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Continuous determination of fruit tree water-status by plant-based sensors

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Determinazione in continuo dello stato idrico degli alberi da frutto tramite sensori sulla pianta

Riassunto. Oggi, per supportare con precisione la gestione irrigua, una crescente attenzione è rivolta al monitoraggio in continuo dello stato idrico degli alberi da frutto attraverso sensori localizzati sulla pianta. In questo lavoro sono stati discussi diversi sensori montati su foglie, fusto e frutti per monitorare lo stato idrico della pianta. Ciononostante, una metodologia univoca per la determinazione in continuo dello stato idrico degli alberi da frutto deve ancora essere trovata. Un approccio integrato che prevede l'utilizzo contemporaneo di sensori su diversi organi dell'albero è suggerito come strategia efficace per ottenere informazioni esaurienti sullo stato idrico degli alberi.

Parole chiave: Acqua, foglie, frutti, gestione irrigua, tronco.

Introduction

In recent years climate change has led to shortages of water worldwide, especially in semi-arid and arid regions (Ward and Pulido-Velazquez, 2008; Schewe *et al.*, 2014; Chartzoulakis and Bertaki, 2015; Gosling and Arnell, 2016). As a consequence, water availability for horticultural crops has become a limiting factor (Costa *et al.*, 2007; Stöckle *et al.*, 2011; Snyder, 2017), leading to an increase in management costs and an overall increased number of technologies for increasing water use efficiency. Conventionally, optimal yields are obtained when irrigation allows soil water content to reach levels close to field capacity (FC) (Jones, 2004a), with optimal readily available water (RAW) levels. However, this approach does not match with the global requirement for water saving. Rainfed agriculture partly limits water wastes but it is not always applicable due to climate or horticultural crop limitations, although some temperate C3 crop species such as olive and almond show drought avoidance or tolerance mechanisms (Connor, 2005; Rahemi and Yadollahi, 2005). Nevertheless, the use of mulching has been found to positively influence fruit production and water use efficiency in rainfed areas (Lal Bhardwaj, 2013; Wang *et al.*, 2015) and is considered a sustainable practice in those areas in which irrigation is not feasible. Most of the fruit crops, though, need irrigation supply in order to produce a profitable yield when rain does not satisfy crop water requirement. However, deficit irrigation is a sustainable approach, which may limit water overuse and improve water productivity (Costa *et al.*, 2007; Du *et al.*, 2015; Chai *et al.*, 2016). The two most adopted deficit irrigation strategies are RDI (regulated deficit irrigation), whose name was firstly introduced by Chalmers *et al.* (1986), and partial root-zone drying (PRD), which consists of an alternation of irrigated root sides (Dry *et al.,* 1995; Dry and Loveys, 1998). While RDI was successfully used in several fruit crops, PRD results in some fruit species are controversial and still subject to debate because conflicting results have been found in previous studies, as reported by Mossad *et al.* (2017). Recently, for instance, PRD application in orange trees has been either found to negatively affect fruit size and yield (Faber and Lovatt, 2014) or to maintain similar results when compared to full irrigation (Consoli *et al.*, 2017).

Although rainfed and deficit-irrigated fruit production are extremely helpful strategies to save water worldwide, the use of the latter is not always rational and consistent with the real plant water status. As mentioned above, in the recent years most of the irri-

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gation methods were based on soil water content, but recently the focus has moved to plant responses to water deficit (Jones, 1990; 2004a). Indeed, the main plant physiological indicators of water deficit respond primarily to changes in tissue water content rather than to soil water dynamics (McCutchan and Shackel, 1992; Jones, 2004a; Steppe *et al.*, 2008). Determination of stem water status is a reliable indicator of plant response to water deficit (Kramer 1988; Boyer 1989), while instead root water status provides only partial insights on the whole plant, due to heterogenous water content in drying soils particularly when localized irrigation method is adopted (Jones, 1990). Today, one of the most widely accepted indicators of plant water status is stem water potential (Ψ_{stem}) (Shackel *et al.*, 1997). Nevertheless, the determination of stem water potential is commonly done with a pressure chamber (Scholander *et al.*, 1965), a destructive, time- and labor-consuming method (Zimmermann *et al.*, 2008; Zia *et al.*, 2011) which cannot provide real-time and continuous information on plant water status, thus not allowing the supply of the right amount of water when mostly needed. Measurements of leaf water potential (Ψ_{leaf}) have been proven to be ineffective for irrigation scheduling, due to stomatal control on leaf water status (Bates and Hall, 1981; Jones 1984; Jones 1990). Leaf relative water content (RWC) may be effectively used as a water deficit indicator (Scalisi *et al.*, 2016; Lo Bianco and Scalisi, 2017; Mossad *et al.*, 2017) but it does not provide information on the actual energy status of water in plants (Jones, 2007), as delivered by water potential readings. Also, the use of RWC in highly isohydric species (e.g. cowpea, maize, poplar, etc.) may provide misleading information for irrigation scheduling (Jones, 2004a), because few changes in water status occur due to adaptive stomatal closure under drought.

