New Phytologist

Research

Methods

Continuous monitoring of plant water potential: sensor-based approaches and best practices

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Received: *19 November 2025*
Accepted: *26 March 2026*

New Phytologist (2026)
doi: 10.1111/nph.71194

Key words: field work, plant hydraulics, plants, sensors, water potential.

Summary

- Plant water potential is a central integrator of plant water status, linking hydraulic function with physiological performance and ecosystem water dynamics across species and systems. This review is motivated by the need to capture these dynamics under rapidly changing environmental conditions, which are often missed by discrete measurements.
- We evaluate the main approaches for continuous monitoring of plant water potential, including direct *in situ* sensors, indirect methods based on plant water content, and remote-sensing proxies. We discuss the principles, measurement mechanisms, practical constraints, and environmental sensitivities of each approach.
- Relative to traditional methods, such as pressure chambers, continuous measurements offer major advantages by resolving rapid variation in water status and strengthening inference on plant–soil–atmosphere interactions. These approaches are especially valuable under dynamic field conditions, where temporal variability in vapor pressure deficit, soil moisture, temperature, and radiation strongly shapes hydraulic behavior.
- We conclude that continuous monitoring has substantial potential to advance plant and ecosystem science, but wider application will depend on careful interpretation and greater harmonization across comparable methodologies. By synthesizing core principles, methodological challenges and best practices, this review provides a practical framework for researchers and practitioners applying continuous water potential measurements.

Introduction

Water potential (Ψ) is a critical indicator of plant water status, influencing many physiological processes and ecosystem dynamics (Choat *et al.*, 2012; Taiz *et al.*, 2015; Anderegg *et al.*, 2016). Historically, most Ψ measurements have been made with pressure chambers. These data have been foundational for understanding how Ψ varies across species and ecosystems and in response to changing environmental conditions. However, because pressure chamber measurements are labor-intensive, they are usually collected over relatively coarse timescales (weekly to monthly). The labor-intensive and destructive nature of pressure chamber measurements hinders our ability to understand how plant hydraulic function responds to fast-acting meteorological drivers and to link these dynamics with carbon and water fluxes (Sack & Holbrook, 2006; Blackman *et al.*, 2022; Saha *et al.*, 2024). In this context, sensors that continuously monitor Ψ are emerging as valuable tools for filling the temporal niche in Ψ measurements (Restrepo-Acevedo *et al.*, 2024). These sensors could enable a deeper understanding of how water status varies with a wider range of environmental factors, such as vapor pressure deficit (VPD), soil water availability, temperature, and radiation. Such insights are crucial for unraveling the complex interactions between plants, soil, and the atmosphere, particularly in the context of climate change and ecosystem management (Carella *et al.*, 2024; Velázquez-Chavez *et al.*, 2024; Gutiérrez-Fernández *et al.*, 2025). However, the development of sensors and approaches for *in situ* Ψ monitoring is a rapidly evolving field, and the community lacks a common knowledge base describing when and where each approach is most promising or even possible. A lack of standards around data formats and quality control procedures also currently hinders cross-site synthesis. Thus, to fully harness the potential of *in situ* continuous Ψ measurements, there is a pressing need for shared best practices and harmonized protocols across comparable sensors, applications, and environmental contexts. Here, we provide an in-depth discussion of three of the most promising techniques for monitoring continuous Ψ in the field: (1) direct *in situ* instruments, such as stem psychrometers and microtensiometers; (2) indirect *in situ* methods that infer Ψ from continuous measurements of plant water content (WC); and (3) remotely sensed proxies for Ψ, such as microwave remote-sensing (RS) and tower-based radar. In this paper, we will discuss each method's underlying principles and mechanisms of operation, explore the inherent challenges associated with each approach, and recommend best practices to overcome those pitfalls. We aim to offer a comprehensive guide for researchers and practitioners in the diverse tools for water status monitoring while inspiring methodological innovation, lowering barriers to sensor adoption, and encouraging broader use.

