A microtensiometer sensor to continuously monitor stem water potentials in woody plants – design and field testing

A.N. Lakso[1,a], S. Zhu[2], M. Santiago[3], K. Shackel[4], V. Volkov[4] and A.D. Stroock[2]

[1]Horticulture Section, Cornell AgriTech, Geneva, NY, USA; [2]School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY, USA; [3]FloraPulse Co., Davis, CA, USA; [4]Department of Plant Science, University of California, Davis, CA, USA.

Abstract

Water is one of the most critical limitations to growth, productivity, fruit or nut quality and profitability in fruit and nut crops. Irrigation is a large user of water resources, thus optimizing the management of water resources is also critical. Directly measuring plant response to soil water, weather and irrigation is the key to optimal water management. To do so, we have developed and tested an electronic, large-range, continuous-reading water potential sensor for embedding in the trunks of woody plants to monitor stem water potentials. The sensor is a microelectromechanical system (MEMS)-based microtensiometer that can measure plant stem water potential continuously with a high degree of precision. The sensor chip has the same principle as the common soil tensiometer, but with a much smaller volume and 100-200 times greater range. Its advantages include unprecedented range of detection, low power consumption, small size, low potential cost due to micromanufacture and ease of integration into sensor networks. The sensor chip is integrated with associated data handling, logging and wireless transmission for online monitoring. Challenges include optimizing installation and insulation methods and materials; learning how different species and varieties react to the embedded sensor and scaling up production for consistency and lowering cost. The microtensiometer has been field tested in potted and field-grown apple, grape and almond. Current designs and methods have given very good long-term results with high correlations to stem potentials by pressure chamber in multiple crops with good installation sensor-tissue contact. The ability to monitor plant stress with the microtensiometer will be a valuable tool for precision irrigation programs, research, and modeling. Scalable microtensiometer arrays in conjunction with wireless networks and remote sensing offers the potential to provide continuous, high-resolution data to optimize irrigation and water resource management for sustainable crop production.

Keywords: stem water potential, sensor, fruit crops, nut crops, irrigation, drought stress

INTRODUCTION

Crop water status is well known to be a crucial determinant of growth, productivity and product composition (Steduto et al., 2012). Irrigation timing and amount is often based on model estimates of crop water use, or use of soil moisture measurements, both of which are indirect estimates of the water status of the crop. In fruit and nut crops the crop structure, the extensive but low-density root systems and high plant hydraulic resistance means that the crop water status is strongly dependent on dynamic evaporative demand (via VPD and stomatal conductance) as well as soil water status (Landsberg and Jones, 1981; Jones et al., 1985; Deloire et al., 2004; Shackel, 2007, 2011). The root clumping of such heterogeneous root systems reduces effective soil water resources and has been estimated to increase soil hydraulic resistance (Jones and Tardieu, 1998; Tardieu et al., 1992), and is likely to lead to localized drying under mid-day transpiration. Additionally, with fruit crops other factors not

---

[a]E-mail: anl2@cornell.edu

Acta Hortic. 1335. ISHS 2022. DOI 10.17660/ActaHortic.2022.1335.39
Proc. IX Int. Symp. on Irrigation of Horticultural Crops
Eds.: C. Xiloyannis et al.

directly related to water status, such as crop load and canopy management, can affect stomatal conductance, transpiration and water potential (Naor, 2006).

Unlike most crops, tree and vine crops can have periods that require some controlled water deficit stress for optimal yield, product quality or management such as reduced canopy growth in grapevines or improved harvest of almonds (Goldhamer et al., 2006; Van Leeuwen et al., 2010; Fereres et al., 2012). This requires fine maintenance of moderate stresses while avoiding the detrimental effects of either too much water or too much stress.

The difficulty for practical management of fruit crops was summed up by Naor (2006) as the *"Grower's Dilemma. In commercial orchards, there is a wide diversity of combinations of cultivars, rootstocks, training systems, crop loads, potential fruit sizes, and irrigation efficiencies…"* Every unique combination can lead to different irrigation requirements and soil monitoring is questionable in deep root systems especially in variable soils. Integrating all of the external factors that affect plant water status with varying physiological factors is difficult.