Alternative approaches might be used for irrigation management. The use of crop evapotranspiration (ET_c), obtained from reference evapotranspiration (ET_0) and crop coefficients (K_c), has become common for irrigation scheduling in several crops (Paço *et al.,* 2006). The ET_c can be easily assessed using the FAO-56 method described by Allen *et al.* (1998). Recently there has been growing interest in two quite different approaches to irrigation management. One relies on broad-scale image analysis of large areas (e.g. satellite, UAVs), while the other allows a more precision-management approach with plant-based sensors. If we accept that the pressure chamber method is not suitable for automated irrigation scheduling (Steppe *et al.*, 2008), other plant-based sensors may be more appropriate for providing the reliable, real-time and continuous plant water status data needed for accurate scheduling of automated, micro-irrigation in fruit crops. Methods that can provide this type of data are very important for efficiently managing modern irrigation systems. Modern drip irrigation systems can be very accurate, precise and efficient at delivering the optimum amount of water to the root-zone of fruit trees to achieve the desired crop production requirements. However, the full potential of drip irrigation can only be achieved with good management decisions that can be made only with good plant water status data. The use of continuous sensing systems allows to determine irrigation requirement at predetermined intervals and/or in real-time with remote data retrieval. Jones (1990, 2004a) has repeatedly emphasized that greater precision in irrigation management is possible with plant stress-sensing methods than with soil-based methods. In this work the main plant-based methods used for plant water status sensing and for irrigation scheduling are discussed. We reviewed leaf, stem and fruit-mounted sensors, whereas roots are not considered as they are less sensitive indicators of water deficit, as reported by Jones (1990). Most of the attention has been directed towards systems which are either already real-time, continuous and remotely controlled, or have the potential to be easily automated. Indeed, today, continuous sensors may be connected straightforwardly to simple and cheap I/O boards (e.g. the open-source single-board microcontrollers ©Arduino), which in turn may be programmed to regulate irrigation levels and timing in response to given water deficit thresholds. However, we should acknowledge the inevitable constraints of plant-based methods which are related to their commonly accepted inability to provide information on the quantity of water to be supplied, when certain thresholds are reached.

Leaf-mounted sensors

Non-destructive and continuous measurement of water status in leaves is difficult due to the intrinsic fragility of these organs. Measurements of RWC and Ψ_{leaf} are relatively easy, but they are destructive and done at set time intervals. Yet, although the data collected can provide insights on the actual status of one leaf, within a multitude of other leaves, that leaves might not be a good representation the entire canopy due to factors such as age, sun exposure, canopy position and others. Nevertheless, scientists have managed to create and test a variety of small leaf-adapted sensors with the aim of collecting valuable information on water dynamics.

Leaf thickness sensors

Variations of leaf thickness over time have long been studied as indicators of water deficit (Bachmann, 1922; Meidner, 1952). Syversten and Levy (1982) measured leaf thickness variations by linear variable displacement transducers (LVDTs) on grapefruit, aiming to find some significant relationships with leaf water potential (Ψ_{leaf}). In their experiment, the authors found a significant correlation between the two indicators over a three-day period (r^2=0.69). Other authors have attempted to determine thickness variations in relation to leaf water status by using LVDTs (Fensom and Donald, 1982; Malone, 1993) or capacitive displacement sensors (McBurney, 1992). Bùrquez (1987) used a gear-wheel type micrometer to measure thickness micro-changes in leaves of rapeseed, bean, impatiens and four o'clock flowers. Leaf thickness had a highly significant correlation with RWC in the four species under study (r^2 between 0.98 and 0.99), in agreement with the results from Meidner (1952). Therefore, thickness changes appear to be best connected with water loss from cells and probably with leaf turgor pressure (Ψ_p), rather than with Ψ_{leaf}. In 1996, Sharon and Bravdo attempted to manage irrigation in citrus through the measurement of leaf thickness by a linear displacement sensing device.

Despite leaf thickness sensors offering a useful approach for continuous monitoring of leaf water content, and possibly leaf water status, most of the available probes cannot be kept on the same leaf for a long time, because they typically damage the leaf's surface after a short time (Zimmermann *et al*., 2008). Also, in young leaves a part of cell shrinkage/enlargement goes in the direction of the leaf axis, while the sensor measures only leaf cross-sectional distance (Jones, 1973). More recently, further displacement sensors were tested for measurements of leaf thickness, although their appropriateness for assessing plant water status is yet to be investigated (Jinwen *et al*., 2009; Hu *et al*., 2013).

