing soil moisture. The most common leaf temperature

irrigation methods are based on the crop water stress index (CWSI) concept introduced by Idso and Jackson and others (Idso et al., 1981; Jackson et al., 1988). Simply, the CWSI is a relative comparison of plant canopy temperature to the surrounding ambient air temperature. A lower limit of this ratio is based on “healthy” unstressed plants that transpire at the potential rate for a given evaporative demand. Temperature measurements to build the CWSI are collected during solar noon across a range of increasingly drier substrate moisture contents. The upper limit represents the temperature ratio when a plant is not transpiring (Osroosh et al., 2015). CWSI can be strongly influenced by ambient weather and works best during hot and dry conditions with open skies. Therefore, CWSI is often complemented with soil moisture measurements to assist decision-making for irrigation scheduling rather than as a stand-alone technique for irrigation monitoring (Maes and Steppe, 2012).

The main advantage of temperature-based methods is that they can be scaled up to field-scale and used with remote sensing platforms. This allows a producer to scan entire fields to better understand which sections are over-or under-irrigated, and if possible, address the problem at the ground level using variable-rate irrigation management to improve field/crop uniformity. Moreover, it allows for large acreages to be assessed quickly. By the same token, the main disadvantage with these methods is that at this scale, they may not be dynamic enough for real-time management or decision-making. By the time data are retrieved (from unmanned aerial vehicles, fixed-wing aircraft, or even satellites) and analyzed, the situation on the ground may be quite different. Furthermore, if a producer is not prepared to employ a variable-rate management approach, there may be less utility in such assessments outside of a simple survey of overall field variability.

SAP FLOW. Like all technologies, there are trade-offs when adopting sap flow sensors for research or management. Benefits of sap flow sensors include continuous measurements, noninvasive options, and low-cost options. The great advantage of sap-flow sensors, compared with leaf gas-exchange and ψ measures, is that sap

Fig. 5. Relationship between net carbon assimilation (A_{net}) and stomatal conductance (g_s) in 'Pinot noir' grapevine.

flow can provide continuous measurements that are autonomously collected. This is especially beneficial if a field site is remotely located or difficult to access. In such a situation, the sap flow sensors can be installed, connected to a data-logger, and have data wirelessly transmitted or collected periodically (e.g., weekly or monthly). Other benefits of sap-flow sensors are that they are relatively simple units and can be constructed for a low cost per sensor (Skelton, 2017), allowing for higher levels of replication. Traditionally, sap flow sensors were constructed of needle-like materials that were inserted directly into the sapwood (Granier, 1987). However, new methods are available for noninvasive, external sap flow sensors that can be attached to small diameter and herbaceous plant material (Clearwater et al., 2009; Nackley, 2019).

The main disadvantage of sap flow systems is that they are data and electronically intensive. The continuous nature of sap flow sensing means that a user can potentially have many data points per minute, creating a large data set over a month, seasons, or year. Thus, data management must either be automated or managed by a data analyst. Although this is possible for research scientists, commercial

growers may need to purchase a consumer-grade sap flow system that incorporates analysis or pay for trained consultants to analyze data. An additional downside of sap flow sensors is that data can regularly be lost. The set-it-and-forget-it aspect that is beneficial for remote locations can also create gaps in data if the sensor becomes damaged or dislodged and the problem is not detected quickly. Cloud-based wireless communication can create alerts, but these types of connections may not be available or may be cost-prohibitive.

Finally, sap flow measurements are highly variable among sensors and also among installation locations on a plant. Sap flow measurements require normalization to trunk or stem cross-sectional area to determine total water flux, but this assumes that sap velocity is radially uniform. However, in woody perennial plants, this is not likely the case, as was demonstrated by Pearsall et al. (2014) in grapevine. Pearsall et al. (2014) showed that when five sensors were installed around a mature grapevine trunk, midday velocities differed by 80 to 90 $\text{cm} \cdot \text{h}^{-1}$ among sensors over a 1-week period. Additionally, the researchers showed that sensor signals varied strongly from year to year despite similarities in vine water

use measured with a weighing lysimeter. Nevertheless, individual sensors were all highly correlated with measured water use. Therefore, sap flow sensors may not be reliable tools for accurate absolute measures of plant transpiration—and subsequent water volume replacement with irrigation—but rather can be used to obtain relative estimates of high or low transpiration.

CARBON STABLE ISOTOPE RATIO. Although traditionally used as an integrated marker of WUE in leaves, the $\delta^{13}\text{C}$ of grape must has been recently shown to be highly correlated with overall grapevine physiological function across diverse mesoclimates, soils, and cultivars in California (Brillante et al., 2020). Importantly, the aforementioned work demonstrated that $\delta^{13}\text{C}$ reflected not only plant water status but was also a reasonable predictive proxy of plant nutrient status, photosynthesis, g_s , and fruit quality. It was also related to soil electrical conductivity, a proxy for soil water content. Thus, $\delta^{13}\text{C}$ serves as a reliable indicator of vineyard performance and WUE over the course of the season and can be used to ground truth other sensing technologies.

The main advantages of $\delta^{13}\text{C}$ measurements are that they are inexpensive and easy data to collect. They can be collected a few times of the year and provide a useful integration of the overall water stress experienced by plants over the course of the sampled organ's lifespan (e.g., a leaf or a fruit). The integrated nature of the measurement coupled with its temporal stability is useful for delineating management zones in the field, allowing for the application of variable rate irrigation management techniques. In addition, it can be used as an auditing tool to check on the effectiveness of other irrigation management practices.

