Sap-Flow Sensors for Small-Diameter Nursery Seedlings

Lloyd L. Nackley

Assistant Professor, Nursery Production, Horticulture Department,
North Willamette Research and Extension Center, Oregon State University, Aurora, OR

Abstract

Sensors can be used to improve irrigation management decisions in nurseries. Optimizing irrigation efficiency aims to apply sufficient water for growth while reducing excessive leaching to reduce costs and environmental pollution. Pairing soil moisture sensors with plant sensors enables irrigation managers to quantify the volume of water to be applied that will directly affect crop productivity. Sap-flow sensors are considered a potential tool for irrigation management because they provide a real-time method to measure how plants respond to above- and belowground environments. This report provides detailed methods to build an external sap-flow sensor that can be used on small-diameter nursery seedlings and discusses how sap-flow sensors can be utilized with nursery seedlings to provide information about plant physiology, improve irrigation scheduling, and monitor outplanting success. This article will be useful to researchers and growers who previously associated sap-flow sensors only with large diameter trees by describing the opportunities for applying sap-flow methodology to small-diameter nursery plants. This paper was presented at the Joint Annual Meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers Association (Coeur d'Alene, ID, October 25-26, 2018).

Introduction

Most greenhouse production systems grow plants in inert, well-drained soilless media, and apply pelletized or liquid fertilizer to deliver essential plant nutrients. In these conditions, water and nutrients are regularly flushed past the root zone when scheduled irrigations exceed plant demands. Leaching the container is important to prevent excessive salt build up. Nutrient-laden runoff from greenhouse production systems can, however, create significant environmental ground- and surface-water pollution. In addition to generating pollution, flushing nutrients also results in significant lost costs in terms of wasted fertilizer and wasted water. Irrigation best management practices for nursery plant production attempts to maximize irrigation efficiency and to minimize leaching and associated loss of nutrients (Yeager et al. 2010). Research has shown that reducing fertilization rates would likely have a substantial impact on both cost savings from reduced fertilizer use and an environmental benefit from reduced nutrient leaching, particularly from greenhouse and container nursery production, and, to a lesser degree, field nursery production (Majsztrik et al. 2018). In many locations, the expense of watering is primarily related to energy costs associated with diesel or electric pumps. Additionally, fertilizer represents one of the more expensive materials used in plant production (Ingram et al. 2016). Too little water can kill a crop; too much water wastes energy and fertilizer and can promote fungal pathogens (Dumroese and Haase 2018). Optimizing irrigation efficiency aims to apply sufficient water for growth while reducing excessive leaching to reduce costs and environmental pollution.

Sensors can be an important tool to improve irrigation management decisions (Lea-Cox et al. 2013). Soil moisture sensors (SMS) are commonly used in field and row crop production settings and can also be modified for greenhouse production systems. Some SMS measure the soil moisture tension, while others measure the volumetric water content of the soil. The merits of these different types of measurements have been debated (Jones, 2007). One common aspect for all SMS is that the moisture information is independent of the plant responses. The implications are notable, considering that the lack of necessary information on plant responses to soil moisture is one of the major causes of inefficient irrigation application (Marin et al. 2016). Thus, using SMS is only half the solution.

Pairing SMS with plant sensors enables irrigation managers to quantify the water volume to be applied that will directly affect crop productivity. The combined plant-soil moisture measures can provide information about the moisture thresholds where plants do not suffer drought stress and irrigators do not excessively leach nutrients. Sap-flow measurement is considered a potential tool for irrigation management as it is a parameter indicative of the interactions between the amount of water available in the growing medium and the atmospheric water demand. Unlike other tools for measuring plant water status, such as leaf gas exchange or plant water potential, sap-flow sensors can be cheaply constructed, provide continuous data, and are non-destructive.