Leaf pressure probes

Green and Stanton (1967) first devised a technique to measure plant cell pressure directly by inserting a microscopic capillary, fused at one end and filled with water, into a *Nitella* internodal cell. Cell pressure led to the compression of a bubble in the capillary, which allowed the authors to determine cell turgor with exceptional precision, after small adjustments due to capillarity. Green (1968) used the same instrument to determine turgor pressure for a subsequent derivation of cell extensibility. This method inspired further research papers which adopted similar pressure probes. In 1969, Zimmermann *et al.* developed a pressure probe which was firstly tested in giant algal cells and used afterwards in bladder cells of higher plants (Steudle *et al.*, 1975). Hüsken *et al.* (1978) were able to miniaturize the same sensor and use it in *Capsicum annuum* for the determination of Ψ_p, hydraulic conductivity, and volumetric elastic modulus. Later, in 1990, Balling and Zimmermann used the pressure probe to measure xylem pressure in tobacco plants, and suggested that both turgor and osmotic pressure in subsidiary cells found along the xylem play a key role in maintaining xylem tension at a constant level. A similar type of pressure probe was used by Wei *et al.* (1999) to test the hydraulic architecture model of maize plants. However, despite its wide use in science, the pressure probe technique is not suitable for automation (Zimmermann *et al.*, 2008). In 1979, Heathcote *et al.* used portable instruments to estimate leaf turgor potential from voltage outputs. However, Turner and Sobrado (1983), found no correlation between the output of the instrument and turgor pressure on two *Elianthus spp.*, arguing that the obtained data might be influenced by leaf thickness and large veins. Another non-destructive method to measure cell turgor pressure is the ball tonometer, well described by Lintilhac *et al.* (2000). The authors found a good correlation between this method and the pressure probe mentioned above. Though, also this type of sensor is very difficult to automate in field studies due to its complex and sensitive assembly.

In 2008, Zimmermann *et al.* used a leaf patch clamp pressure (LPCP) probe for the continuous monitoring of leaf water status. This relatively new sensor has caught the attention of many scientists worldwide, for its non-invasive nature and real-time data retrieval through an online platform. The sensor was composed of a piezoresistive Wheatstone bridge mounted on a circular metal pad of a spring clamp. LPCP sensors were tested on chestnut vines (*Tetrastigma voinierianum*) with output readings ranging from 0 to 100 kPa. Sensors were firstly calibrated using a pressure chamber, and subsequently they were attached to leaves and connected to radio transmitters via wires. Data were afterwards sent to a receiving base station and transmitted to an internet server through a GPRS network. Output of LPCP probes with oil-filled capillaries inserted in the abaxial leaf surface were compared with results obtained from the turgor pressure probe and the results were found to be consistent (Zimmermann *et al.*, 1969). Westhoff *et al.* (2009) mounted the pressure sensor chip on a metal pad with a toric magnet, and built a counter pad with a second toric magnet moving along a threaded rod. Data obtained by LPCP probes represent the attenuated pressure of leaf patches (P_p) as a reaction to clamp pressure (P_{clamp}). P_p values might be influenced by temperature (i.e. effects on cell elasticity) or leaf height within the tree canopy. Zimmermann *et al.* (2008) eventually concluded that P_p values are inversely related to cell turgor pressure (P_c), although a certain delay occurs in P_p morning changes compared to P_c, based on leaf height in the canopy. The authors found a delay of 1, 1.5 and 2.5 hours for leaves from 10, 6 and 0.2 m height, respectively, most likely due to different transpiration influences. Ehrenberger *et al.* (2012) found an inverse relationship between P_p and P_c in well turgescent olive leaves, whereas the same P_p response was not observed at low, or near-to-zero P_c values. They also noticed that a reversal of P_p curves occurred towards low turgor pressure values in both laboratory and field conditions (fig. 1). According to the authors, this is likely to be due to a higher volume of air residing within the leaf's spongy mesophyll in leaves experiencing low P_c, compared to turgescent leaves. Therefore, P_c contribution to P_p values is nearly negligible and values mostly reflect the changes in air volume in leaves, although a part of the turgor pressure is restored by nocturnal water uptake. After re-watering, reversed P_p responses are easily resettable and leaf turgor returns to its previous state. Similar reversed responses of P_p to drought were found by other authors in olive trees (Fernández *et al.*, 2011a; Rodriguez-Dominguez *et al.*, 2012; Padilla-Díaz *et al.*, 2016; Marino *et al.*, 2016). So far, LPCP probes have been successfully used to monitor leaf water status in fruit crops such as banana (Zimmermann *et al.*, 2010), grapevine (Rüger *et al.*, 2010), clementine (Ballester *et al.*, 2015) and persimmon (Ballester *et al.*, 2015; Martínez-Gimeno *et al.*, 2017). Nevertheless, the practical application of the LPCP probe for use with irrigation scheduling is still controversial because, unless many sensors are placed in different parts of the canopy, it can provide only partial insights on total plant water status. In this case, the use of a sensor system (Yara International ASA, Oslo, Norway) necessary for accurate monitoring of orchards would most likely be too costly for most smallholder farm managers. Also, most of the studies have been conducted in a tough-leaved species such as olive, suggesting prolonged use of sensors on fruit crops with soft leaves might damage leaf tissue and alter P_p readings (fig. 2).