Consequently, the solution is to allow the plants to integrate their environment and physiology, then measure the resulting water status directly. Fruit and nut growers need tools to more easily directly monitor the integrated plant water status to be able to determine: (1) the level and dynamic changes of water deficit stress over time, and (2) whether their irrigation reaches a target water status for a desired growth, fruit quality or improved management.

The only current practical, rugged method to directly estimate plant stress in the commercial field is the estimation of leaf or stem water potential by the manual Scholander pressure chamber (Turner, 1988). It is a good direct measurement but it is a point measure, manual, slow and significant operator error can occur in selection of tissue and measurement procedures. It can be used to estimate the water potential of exposed leaves. Also if the leaf is stopped from transpiring by enclosing in dark bag, then it equilibrates with the stem water potential. Measured pre-dawn when there is little to no transpiration, it is considered to estimate the effective soil water potential of the root system. Leaf and stem potentials have been compared and found to generally well correlated though there may be conditions and times of the day where they differ (Chone et al., 2001; Naor, 2006; Shackel 2007, 2011; van Leeuwen et al., 2010; Williams, 2017). Although all measures are useful, our experience agrees with many that mid-day stem potential is the best integrator of tree or vine water status, especially in non-irrigated fields with variable soils (Patakas et al., 2005; Naor, 2006; van Leeuwen et al., 2010).

A major limitation to the pressure chamber use in the field is that plant water status is only measured at infrequent intervals. Yet, tree and vine water potentials vary dynamically with the current weather as well as with soil moisture. To adequately measure such a dynamic system requires continuous or high frequency measurement. Given these limitations of existing techniques to measure water potential in soils and plants, we feel that an internal stem potential sensor in trunks or large branches is the best option. Similar to Fernandez (2014), we can identify the following characteristics of an ideal sensor:

- capable of direct measurement of vine water potential;
- accurate (0.01 MPa or better) and stable over the full physiologically relevant range of vine water potential (0 to -3 MPa or lower);
- produces continuous, real time measurements over months to years;
- simple to install and operate with minimal sensitivity to temperature variations and contaminants;
- as small as possible to allow precise spatial measurements and to minimize disruption of tissue upon embedding;
- reasonable cost to manufacture and deploy; many sensors may be needed to resolve spatial variations;
- compatible with wireless networks for real-time data collection and spatial integration.

Description of sensor

Recent developments in the A. Stroock laboratory at Cornell University in the field of microfluidics have opened the opportunity to manipulate water in a manner that mimics that in plants (Wheeler and Stroock, 2008). Based on this development, appropriate microfluidic structures were incorporated into a microelectromechanical system (MEMS) to create a miniaturized tensiometer (Pagay et al., 2014) that has the same principle as the classic soil tensiometer. The sensor chip, a sandwich of silicon and glass has an extremely small water volume, about 5-10 nanoliters and a tiny piezoresistive pressure transducer. The exchange surface to the environment is made of porosified silicon with pores of only a few nanometers that provide a potential range of water potentials to below -10 MPa. The exposed edge of the chip slightly extends to contact the xylem (see photo left) where it directly exchanges water with the adjacent vessels.

The 5×5 mm microtensiometer sensor chip is housed in a cylindrical protective probe that is currently 8 mm in diameter with associated electronics embedded. It meets critical targets identified above: it operates over an extended range of water potentials of more than 5 MPa covering the entire useful range in plants, and is small enough for direct embedding within the xylem tissue of plant stems.

Challenges include engineering the sensor and probe for long-term continuous measurement with excellent protection of the electronics while allowing interaction with the environment in the plant; optimizing efficient installation and insulation methods and materials to ensure continued good contact with the tissue in a growing stem; and especially learning how different species and varieties react to the embedded sensor.