Methods for measuring sap flow were pioneered nearly 100 years ago by Huber and colleagues in the 1930s (Clearwater et al. 2009, Skelton 2017). The modified Huber method, now known known as Heat Pulse Velocity (HPV), calculates the velocity of a short pulse of heat carried by convection in the transpirational stream. The basic premise of HPV is that a short pulse of heat (1 to 6 sec) is released into the sap stream, and sapwood temperature is monitored at points upstream and downstream from the heater (Kirkham, 2014). Sap flow may already be familiar to foresters because some manner of this technique has been used in many studies of tree responses to drought and climate in mature timber stands (Simonin et al. 2007, Vanclay 2009). For example, sap-flow methods have been used to investigate how transpiration is affected by air turbulence near plantation edges, firebreaks, and streamlines, and how hydrology in mixed stands differs from hydrology in monocultures (Vanclay 2009). Alternatively, sap-flow methods have been used to identify differences in stand-level evapotranspiration (Simonin et al. 2007). These types of plot- or forest-scale investigations dominate the forestry sap-flow literature. While the theoretical underpinnings of forest-level sap-flow measurements are the same, the methods used for large trees are wholly inappropriate for seedlings in forestry nurseries. In particular, measuring sap flow on large, woody species involves inserting metal needles into the sapwood. This technique would critically damage vascular tissue and potentially destroy young nursery plants. Fortunately, non-destructive methods for sap flow have been developed for horticulture that are effective for small-diameter stems.

Sap-Flow Sensors for Nursery and Field Applications

The external sap-flow sensors we use on nursery seedlings were inspired by a system developed for measuring the pedicles of fruits (Clearwater et al. 2009). Commercially produced external sap-flow gauges may be purchased from a supplier. On the other hand, if you can solder, constructing your own sensor is relatively easy with some basic electronic supplies and parts from a hardware store (figure 1). The following is a description of the method we used to build sap-flow sensors.

Figure 1. Using basic supplies, growers and researchers can construct sap-flow sensors for small-diameter plants. This model is not described in detail but shows how growers can modify the design. For this sensor, we added Velcro® to attach to the stem, used thermistors instead of thermocouples, and used a pile resistor in place of the chip resistor. (Photo by Lloyd Nackley)

1. Create thermocouple
    a. Strip 5 mm of insulation from each wire 0.05-mm type T thermocouple wire and form the junction of the thermocouple twisting the two wires together; apply solder to make a reliable connection. Trim the soldered junction with a pair of snips to minimize the length of the junction to approximately 1 mm.
2. Assemble resistor chip
    a. Strip 2 to 3 mm of insulation from 30 AWG (American wire gauge) wire, twisting a small loop in the end, and tinning the wire so that the loop is filled with solder. Note that the loop should not be wider than the width of the chip resistor.
    b. Secure a chip resistor with cross-locking tweezers so that the contacts on the bottom of the resistor are accessible.
    c. To complete the joint, hold the loop of the tinned wire against the bottom surface of the solder point on the resistor and applied heat with a soldering iron. Repeat this step for the other wire. The wires should not extend past the top surface of the resistor, as this is the part of the resistor that will be in direct contact with the plant stem once installed.
3. Install the connector to the heating resistor (figure 2)
    a. Strip approximately 3 mm of insulation from each wire and solder the wires to the two pins for the connector. When the pins are cool to the touch, press each pin into the plastic housing of the connector until the pin clipped into place. To test that wires are locked, gently pull on each wire.
4. Mount heating resistor and thermocouples
    a. Tape the resistor and thermocouples to the 13-mm foam block insulation (figure 3) and mark the locations of the resistor and thermocouples with a fine tip marker, making sure not to dent the foam with the marker.
    b. Place the resistor against the foam with the face up and pressed lightly to make an indentation for the chip resistor.
    c. Route the thermocouple wires around the top and bottom of the foam block. Additional tape can then be added to hold the two wires for the resistor against the face of the foam block.

Sensor Data Analysis

Our analysis method (figure 4) examined temperature variation (ΔT_h) values measured at 10 and 90 seconds after the heat pulse and 100 and 180 seconds after the end of the heat pulse using the equation below.

$$\Delta T_h = \frac{(T_{90} - T_{10}) + (T_{180} - T_{100})}{2}$$

Where:

ΔT_h = Temperature changes in the plant during the pulse

ΔT_{10} = Temperature measured by the sensor at 10 seconds after the start of the pulse

ΔT_{90} = Temperature measured by the sensor at 90 seconds after the start of the pulse

ΔT_{100} = Temperature measured by the sensor at 100 seconds after the end of the pulse

ΔT_{180} = Temperature measured by the sensor at 180 seconds after the end of the pulse