Leaf thermal sensing

Measurements of canopy temperature (T_c) as an index of water stress can be carried out by thermal imaging both at ground level and from above the crop (e.g. towers, unmanned aerial vehicles (UAVs), planes, satellites, etc.) (Fernández *et al.*, 2017). The application of thermography or infra-red thermometry and the resulting T_c have been related to leaf stomatal

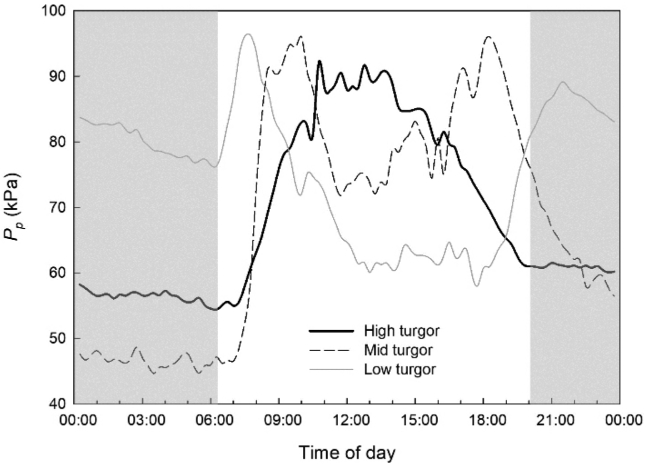

Fig. 1 - Diel curves of attenuated pressure (P_p) of leaf patch clamp pressure probes in olive leaves at high, mid (half-inverted curve) and low turgor (fully-inverted) states.

Fig. 1 - Curve giornaliere di pressione attenuata (Pp) dei sensori LPCP in foglie di olivo in stato di elevato, medio (curva parzialmente invertita) e basso turgore (curva totalmente invertita).

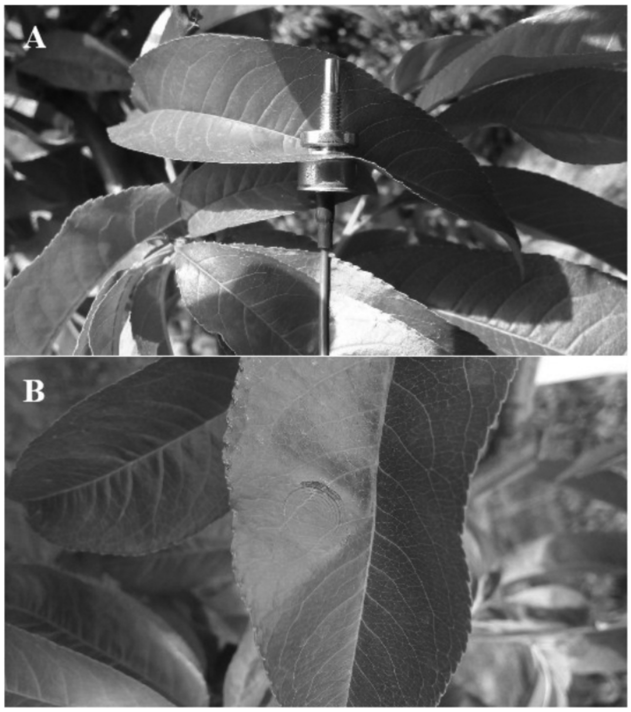

Fig. 2 - Leaf patch clamp pressure probe mounted on a 'September Bright' nectarine leaf (A) and mark left on the leaf after a three-day measurement period (B).

Fig. 2 - Sensore LPCP montato su una foglia di nettarina 'September Bright' (A) e marchio lasciato sulla foglia dopo un periodo di misurazione di tre giorni (B).

aperture (Jones, 2004b; Jones and Schofield, 2008; Lima *et al.*, 2016; Park *et al.*, 2017) and to Ψ_{stem} (Park *et al.*, 2017). However continuous measurements of plant water status by UAVs or planes are not currently achievable and satellite images often have low resolution. In order to get more accurate data on the response of each plant to water stress, leaf thermal sensors might represent a better solution. In 2012, Atherton *et al.* developed a microfabricated thermal sensor for the assessment of water content in leaves. This device is composed of a thin-film resistive heater and two thin-film thermocouple temperature sensors patterned on a 10μm thick polyimide substrate. The thermal sensor was clamped to pak choi and lettuce leaves, and provided results about the overall thermal resistance of the leaf. When the device's output (ΔT) was compared to RWC, a positive, linear correlation was found. Despite the device being suitable for automation and for continuous data collection, it has not been tested on smaller leaves of fruit trees. In addition, as highlighted in the introductory section, RWC is not the most appropriate indicator for irrigation scheduling.

Stem-mounted sensors

Water status in fruit plants is a complex response to climatic conditions and water availability in the soil (Reicosky *et al.*, 1975). Stems and shoots are the bridges that establish the driving force between these two factors. Thus, continuous measurements of stem water status by non-destructive sensors provide insights not only on the variations of soil water availability but also on the reserves of plant tissues.