The main disadvantages of $\delta^{13}\text{C}$ measurements are that they are not dynamic and as such are not useful for in-season management decisions. Despite their affordability and ease of sample collection, the time from sampling to actionable data is longer than that of typical irrigation cycles (e.g., 1 week). Thus, $\delta^{13}\text{C}$ measurements remain most useful for auditing, planning, and/or zoning.

Conclusions

All of the plant-based irrigation management tools reviewed in this

Table 1. Summary of reviewed plant-based methods including their applications and the advantages and disadvantages for each one.

Method/tool	Overview	Application	Advantages	Disadvantages
Predawn leaf water potential (ψ_{pd})	Pressure chamber measurement of water potential before sunrise when there is little to no transpiration	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Should be highly correlated with soil water content if irrigating to keep soil at field capacity Correlated with leaf and plant physiology Low within-plant and between-operator variability 	<ul style="list-style-type: none"> Must make measurements in the dark before sunrise May not be highly correlated to soil water content if deficit irrigating Small signal across a broad range of soil water content Only provides plant or plot-scale information Discontinuous measurement High within-plant and between-operator variability Measurement time window is limited Only provides plant or plot-scale information Discontinuous measurement Must prebag leaves and wait for equilibration before measurement Prebagged leaves may be hard to locate Measurement time window is limited Only provides plant or plot-scale information Discontinuous measurement Equipment is expensive and more difficult to troubleshoot Measurement time window is limited Variability can be high within and across leaves, as well as across operators Only provides plant or plot-scale information Discontinuous measurement Equipment is expensive and more difficult to troubleshoot Data intensive Highly dependent on ambient temperature conditions Relative measure that requires direct measurement or accurate temperature estimates of well-watered and/or droughted plants, as well as ambient temperature
Midday leaf water potential (ψ_{leaf})	Pressure chamber measurement of water potential at or just after midday when transpiration is at steady state	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Determinations can be made quickly Large signal across a broad range of soil water content Highly correlated with leaf and plant physiology 	
Midday stem water potential (ψ_{stem})	Pressure chamber measurement of water potential at or just after midday when transpiration is at steady state and leaf sample has been prebagged to equilibrate to plant stem	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Low within-plant and between-operator variability Large signal across a broad range of soil water content Highly correlated with leaf and plant physiology 	
Gas exchange [e.g., infrared gas analyzer (IRGA) or porometer]	Measurement of carbon assimilation (IRGA) or stomatal conductance (IRGA or porometer)	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Provides direct information regarding plant physiology with respect to carbon and water relations Gas exchange one of first and most sensitive processes affected by water deficits 	
Canopy or leaf temperature (e.g., crop water stress index)	Measurement of whole-canopy or single leaf temperature using infrared thermometers	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot- or field-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Provides indirect information regarding plant physiology with respect to carbon and water relations Continuous measurement that can be linked with telemetry Can provide field-scale information Can be leveraged by remote sensing platforms 	

(Continued on next page)

Table 1. (Continued)

Method/tool	Overview	Application	Advantages	Disadvantages
Sap flow	Measurement of sap velocity in plant stem using heat pulse	<ul style="list-style-type: none"> Regular (e.g., weekly) monitoring of plants for irrigation management decisions Plot- or field-scale characterization of treatment effects on physiology 	<ul style="list-style-type: none"> Provide direct estimates of plant transpiration Large signal across a broad range of soil water content Continuous measurement that can be linked with telemetry Low-cost per sensor 	<ul style="list-style-type: none"> High sensor-to-sensor variability Sensors are hard to calibrate Data intensive Equipment is expensive and more difficult to troubleshoot Cannot provide accurate values of plant water use due to radial variability in sap flow velocity
Carbon stable isotope ratio ($\delta^{13}\text{C}$)	Measurement of relative abundance of heavier carbon isotopes in plant tissue	<ul style="list-style-type: none"> Plot- or field-scale characterization of treatment effects on physiology Useful for planning and zoning irrigation management decisions and auditing subsequent outcomes 	<ul style="list-style-type: none"> Low-cost per sample analysis Integrative measure of plant stress over a given period of time (depending on tissue age relative to sampling time) Can be leveraged to create zones for variable rate irrigation management Highly correlated to soil water content and other measures of plant physiology 	<ul style="list-style-type: none"> Not a dynamic measurement, thus cannot be used for decision support

article meet the requirements outlined in the introduction: 1) they are sensitive and consistent indicators of plant water status (or proxies thereof), 2) they accurately reflect soil water availability (although some better than others), and 3) they are highly correlated to other physiological processes of importance. However, each tool or method has its own unique set of advantages or disadvantages (summarized in Table 1). As the American economist Thomas Sowell famously said: “There are no solutions, there are only trade-offs; and you try to get the best trade-off you can get, that’s all you can hope for.” In other words, all tools get the job done but in different ways. Some are inexpensive and great for integrated/long-term assessments but are not dynamic enough for real-time management (e.g., $\delta^{13}\text{C}$ or even remotely sensed CWSI), whereas others can provide useful information that can be used for real-time management (e.g., pressure chamber or sap-flow) but are expensive. Thus, the user must carefully weigh each method in the context of their specific objectives and production goals.

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