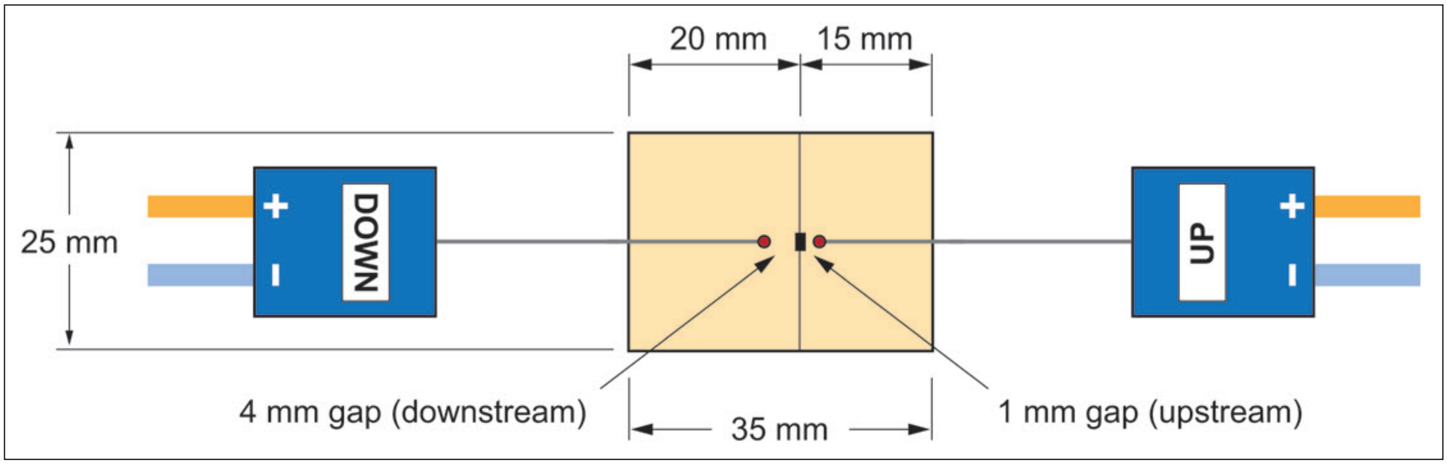

Figure 2. Schematic of the sap-flow sensor design. The foam block is represented by the square in the middle. The thermocouples are represented by the small circles and are spaced at 4 mm and 1 mm away from the small resistor chip (small black rectangle).

Figure 3. Sap-flow sensor constructed using foam insulation rather than a cork. The sensor is attached to an elderberry seedling (*Sambucus nigra* L.). The measurable sap flow is relative to the leaf area downstream (i.e., above) the sensor. Therefore, sensors should be located low on the seedling, or near to the main stem if placed on a lateral branch. (Photo by Lloyd Nackley)

The actual output of the sensor (Λ) was determined as:

$$\Lambda = 1 - \frac{\Delta T_h}{\Delta T_h^0}$$

Where:

Λ = Sensor signal (dimensionless)

$\Lambda T_h{}^0$ = Temperature range measured by the sensor installed in the plant at zero flow condition

ΛT_h = Temperature range measured by the sensor installed in the plant in one point in time during the day

Assuming a linear relationship between the signal measured by the sensor and the plant's sap flow, the amount of sap flow can be estimated as:

$$J = k.\Lambda$$

Where:

J = Sap flow density, in $m^3\ s^{-1}\ m^{-2}$

k = Coefficient on the basis of the thermal properties of the stem and the sap (diffusivity and thermal capacity), and the sensor geometry.

Application of Sap-Flow Sensors

Pairing sap-flow sensors with SMS has a number of promising applications in a forestry nursery setting. Three research areas that offer significant opportunity are: deficit irrigation scheduling, native plant ecophysiology, and outplanting performance evaluation.

Centuries of cultivation have made clear distinctions between wild-type and agricultural plant species. Over countless generations, the genetic variability of particularly prized plants has been reduced in favor of desirable traits such as flower size and color. In recent decades, seeds and cuttings of wild-type native plants have also been collected for propagation in nursery and greenhouse production facilities. Yet, the cultivation requirements for many native species remain largely unknown. People often incorrectly assume that cultivating native plants will be easy since native plants do not require human intervention to regenerate in natural conditions. Unlike commercially selected cultivars whose genetic profiles have been narrowed to emphasize specific traits, however, the horticultural needs of native plants can be obscured by genotypic and phenotypic plasticity. Natural selection processes like frost, flood, and fire have bred variability into the cultural requirements for wild-type native plants. Unpredictable growth habits of native plants can frustrate novice and experienced growers with failed attempts to propagate rare and endemic species,