Field testing

Initial field tests began at Cornell in the summer of 2016 by embedding the sensor probe in apples and grapevines with a simple procedure: a radial hole was drilled in the trunk to a depth slightly deeper than the length of the probe, rinsed with water, the probe inserted to give a tight fit, silicone caulk was applied to seal around the insertion and probe wires, and the trunk insulated to reduce temperature variations (Figure 1). The sensor output was recorded at one-minute intervals with Campbell dataloggers (Campbell Scientific, Logan, Utah, USA). Since then, many refinements have been made in the sensor, the probe configuration and materials, installation methods and sensor packaging. A cellular wireless communication system has been developed as well as a user interface to display the data stream though the system is readily compatible with other IoT systems.

Figure 1. The sensor probe installed with support sleeve in an apple tree prior to sealing and insulation. The probe also houses the associate electronics.

Tests in the past three growing seasons have been done with potted and field apple trees and grapevines at Cornell University in New York (A. Lakso, S. Zhu and A. Stroock) and with potted and field almonds and grapevines in California (M. Santiago, K. Shackel and V. Volkov) at the University of California, Davis and in commercial plantings in California in collaboration with E&J Gallo Winery, Chimney Rock Winery, Matchbook Vineyards and DoneAgain Farms. The sensor readings were correlated to the standard bagged-leaf pressure chamber readings of stem potential in each case. Data presented here are from university trials.

RESULTS AND DISCUSSION

An initial question was how quickly the sensor could begin providing acceptable stem potential readings after installation. Over many installations we found that the sensor could give reasonable readings within a few hours after a successful installation though in some cases it appeared to take several days. The sensor and plant interaction does not appear to require tissue growth to incorporate the sensor.

There is a general correlation between daily patterns of temperature and VPD and the sensor reading although there is a large hysteresis. This is expected since temperature and VPD affect transpiration and stem potentials. However, when holding the sensor in constant temperature water or examining the results on days with variable radiation or unusual environmental pattern, the sensor has a very slight temperature response.

The sensor response in a field apple tree to partly cloudy conditions followed by a short, heavy rainfall and overcast was quite rapid (Figure 2). In the same trial under partly cloudy conditions with very rapid changes in radiation, the bagged-leaf measurements were somewhat more responsive to rapid changes (1-3 min) in radiation when clouds passed than was the sensor. Although the sensor chip was found in lab tests to respond within minutes to large changes in water potential, the factors controlling responsiveness of the chip in the probe inside the vine xylem was not clear.

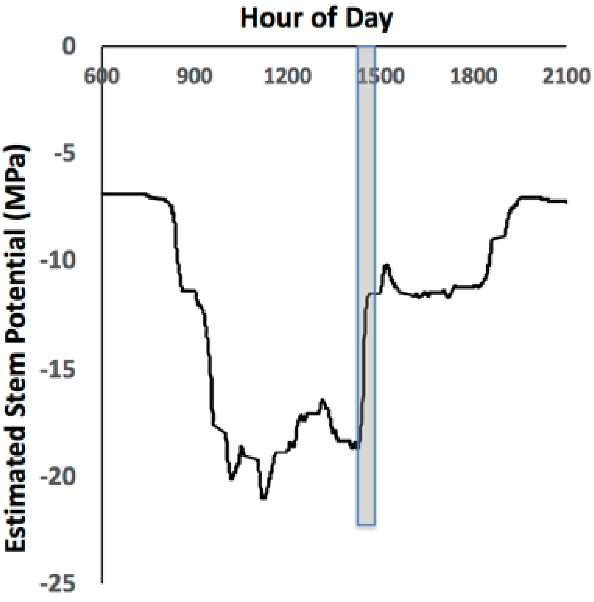

Figure 2. Sensor monitoring of apple stem potential on a day with partly cloudy morning, then a 20-min period of rain (gray bar) followed by overcast.

An example of microtensiometer data in an almond tree and in a grapevine in 2018 in Davis, California shows the expected diurnal pattern of potentials with maxima near dawn and mid-day minima in mid-afternoon (Figure 3). Similar results were found in grapevines (Figure 4).