Description

Techniques for continuously monitoring plant ψ

The evolution of Ψ measurement techniques began > 200 yr ago, when Ernst Ferdinand August introduced the *psychrometer*, derived from Greek for 'cold measure', to estimate relative humidity using two thermocouples – one dry and one wet (August, 1818). The first application of psychrometric principles to plant water status specifically was H. H. Dixon's apparatus in 1914 (Dixon, 1914), which was designed to quantify xylem tension using principles from cohesion–tension theory. Although pioneering, Dixon's method was fragile and limited to laboratory use. A major advance came in 1962 with Ehlig's introduction of thermocouple psychrometers, which enabled estimation of plant Ψ from the relative humidity of air equilibrated with plant tissues (Ehlig, 1962). This approach was further refined over the following decade (Barrs, 1964; Campbell *et al.*, 1973) and extended to *in situ* field applications through the development of temperature-compensated leaf psychrometers (Calissendorff & Gardner, 1972). Around the same time, Scholander introduced the pressure chamber (Scholander *et al.*, 1965), which enabled standardized and reliable measurements of Ψ on detached twigs and leaves. Although the pressure chamber has become the most widely adopted method for plant Ψ measurements, its destructive and time-intensive nature limited its applicability for continuous monitoring, motivating the development of alternative approaches (Savage & Cass, 1983; Turner, 1984). In the 1980s, Dixon & Tyree (1984) introduced the stem psychrometer which enabled continuous, *in situ* measurements of xylem Ψ (Ψx) in woody plants. This design accounted for temperature gradients between plant tissue and ambient air and operated by determining the dew point of air in equilibrium with xylem sap. Building on this foundation, modern stem psychrometers (e.g. PSY-1 from ICT International) and microtensiometers (e.g. FloraPulse sensors) have permitted a substantial increase in continuous Ψx measurement across a wide range of ecosystems (Guo *et al.*, 2020; Dainese *et al.*, 2021, 2022; Pagay, 2021; Lakso *et al.*, 2022; Conesa *et al.*, 2023; Christenson *et al.*, 2024). These sensors are engineered to be installed in stems for periods up to months with high measurement fidelity along the hydraulic pathway (Christenson *et al.*, 2024; Velázquez-Chavez *et al.*, 2024). They can capture both diel and seasonal Ψ_x extremes providing an integrated perspective on cumulative water stress (e.g. Haberstroh *et al.*, 2025; Zhang *et al.*, 2025).

Other recent innovations permit indirect monitoring of Ψ by linking it to continuous observations of plant WC. These approaches rely on the often–nonlinear relationship between tissue WC and Ψ (Restrepo-Acevedo *et al.*, 2024). For decades, plant physiologists have measured this relationship (sometimes called the pressure–volume curve) as its shape can reveal important information about plant traits like the turgor loss point (Schulte & Hinckley, 1985). More recently, advanced technologies like time domain-reflectometry (TDR) and frequency domain reflectometry (FDR, Matheny *et al.*, 2017), high-resolution stem dendrometry (Drew *et al.*, 2011; Zweifel *et al.*, 2016, 2021; Peters *et al.*, 2025), and remotely sensed microwave measurements (Rodriguez-Alvarez *et al.*, 2012; Humphrey *et al.*, 2021; Konings *et al.*, 2021; Yao *et al.*, 2024) permit monitoring of WC at a wide range of temporal scales. Thus, there has been renewed interest in using WC data to infer Ψ by leveraging empirical or theoretical knowledge of the shape of WC–Ψ relationships (Konings *et al.*, 2021; Novick *et al.*, 2022). These indirect approaches are attractive because, as we will discuss in more detail later, WC sensors can be more reliable than Ψ sensors *in situ*, and WC can be sensed more directly than Ψ using RS platforms.

Despite these advances, all approaches for continuous Ψ monitoring remain subject to methodological challenges that can limit measurement's reliability, including instrument malfunction, uncertainties associated with installation and calibration, and scaling issues when linking point-scale measurements to remotely sensed information. Additional challenges arise in selecting the most appropriate sensor for a given application, with key considerations, including cost (which often limits replication in field settings), plant growth habit and structural characteristics (e.g. woody, herbaceous and resin-producing or not), ease of access (ground-level vs canopy, local vs remote sites), temporal and spatial resolution, and robustness in terms of the desired duration of data collection. While much of the current literature emphasizes forest and woody systems, these same constraints – and their associated trade-offs – are equally consequential in agricultural contexts, where sensor scalability, affordability, and integration with irrigation management have direct economic and food-security implications. Increasingly, the growing volume and heterogeneity of high-frequency sensor data also introduce challenges related to a lack of data standardization which can limit compatibility across platforms, sensors, and studies. All these challenges underscore the need for a common knowledge base to help the community select the optimal Ψ monitoring techniques for specific research applications, and to develop best practices for data and metadata management and quality control to support cross-site synthesis. The latter is especially important given the recent emergence of environmental monitoring networks that aggregate and redistribute ecohydrological time series (cite FLUXNET, SAPFLUXNET), including plant water potential (e.g. the PSInet network, Restrepo-Acevedo *et al*., 2024). We note that a completely standardized approach for continuously monitoring plant Ψ is likely not only infeasible (given the unique limitations of sensor technologies) but also arguably undesirable, as flexibility in instrument and experimental design is an important breeding ground for scientific innovation (Novick *et al*., 2018). Nonetheless, best practices around sensor installation, quality control, and metadata documentation are important for ensuring compatibility among datasets and enabling synthesis across broad ecological and geographic gradients.