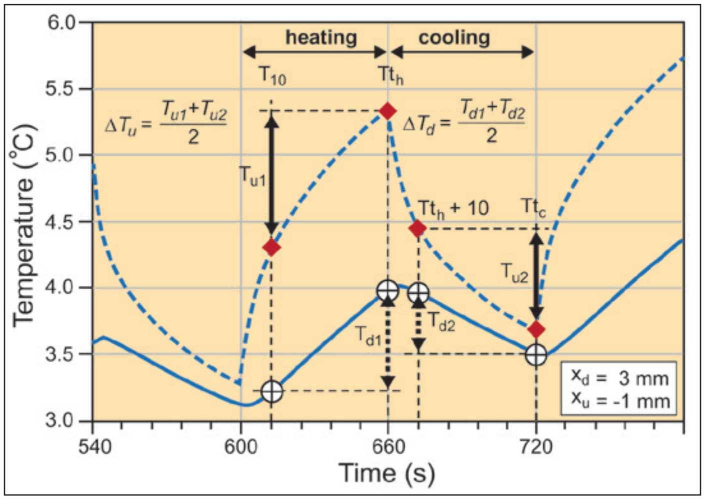

Figure 4. With the heat pulse method, temperatures, upstream (Xu) and downstream (Xd) of the heating resistor are measured by thermocouples. The (ΔTh) values are measured at 10, 90, 100, and 180 seconds after the start of heating supply. The heat pulse is evidenced by the wave form thermal signature.

stalled development following germination, and high mortality after outplanting in recently disturbed restoration conditions. The need for greater understanding of the optimal environmental conditions necessary for producing native plant nursery stock is ecologically important now because endemic species from isolated populations face increasing threats from catastrophic exogenous disturbance.

Pairing SMS with sap-flow sensors can provide a real-time method for examining how native plants respond to above- and belowground environments. Sap flow of small plants are more responsive to environmental cues compared to large trees that have stored water reserves and may experience considerable (i.e., hourly or daily) lags in sap-flow signals (Čermák et al. 2007). Linking SMS with sap-flow sensors allows researchers to measure the plant's transpirational pulse that is driven by the atmosphere and restricted by the rhizosphere. Taking the pulse of native plant species during nursery production provides fundamental insights about variability within a species and among populations from different regions. In ecology, location is sometimes used as a proxy for function. For instance, when a species expresses different morphological characteristics along a precipitation gradient, dry-side varieties have been considered discrete populations from wet-side varieties (Nackley et al. 2018). Concerns with this method suggest that ecotype comparisons are rarely conducted for a long enough time for long-lived species, and that the genetic basis of local adaptation and genetic associations with climate has rarely been identified (Galliart et al. 2019). Adding sensors to a nursery production system can elucidate if phenotypic differences between ecotypes are correlated with physiological differences. More specifically, sensor data can help determine if source material collected across a latitudinal (or precipitation) range needs to be cultivated differently, or if growers can apply the same irrigation to all plants within the same species, even between sub-species.

Pairing sap flow with SMS is an excellent way to optimize irrigation scheduling. Typically, growers tend to overwater in nursery production (Lea-Cox et al. 2013) because the direct consequences of under-watered plants are more immediate than the indirect consequences of overwatered plants, such as nutrient leaching and fostering conditions for moisture-loving pathogens (Dumroese and Haase 2018). Sap flow can be used to determine the safe threshold for deficit irrigation in two ways. First, this method can be used to determine the soil moisture level at which plants close stomata. This threshold would represent when irrigation should be turned back on. Growers could pair sap-flow techniques with gravimetric measures of soil water content to learn at what moisture contents (i.e., weights) plants stop transpiring. Gravimetric techniques for scheduling irrigation have previously been shown to be simple and effective (Dumroese et al. 2015). When plant stress is appropriately linked to soil moisture status, monitoring soil moisture becomes a suitable proxy that can be used to schedule irrigation to maximize water-use efficiency. Secondly, drought research can determine at what point after this low-moisture threshold is reached a plant can revive when re-irrigated. This point is also known as the permanent wilting point. The physiological consequences of deficit irrigation depend on the duration of the drought. Obviously, prolonged drought will kill a plant. Yet, less devastating effects include reduced leaf expansion and growth rate, and increased water-use efficiency and root-to-shoot ratio. Deficit-irrigated plants are comparably shorter than well-watered plants with smaller leaves or fewer leaves, or both (Hsiao 1973, Villar-Salvador et al. 2013). Deficit-irrigation strategies can be used as a form of moderate drought conditioning, which is a technique that has increased stress tolerance and seedling survival in semi-arid environments (Villar-Salvador et al. 2013). Sap-flow sensors can be invaluable in drought conditioning during which drought intensity and duration should be considered. In addition, the levels of stress applied should be species specific (Vallejo et al. 2012). Lastly, drought-induced smaller, thicker leaves may be less attractive to foliage-eating insects and herbivores.