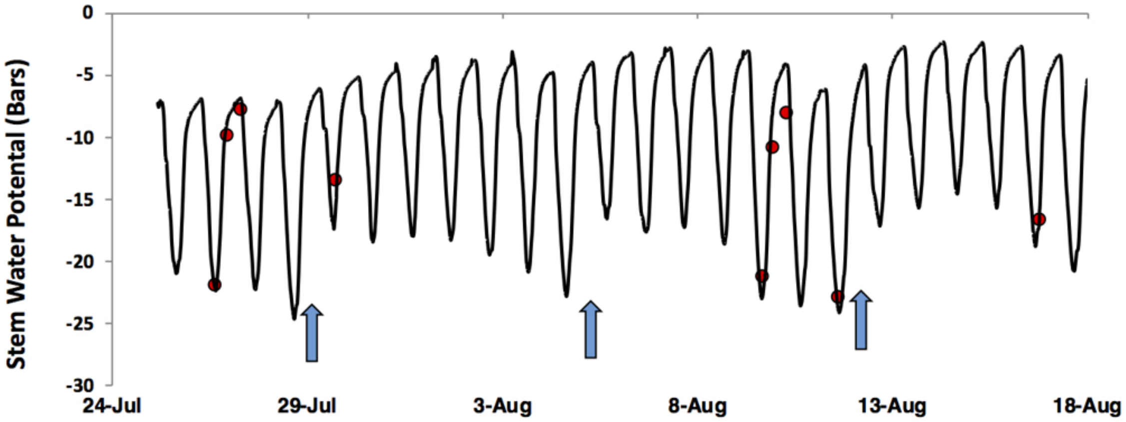

Figure 3. An example of the continuous stem potential measurements with the microtensiometer in an almond tree in California with concurrent pressure chamber stem potential readings (dots). Sensor installation made by M. Santiago and pressure chamber data from K. Shackel and V. Volkov.

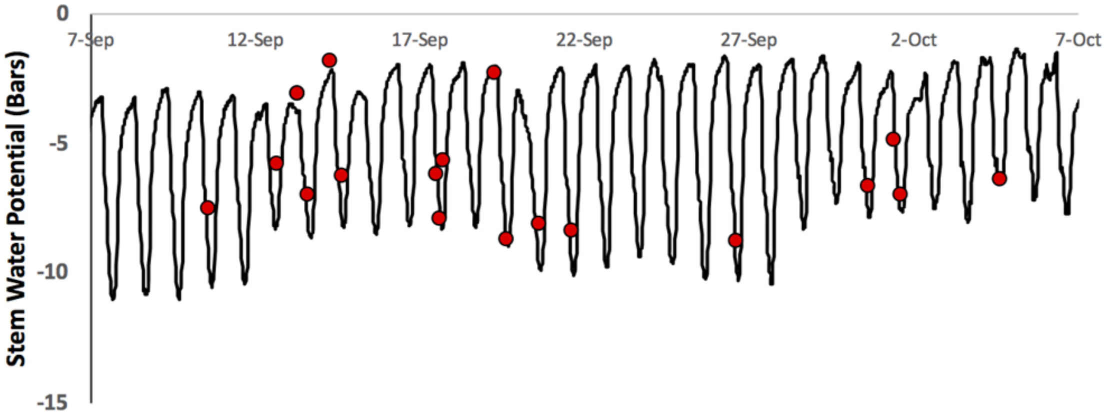

Figure 4. An example of the continuous stem potential measurements with the microtensiometer in a grapevine in California with concurrent pressure chamber stem potential readings (dots). A direct field calibration of the sensor was made with the first two pressure chamber readings after installation. The box labels show data values on the graph on the web. Sensor installation made by M. Santiago and pressure chamber data from K. Shackel and V. Volkov.

In each installation the estimated stem potentials from the sensor were compared to pressure chamber estimates of stem potential with bagged leaves on the same plants. The correlations between sensor and pressure chamber methods (Figure 5) show good to excellent relationships. Generally, the highest correlations occur with pre-dawn or early morning and mid-day data. Data taken mid-morning or late afternoon or during partly cloudy conditions with rapid changes in potentials tend to give lower correlations. Trunk capacitance and the speed of water potential gradient propagation inside the trunk tissues are not known, but we have observed that responses from the exterior of the canopies tend to be faster. However, for any practical water management purposes the responsiveness of the sensor was certainly fast enough.