Stem dendrometers

Diel changes in stem diameter are indirectly caused by the aperture/closure mechanism of stomata, which respond both to air temperatures and vapor pressure deficit (VPD), and soil water availability. While seasonal changes in stem and shoot diameter are a result of plant growth and changes in tissue reserves (Kozlowski and Winget, 1964), diurnal changes are caused by plant tissue hydration (Simonneau *et al.*, 1993). Trees with a C3 photosynthetic metabolism usually shrink during the day and swell at night (fig. 3). However, CAM plants show an inverse behavior due to their nocturnal stomatal opening (Scalisi *et al.*, 2016) (fig. 3). During the day, as xylem water potential becomes more negative, a radial diffusion of water from bark tissues into the xylem occurs (Parlange *et al.*, 1975). In the late afternoon, plant water uptake exceeds water loss by transpiration and there is a recovery in xylem water potential. This leads to a reversal in the radial flow of water from the xylem back to the phloem. Thus, xylem water potential is the driving force for diurnal stem trunk diameter variation (Klepper *et al.,* 1971; Whitehead and Jarvis, 1981; Sevanto et al., 2011). The magnitude of stem shrinkage is dependent on the elastic modulus (Génard et al. 2001) and diffusive water properties of phloem tissues (Parlange *et al.*, 1975). The magnitude of stem diameter changes is also affected by differences in osmotic pressure between bark and xylem (Cochard *et al.*, 2001), by the reflection coefficient to solutes (Génard *et al.*, 2001) and by stem growth rates (McBurney and Costigan 1982). Stem diameter variations provide several water stress indicators for irrigation management, such as maximum and minimum daily stem diameters, maximum daily shrinkage, daily recovery, daily growth, stem growth rate, cumulative growth and early daily shrinkage, as summarized by Fernández (2017). As for other continuous methods, good data interpretation is crucial to allow the sensors to be used for accurate irrigation scheduling (Fernández and Cuevas, 2010; Fernández *et al.*, 2014). Stem diameter variations have been effectively related to plant water content in peach (Simonneau *et al.*, 1992). Fereres and Goldhamer (2015) found a weak relationship between changes in stem diameter and Ψ_{stem}., whereas Intrigliolo and Castel proposed a phenology-dependent relationship between Ψ_{stem} and maximum daily stem shrinkage in plum (2004) and grapevine (2007).

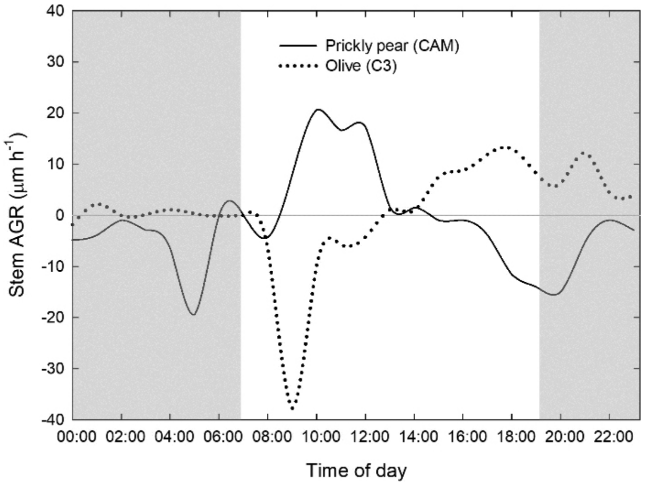

Fig. 3 - Diel stem absolute growth rate (AGR) in 1-year-old prickly pear (CAM metabolism) and olive (C3 metabolism) plants.

Fig. 3 - Andamento giornaliero del tasso di crescita assoluta (AGR) in un cladodio di fico d'India (metabolismo CAM) e in un fusto di olivo, entrambe piante aventi un anno di età.

Fernández and Cuevas (2010) published an exhaustive review on the use of stem diameter variations as a tool for irrigation management in many fruit crops. Measuring stem/shoot diameter variations is relatively easy and the use of reliable and cheap dendrometers makes this method easily accessible for fruit growers as an irrigation management tool (Goldhamer and Fereres 2001). Nevertheless, stem diameter variations often do not reveal useful information on fruit and leaf status and their use is not extremely reliable in young plants, as the effect of organ growth might cause misleading results.

Sap flow probes

Sap flow probes have been widely used for the determination of transpired water in fruit trees, and several methods can be applied for the quantification of sap flow related indexes. All the available methods use heat as the main component of water flow determinations. The methods include stem heat balance (SHB), trunk sector heat balance, heat dissipation, heat field deformation, Cohen's heat-pulse, Green's heat pulse velocity (HPV), heat radio, SapFlow+ and transient thermal dissipation. These technologies are exhaustively described on the website of the Working Group on Sap Flow of the International Society for Horticultural Science, in the paper of main methods (http://www.ishs.org/sites/default/files/documents/methods_0.pdf).

Field data based on diurnal patterns of transpiration through continuous stem flow measurements were reported by Sakuratani (1987), using the SHB method described by Sakuratani (1981). Today, one of the most used methods takes into account the use of thermal dissipation probes (Granier, 1985), whose efficacy depends on some factors such as xylem thermal dissipation and tree size, as described in the review paper published by Lu *et al.* (2004). Heat pulse velocity methods were recently reviewed by Forester (2017).