Investigations of seedling physiology with sap-flow sensors highlights the components of the Target Plant Concept (TPC) that put an emphasis on seedling quality, which is measured by outplanting performance (Dumroese et al. 2016). Water stress is commonplace in afforestation, reforestation, and restoration sites where nursery seedlings are typically expected to survive without supplemental irrigation. The timing and degree of drought will dictate whether stocktype choice, deep planting, or adequate root growth will compensate for the low water potential conditions in the upper soil profile (Vallejo et al. 2012, Pinto et al. 2016). Water stress occurs when plant leaf and stem evapotranspiration rates exceed water absorption by the roots. Water stress impairs plant processes and may cause vascular embolisms that can kill the seedling (McDowell et al. 2008). Revegetation in droughty environments prioritizes plant water conservation through site modifications such as micro-catchments for "run-off harvesting," mulching (Vallejo et al. 2012), temporary shade structures, and nurse planting (Badano et al. 2011). Soil moisture readings can be taken concurrently with plant metrics to develop a relationship between plant physiology and soil moisture status.

Investigating outplanting success of nursery-grown seedlings is another opportunity for pairing SMS with sap flow. In research and non-research contexts, binary plant survival monitoring, (e.g., "dead or alive") is commonly used to assess outplanting success. Although survival monitoring is better than no monitoring, it provides limited information about critical environmental gradients by conflating various environmental stresses. It is these same gradients and stressors that foresters and restoration ecologists can take advantage of to adaptively manage restoration projects and improve upon in future designs (Badano et al. 2011, Vallejo et al. 2012). For revegetation to succeed, it is imperative to describe the restored environment in terms of the factors that pertain to long-term plant growth, survival, and reproduction. The TPC calls for a strong a nursery-client partnership for circular feedback evaluation, generating more realistic expectations by both parties throughout the plant material ordering, production, and outplanting process (Dumroese et al. 2016). Pairing plant and soil moisture sensors can provide new insights about how moisture stress affects outplanting success, thereby providing greater clarity in the feedback evaluation for nursery growers.

This report is not an assertion that sap-flow is the only, or even the best, method for measuring plant moisture responses. It is, however, an under-utilized tool for growers, foresters, and ecologists working with small-diameter plants. Applying low-cost, data-intensive tools like sap-flow sensors to the production and revegetation system can help take the guesswork out of correlating environmental factors with plant performance. The methodologies described here provide a framework by which practitioners may consider physiological plant monitoring when working with stressful environments. Within this framework, installing plants appropriate to the region, ecosystem, and most importantly, project goals is required to prevent unnecessary plant death (Dumroese et al. 2016). Without installing plants suited to local conditions—plants whose physiological performance is matched to the site's potential performance—no amount of stress consideration or mensuration can help build a successful project.

Address correspondence to—

Lloyd Nackley, Oregon State University, North Willamette Research and Extension Center, 15210 NE Miley Road, Aurora, OR 97002; email: lloyd.nackley@oregonstate.edu; phone: 971–801–0385.

Acknowledgments

The author thanks: Robert Skelton for introducing me to the Clearwater method; Galen Wolf for innovating our design-build process, and Elias Fernandez de Sousa for technical and analytical advice; Lorence Oki for providing physical and mental space for the development of our methods; and Bruno Pitton and Jared Sisneroz for providing a sounding board through the design-build process.

REFERENCES

Badano, E.I.; Samour-Nieva, O.R.; Flores, J. 2011. Emulating nurse plants to restore oak forests. Ecological Engineering. 37: 1244–1248.

Cermák, J.; Kucera, J.; Bauerle, W.L.; Phillips, N.; Hinckley, T.M. 2007. Tree water storage and its diurnal dynamics related to sap flow and changes in stem volume in old-growth Douglas-fir trees. Tree Physiology. 27: 181–198.

Clearwater, M.J.; Luo, Z.; Mazzeo, M.; Dichio, B. 2009. An external heat pulse method for measurement of sap flow through fruit pedicels, leaf petioles and other small-diameter stems. Plant, Cell, and Environment. 32: 1652–1663.