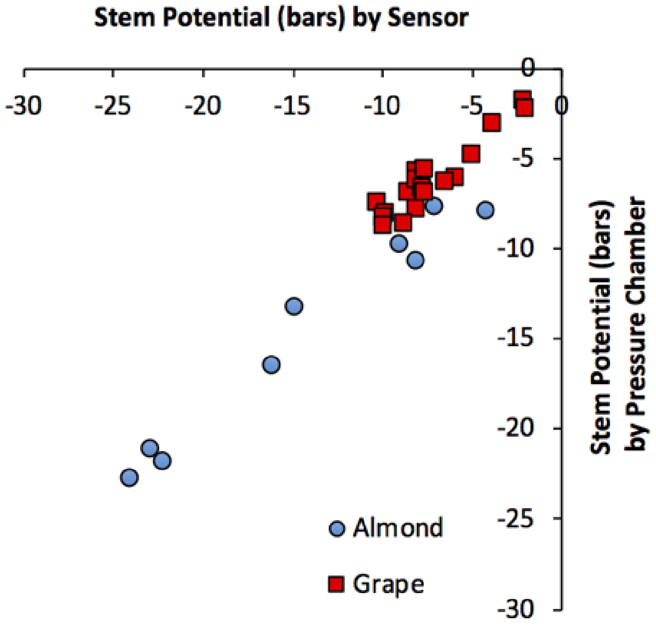

Figure 5. Correlation of stem potentials estimated by the microtensiometer sensor versus the pressure chamber in almond and grape, from the data in Figures 3 and 4.

Not every sensor installment during development has given excellent results. Some installations have lost the sensor-tissue contact and cavitated relatively soon after installing. Others worked well for weeks, then cavitated. Currently, the sensor chip prototypes are made in small batches in academic clean rooms and are inherently more variable than from commercial MEMS foundries. As discussed above there are engineering, materials and plant-sensor interaction challenges, but one that is particularly difficult is the maintaining good sensor contact with a wet biological material that has internal pressure cycles of stem shrinking and swelling and changes in physical properties of the xylem with growth over the season. However, the long-term performance has improved with each refinement in the crops.

These field test results have shown that accurate, continuous monitoring of tree fruit, nut and grapevine stem potentials is feasible with a new microtensiometer embedded in the vine or tree trunk. The microtensiometer probe, with associated electronics is being further developed and tested and wireless data transmission and web monitoring capability has been added. In addition to use in irrigation, the small sensor provides many opportunities for field research in plant water relations such as detailed measurement of hydraulic gradients. With increasing use of remote sensing, direct stem potential measurements will be important to integrate and ground-truth the remote sensing intended to estimate crop water status.

For full disclosure, the sensor is being developed for commercial application by a company, FloraPulse Co. (www.florapulse.com) developed by the inventors A. Lakso, A. Stroock and M. Santiago as co-founders of FloraPulse Co.

ACKNOWLEDGEMENTS

We would like to acknowledge the contributions of Vinay Pagay and Richard Piccioni in sensor design, embedding issues and field data handling, and Justin Fontes in probe engineering. Additionally, we acknowledge grant funding from USDA Engineering Products and Processes program, USDA and NSF Small Business Innovation grants, and American Vineyard Foundation as well as base funding from Cornell University and the University of California, Davis.

Literature cited

Chone, X., Van Leeuwen, C., Dubordieu, D., and Gaudillere, J.P. (2001). Stem water potential is a sensitive integrator of grapevine water status. Ann. Bot. *87* (*4*), 477–483 https://doi.org/10.1006/anbo.2000.1361.

Deloire, A., Carbonneau A., Wang, Z., and Ojeda, H. (2004). Vine and water – a short review. J. Int. Sci. Vigne Vin. (Oeno-One) *38*, 1–13 https://doi.org/10.20870/oeno-one.2004.38.1.932.

Fereres, E., Goldhamer, D.A., and Sadras, V.O. (2012). Yield Response to Water of Fruit Trees and Vines. In FAO Irrigation & Drainage Paper 66, P. Steduto, T.C. Hsiao, E. Fereres, and D. Raes, eds. (Rome: FAO), p.246–295. https://doi.org/10.1017/s0014479712001366

Fernández, J.E. (2014). Plant-based sensing to monitor water stress, applicability to commercial orchards. Agric. Water Manage. *142*, 99–109 https://doi.org/10.1016/j.agwat.2014.04.017.