The compensation heat pulse (CHP) method (Swanson, 1962) has been successfully tested on species such as olives and pistachios, providing more accurate results than other sap-flow methods even with limitation under reduced transpiration rates (i.e. night, high humidity and cloudy conditions) (Swanson and Whitfield, 1981; Green *et al.*, 2003; Steppe *et al.,* 2010). Testi and Villalobos (2009) built a new calibration that not only allow measurements at low transpiration rates but also assesses the sensor performance along usage. Additional errors may arise during the installation of the probes. Lopez-Bernal *et al.* (2017) developed a single-probe heat pulse method for estimating sap velocity. These probes were tested on several plant species and generated similar results to CHP method, with the advantage of being simpler and causing less damage to plants. Furthermore, in 2017 Miner *et al.* developed affordable and simple probes based on the heat pulse theory. The latter can be fabricated by a 3D printer and connected to an ©Arduino board for data acquisition. Despite these probes show some limitations for low or very high sap flow rate determination, they are a good option when a large number of probes is needed.

In 1999, Nadezhdina associated apple plant water status with sap flow measurements, by matching Ψ_{leaf} with HPV and sap flow index (SFI). Sap flow measurements were also associated with other Ψ_{stem} in lemon (Ortuno *et al.*, 2006) and olive (Fernández *et al.*, 2011b), among others.

The changes in sap flow indicators are highly affected by stomatal aperture; however, transpiration responses are driven by other factors such as air VPD (fig. 4). Despite sap flow measurements being highly suitable for irrigation automation (Jones, 2004a), the appropriateness of the probes for estimating the correct threshold of plant water status is questionable. The use of sap flow probes is therefore suggested in combination with other sensors on the plant, in order to obtain enough information on tree water status.

Additional sensors

A number of other interesting stem-mounted sensors have been studied for their appropriateness for continuous plant water status determination. McBurney and Costigan (1982), and Dixon and Tyree (1984) obtained continuous Ψ_{stem} data by using a stem-mounted hygrometer, which yielded results concordant with those obtained with a pressure chamber. However, these devices are known to be unreliable

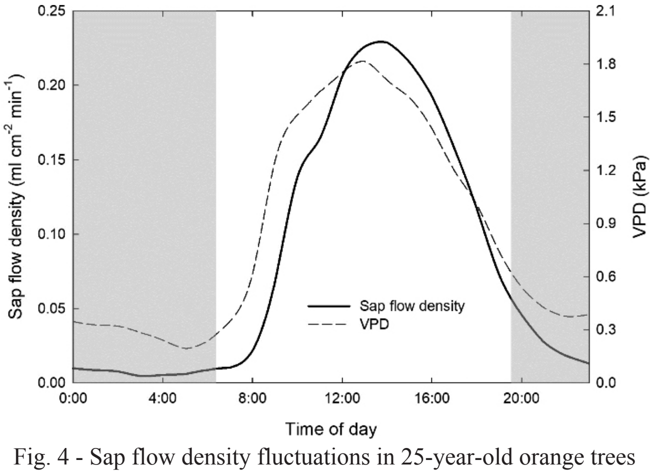

Fig. 4 - Sap flow density fluctuations in 25-year-old orange trees and vapor pressure deficit (VPD) variations over 24 hours in spring.

Fig. 4 - Andamento giornaliero della densità di flusso linfatico in alberi di arancio di 25 anni e variazioni del deficit di pressione di vapore (VPD) nell'arco di 24 ore in primavera

(Jones, 2004a). Meron *et al.* (2015) recently tested an osmometric stem water potential sensor on tangerine and peach stems. The sensor is based on the fluid-to-fluid contact osmometer principle, rather than well-known psychrometry of the vapor phase. Sensor outputs were found to be highly related with pressure chamber Ψ_{stem} results, although delayed in time. Finally, a recent patent of a stem-embedded microtensiometer has been released by Stroock *et al.* (2014). Although non-destructive and relatively easy to install, this method is still in the development phase.

Fruit-mounted sensors

Optimum water supply is extremely important for horticultural commercial yield, and it water makes up around 90% of the harvest weight of most fruit crops (Schroeder and Wieland, 1956). In different studies, it has been demonstrated that fruit water relations have key implication on production and quality (Cuartero and Fernandez-Munoz, 1999; Johnson et al., 1992; Mitchell et al., 1991). Fruit volume is the overall balance of water inflows and outflows from phloem and xylem, as well as from atmosphere through skin exchanges. The latter is a highly complex system and depends on many factors (Lang, 1989).

Whilst presenting a very intuitive way to measure fruit growth patterns, the different sensors ranging from LVDTs, strain-gauges, potentiometers and/or optoelectric sensors, still have many constraints due to the nature of the fruit and to its relation to overall tree water content.