Dumroese, R.K.; Haase D.L. 2018. Water management in container nurseries to minimize pests. Tree Planters' Notes. 61: 4–11.

Dumroese, R.K.; Pinto, J.R.; Montville, M.E. 2015. Using container weights to determine irrigation needs: a simple method. Native Plants Journal. 16: 67–71.

Dumroese, R.K.; Landis, T.D.; Pinto, J.R.; Haase, D.L.; Wilkinson, K.W.; Davis, A.S. 2016. Meeting forest restoration challenges: using the target plant concept. Reforesta. 1: 37–52.

Galliart, M.; Bello, N.; Knapp, M.; Poland, J.; St. Amand, P.; Baer, S.; Maricle, B.; Smith, A.B.; Johnson, L. 2019. Local adaptation, genetic divergence, and experimental selection in a foundation grass across the U.S. Great Plains' climate gradient. Global Change Biology. 25: 850–868.

Hsiao, T.C. 1973. Plant responses to water stress. Annual Review of Plant Physiology. 24: 519–570.

Ingram, D.L.; Hall, C.R.; Knight, J. 2016. Carbon footprint and variable costs of production components for a container-grown evergreen shrub using life cycle assessment: an East Coast U.S. model. HortScience. 51: 989–994.

Jones, H.G. 2007. Monitoring plant and soil water status: established and novel methods revisited and their relevance to studies of drought tolerance. Journal of Experimental Botany. 58: 119–130.

Kirkham, M.B. 2014. Sap flow. In: Kirkham, M.B. Principles of soil and plant water relations, 2nd ed. Boston, MA: Academic Press: 375–390. Chapter 21.

Lea-Cox, J.D.; Bauerle, W.L.; van Iersel, M.W.; Kantor, G.F.; Bauerle, T.L.; Lichtenberg, E.; King, D.M.; Crawford, L. 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: an overview. HortTechnology. 23: 717–724.

Majsztrik, J.C.; Ristvey, A.G.; Ross, D.S.; Lea-Cox, J.D. 2018. Comparative water and nutrient application rates among ornamental operations in Maryland. HortScience. 53: 1364–1371.

Marin, F.R.; Angelocci, L.R.; Nassif, D.S.P.; Costa, L.G.; Vianna, M.S.; Carvalho, K.S. 2016. Crop coefficient changes with reference evapotranspiration for highly canopy-atmosphere coupled crops. Agricultural Water Management. 163: 139–145.

McDowell, N.; Pockman, W.T.; Allen, C.D.; Breshears, D.D.; Cobb, N.; Kolb, T.; Plaut, J.; Sperry, J.; West, A.; Williams, D.G.; Yepez, E.A. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist. 178: 719–739.

Nackley, L.L.; Betzelberger, A.; Skowno, A.L.; West, A.G.; Ripley, B.; Bond, W.J.; Midgley, G.F. 2018. CO_2 enrichment does not entirely ameliorate *Vachellia karroo* drought inhibition: a missing mechanism explaining savanna bush encroachment. Environmental and Experimental Botany. 155: 98–106.

Pinto J.R.; Marshall, J.D.; Dumroese, R.K.; Davis, A.S.; Cobos, D.R. 2016. Seedling establishment and physiological responses to temporal and spatial soil moisture changes. New Forests. 47: 223–241.

Simonin, K.; Kolb, T.E.; Montes-Helu, M.; Koch, G.W. 2007. The influence of thinning on components of stand water balance in a ponderosa pine forest stand during and after extreme drought. Agricultural and Forest Meteorology. 143: 266–276.

Skelton, R. 2017. Miniature external sap flow gauges and the heat ratio method for quantifying plant water loss. Bio-protocol. 7(3): e2121.

Vallejo, V.R.; Smanis, A.; Chirino, E.; Fuentes, D.; Valdecantos, A.; Vilagrosa, A. 2012. Perspectives in dryland restoration: approaches for climate change adaptation. New Forests. 43: 561–579.

Vanclay, J.K. 2009. Managing water use from forest plantations. Forest Ecology and Management. 257: 385–389.

Villar-Salvador, P.; Peñuelas, J.L.; Jacobs, D.F. 2013. Nitrogen nutrition and drought hardening exert opposite effects on the stress tolerance of *Pinus pinea* L. seedlings. Tree Physiology. 33: 221–232.

Yeager, T.; Million, J.; Larsen, C.; Stamps, B. 2010. Florida nursery best management practices: past, present, and future. HortTechnology. 20: 82–88.