Goldhamer, D.A., Viveros, M., and Salinas, M. (2006). Regulated deficit irrigation in almonds: effects of variations in applied water and stress timing on yield and yield components. Irrig. Sci. *24* (*2*), 101–114 https://doi.org/10.1007/s00271-005-0014-8.

Jones, H.G., and Tardieu, F. (1998). Modelling water relations in horticultural crops. Sci. Hortic. (Amsterdam) *74* (*1-2*), 21–46 https://doi.org/10.1016/S0304-4238(98)00081-8.

Jones, H.G., Lakso, A.N., and Syvertsen, J.P. (1985). Physiological control of water status in temperate and subtropical fruit trees. Hortic. Rev. (Am. Soc. Hortic. Sci.) *7*, 301–344 https://doi.org/10.1002/9781118060735.ch7.

Landsberg, J.J., and Jones, H.G. (1981). Apple Orchards. In Water deficits and plant growth, T.T. Kozlowski, ed. (New York: Academic Press), p.419–469. https://doi.org/10.1016/b978-0-12-424156-5.50012-3

Naor, A. (2006). Irrigation scheduling and evaluation of tree water status in deciduous orchards. Hortic. Rev. (Am. Soc. Hortic. Sci.) *32*, 111–165 https://doi.org/10.1002/9780470767986.ch3.

Pagay, V., Santiago, M., Sessoms, D.A., Huber, E.J., Vincent, O., Pharkya, A., Corso, T.N., Lakso, A.N., and Stroock, A.D. (2014). A microtensiometer capable of measuring water potentials below -10 MPa. Lab Chip *14* (*15*), 2806–2817 https://doi.org/10.1039/C4LC00342J. PubMed

Patakas, A., Noitsakis, B., and Chouzouri, A. (2005). Optimization of irrigation water use in grapevines using the relationship between transpiration and plant water status. Agric. Ecosyst. Environ. *106* (*2-3*), 253–259 https://doi.org/10.1016/j.agee.2004.10.013.

Shackel, K.A. (2007). Water relations of woody perennial plant species. J. Int. Sci. Vigne Vin. (Oeno-One) *41*, 121–129. https://doi.org/10.20870/oeno-one.2007.41.3.847.

Shackel, K.A. (2011). A plant-based approach to deficit irrigation in trees and vines. HortScience *46* (*2*), 173–177 https://doi.org/10.21273/HORTSCI.46.2.173.

Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D., eds. (2012). Crop Yield Response to Water. FAO Irrigation & Drainage Paper 66 (Rome: United Nations). 10.1017/s0014479712001366

Tardieu, F., Bruckler, L., and Lafolie, F. (1992). Root clumping may affect the root water potential and the resistance to soil-root water transport. Plant Soil *140* (*2*), 291–301 https://doi.org/10.1007/BF00010606.

Turner, N.C. (1988). Measurement of plant water status by the pressure chamber technique. Irrig. Sci. *9* (*4*), 289–308 https://doi.org/10.1007/BF00296704.

Van Leeuwen, C., Pieri, P., and Vivin, P. (2010). Comparison of Three Operational Tools for the Assessment of Vine Water Status: Stem Water Potential, Carbon Isotope Discrimination Measured on Grape Sugar and Water Balance. In Methodologies and Results in Grapevine Research, S. Delrot, et al, eds. (Dordrecht: Springer), p.87–106. https://doi.org/10.1007/978-90-481-9283-0_7

Wheeler, T.D., and Stroock, A.D. (2008). The transpiration of water at negative pressures in a synthetic tree. Nature *455* (*7210*), 208–212 https://doi.org/10.1038/nature07226. PubMed

Williams, L.E. (2017). Physiological tools to assess vine water status for use in vineyard irrigation management: review and update. Acta Hortic. *1157*, 151–166 https://doi.org/10.17660/ActaHortic.2017.1157.24.