In 1996 Gherard and Huguet developed a model to calculate the fruit water content during the monocarp development stage on peach. Based on earlier research on in-out fluid flow of fruit, the model assumed that the flow into the fruit increases with fruit weight and diameter and decreases with maximum daily shrinkage of the trunk, which was used as an indicator of water stress. Fruit transpiration plays a huge role in increasing fruit size as does radiation and other environmental factors (Lang and Thorpe, 1989). Almost all the work in literature links fruit relative water content to volume/size changes. Due to the nature of fruit and their sensitivity, it is very difficult to estimate the plant water content based solely on fruit water content (Lang and Thorpe, 1989). However, different studies have shown how custom-built fruit growth sensors can be used for the overall plant water status determination (Jones and Higgs, 1982; Ho *et al.*, 1987; Berger and Selles, 1993; Morandi *et al.*, 2007a; Thalheimer, 2016). In 1989, using Archimedes' principle, Lang and Thorpe studied the water balance between xylem and phloem in berry fruits. The procedure was easy to perform and needed only common laboratory equipment and a modern electronic scale. They measured the volume increases of fruit by immersing it completely in water. Although the data was influenced by air movement and winds, it responded to a greater extent to other influences like air temperature, water content, evaporation and fruit surface tension. Changes in fruit diameter have been commonly studied with non-destructive equipment such as calipers, although they require intensive work and they are non-continuous (Higgs and Jones 1984). Klepper *et al.* (1971) started using LVDTs to continuously measure stem diameters, while Beedlow *et al.* (1986) designed a strain gauge (dendrometer) to detect changes in stem size through deformation of an attached metal. LVDTs were developed for precision and continuous measurement of stem diameter and they are commonly composed of the sensing part, a frame and data logging unit.

Lang (1989) used LVDTs to measure apple fruit growth. In order to be less sensitive to air and wind movement, hot glue was applied on two sides of the apple where the sensor touched the fruit. In addition, the whole system was covered with aluminum foil to obtain a thermal equilibrium, and to protect the fruit from rain as osmotic water uptake through the skin of the fruit would modify results that assume only xylem, phloem and transpiration exchanges have taken place. The sensor then interfaced to data logging equipment to record data at specific intervals. Subsequently, signals in millivolts can be converted to micrometers (Link et al. 1998). LVDTs and/or strain-gauges have a <10μm accuracy to estimate diameter changes. Volume change (volume growth) can be calculated using the elliptical equation (Yuan and Sun 1994) or an easier perfect sphere equation of the fruit (Hamilton 1929). Different supporting frames have been tested. Primarily, LVDTs or strain-gauges (dendrometers) were used. Although very accurate, these sensors are relatively expensive, taking into consideration that a large number of sensors is needed, both for research or orchard management (Morandi *et al.*, 2007). Morandi *et al.* (2007) worked on a low-cost frame to be built around the LVDT. It was composed of a light-stainless steel frame that reinforces the sensor (a 50 kOhm linear potentiometer) and attaches it to the fruit and to the tree (fig. 5). Sensors' mV outputs can be easily converted to fruit diameter, absolute growth rate (AGR) and relative growth rate (RGR) (fig. 6). The fruit gauges were used to study vascular flows in peach (Morandi *et al.*,

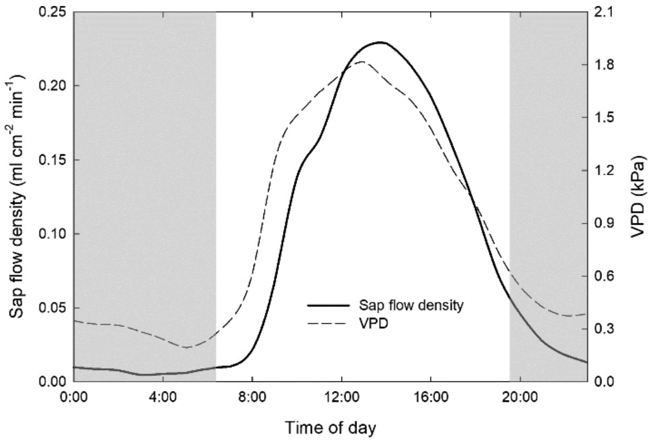

Fig. 5 - Fruit gauge mounted on an olive drupe at its growth stage III (A) and on a nectarine fruit at its growth stage I (B).
Fig. 5 - Fruttometro montato su un'oliva nel suo stadio di crescita III (A) e su una nettarina nel suo stadio di crescita I (B).

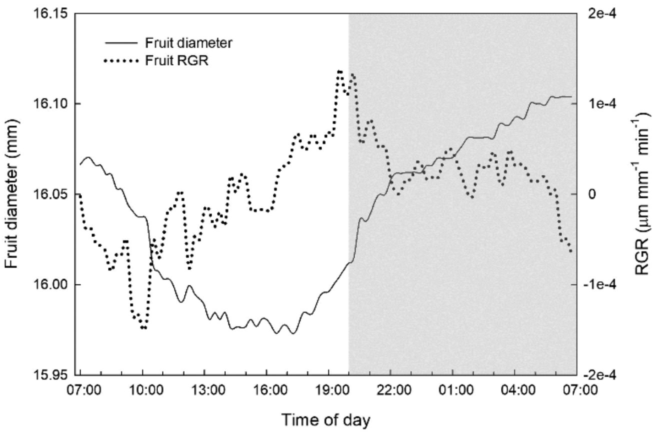

Fig. 6 - Diel fruit diameter and relative growth rate (RGR) variations in an olive drupe at its growth stage III.
Fig. 6 - Variazioni giornaliere di diametro del frutto e tasso di crescita relativo (RGR) in un'oliva al suo stadio di crescita III.

2007b), kiwifruit (Morandi *et al.*, 2010) and pear (Morandi *et al.*, 2014). In 2016, Thalheimer described another method for monitoring radial fruit growth, based on ow-cost optoelectronic sensors. The reflective sensor detects the movement of flexible tape with black and white bars which correspond to logic state, and the microcontroller assigns the values to upper or lower thresholds. Despite having a relatively low cost, this technique is not suitable for water status detection, as the sensor is only able to detect fruit enlargement and not shrinkage.

Despite the fact that the measurement of fruit water status and fruit growth dynamics under different irrigation strategies might be crucial in order to increase water use efficiency, maintain yield and/or improve fruit quality, assessing stem water potential through fruit attached sensors is usually not practical. Therefore, continuous fruit diameter sensors can be a powerful tool if their output is supported by other continuous data on leaves and/or on stem water status indicators.

Conclusions

One of the biggest challenges for scientists and farmers to increase water use efficiency worldwide is to develop and understand better sensors and methods for measuring plant water status to use for irrigation scheduling. Indeed, there is not a single best method for plant water status determination that can be universally applied (Jones, 2007). This paper presents a subjective classification of the relevance or usefulness of the different sensors that are available (tab. 1).

A more integrated approach, which takes into consideration the contemporary use of sensors mounted

Tab. 1 Authors' subjective relevance of sensors discussed in this paper for each plant water indicator. Scale from 1 to 5, where 1= poor relevance, and 5= high relevance.
Tab. 1 - Classificazione soggettiva dell'importanza di utilizzo dei sensori discussi in questo lavoro per stimare diversi indicatori dell'acqua nella pianta. Scala da 1 a 5, dove 1=scarsa rilevanza, e 5 = alta rilevanza.

Sensor type	Plant water indicators							
	Ψ_{stem}	Ψ_{leaf}	Ψ_{fruit}	Ψ_{p}	Leaf RWC	Fruit RWC	g_s	E
Leaf thickness sensors	1	2	1	4	5	1	2	2
Leaf pressure probes	2	3	1	5	4	1	2	1
Leaf thermal probes	1	2	1	3	5	1	2	2
Stem dendrometers	3	1	1	1	1	1	4	4
Sap flow probes	2	1	2	2	1	1	4	5
Stem hygrometers	4	1	1	1	1	1	2	2
Stem microtensiometers	5	1	1	1	1	1	2	2
Fruit diameter sensors	2	1	3	1	1	5	1	1

Ψ_{stem} = stem water potential; Ψ_{leaf} = leaf water potential; Ψ_{fruit} = fruit water potential; Ψ_{p} = leaf turgor pressure; RWC = relative water content; g_s = leaf stomatal conductance; E = transpiration.

on several plant organs is suggested in future studies in order to collect integrative information on plant water status. The development of a plant water model which provides real-time information on water indicators based on continuous sensors outputs is certainly a future challenge for scientists, farmers and entrepreneurs who aim to an efficient total automation of irrigation in horticulture.

Abstract

Recently, climate change has caused shortages of water worldwide, especially in semi-arid and arid regions. Several irrigation strategies have been studied with the aim of saving water overuse in agriculture. In the past most of the attention was directed towards soil water content, but recently the focus has moved to plant responses to water deficit. In recent years, crop evapotranspiration (ET_c) obtained from reference evapotranspiration (ET_0) and crop coefficients (K_c), has become common for irrigation scheduling in several crops, but it does not provide precise insights on the tree water status. Today an increasing focus is being given to plant-based sensors for the continuous monitoring of plant water status to provide support to irrigation management strategies with a precision approach. In this work several plant-based (leaf, stem and fruit) devices used for plant water status sensing and for irrigation scheduling are reviewed. Scientists have managed to create and test a variety of small leaf-adapted sensors with the aim of collecting valuable information on water dynamics. Non-destructive continuous water status detection in leaves is difficult due to the intrinsic fragility of these organs. Yet, the data collected can provide insights on the actual status of one leaf, within a multitude of other leaves which might have a slightly different behavior because of factors such as age, sun exposure, canopy position and others. Leaf thickness sensors, leaf pressure and leaf thermal probes are discussed in this review. Stems and shoots establish the connection between climatic conditions and water availability in the soil. Continuous measurements of stem water status by non-destructive sensors provide information not only on the variations of soil water availability but also on the reserves of plant tissues. The use of stem dendrometers, sap flow probes, stem hygrometers and stem microtensiometers for continuous determination of plant water status and irrigation management is discussed. Moreover, it has been demonstrated that fruit water relations have key implication on horticultural production and quality. Measurements of fruit water status and fruit growth dynamics under different irrigation strategies might be crucial in order to reduce water use, maintain yield and/or improve fruit quality. Advantages and disadvantages of different sensors ranging from linear variable displacement transducers (LVDTs), strain-gauges, potentiometers and/or optoelectric sensors, are discussed. However, a unique methodology for continuous plant water status determination in fruit trees has yet to be found. An integrated approach, which considers contemporary use of sensors on different plant organs is proposed as effective strategy to collect exhaustive information on tree water status.

Key words: fruit, irrigation management, leaf, probes, stem.

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