Beyond technical and methodological considerations, the development of novel plant water status sensors also raises broader questions regarding accessibility and dissemination. Some emerging approaches are commercialized, which can promote robustness, standardization, and long-term support but may limit transparency or access to technical details. By contrast, open and community-driven sensor development can accelerate knowledge sharing, training, and reproducibility while also posing challenges related to quality control and misuse. Balancing innovation, accessibility, and transparency will be increasingly important as continuous Ψ measurements become more widespread.

Direct and indirect sensor-based approaches for continuous plant Ψ monitoring

This section reviews direct and indirect sensor-based approaches for continuous plant Ψ monitoring. For each method, we describe the operating principles, installation and practical constraints, advantages, and limitations, with emphasis on how these factors influence applicability across species, environments, and research scales. A comparative synthesis of the key characteristics of each approach is provided in Table 1, which summarizes the main strengths, limitations, and deployment considerations discussed in this section.

Direct *in situ* instruments

Psychrometers ***Operating principles.*** Psychrometers emerged as early alternatives to the pressure chamber (Fig. 1). They operate on the principle that liquid-phase water in the xylem establishes a vapor pressure equilibrium within a sealed chamber attached to stems, branches, and leaves. The psychrometer thus measures the vapor pressure in the chamber by recording the psychrometric Wet Bulb Depression (WBD) – the temperature drop when condensed water from the chamber air evaporates from the thermocouple junction. This occurs when a Peltier cooling current is applied, causing condensation, which then evaporates, cooling the thermocouple. The raw WBD value is corrected for ambient temperature using an empirically derived algorithm and then converted to Ψ using a calibration slope and intercept obtained during sensor calibration. A final correction is applied for ΔT, the temperature gradient between the plant tissue and the measuring junction, ensuring accurate Ψ readings. The range of commercial psychrometers is reported by the manufacturer to be -0.1 to -10 MPa in Ψ with an accuracy of ± 0.1 MPa (ICT, 2000).

Installation and practical constraints. Reliable use of psychrometers requires strong knowledge of the target species' anatomy and physiology as well as careful attention to laboratory calibration, installation, and validation. Psychrometer use is not recommended for rapidly growing tissues or species with strong exudation responses. Because psychrometry is sensitive to small imperfections and differences among thermocouples, it is highly recommended that they be cleaned and calibrated before deployment. A vapor seal is required to make accurate measurements; during calibration, a small dab of vacuum grease is sufficient and reduces the chance of contaminating a clean chamber.

During installation, the outer bark, phloem, and cambium should be carefully removed to expose the xylem while minimizing additional tissue damage. This is most easily done by holding the sensor to the stem and making two transverse cuts with a sharp razor blade, one above and one below the sensor. Once the outer layers are removed, the exposed xylem should be shaved until a flat surface of xylem larger than the chamber opening is visible. To ensure a vapor seal under field conditions, self-adhesive silicone tape is recommended, which ensures that

Table 1 Summary of direct and indirect sensor-based approaches for continuous plant water potential (Ψ) monitoring.

Sensor	Advantages	Limitations	Installation and practical constraints
Stem/leaf psychrometers	Direct thermodynamic measurement of Ψ; high temporal resolution; applicable across diverse plant functional types and wood anatomies; suitable for both field and laboratory studies; reusable with recalibration	Sensitive to temperature gradients and condensation; poor performance near saturation (*c.* 0 MPa); affected by wound responses, resin, and positive xylem pressure; technically demanding installation; limited use in small stems or thin leaves	Requires careful exposure of xylem or leaf tissue; minimum stem/leaf size; insulation from radiation and precipitation; meticulous cleaning and vapor sealing; frequent quality control and validation against pressure chamber
Microtensiometer	Direct, continuous Ψ measurements; relatively easy and fast installation; less sensitive to temperature fluctuations; robust for long-term deployment; compatible with common dataloggers	Limited deployment history outside of agriculture; constrained to woody tissues and minimum stem sizes; potential lag in response time; sensitive to VPD and xylem pressure dynamics; possible single-use limitation	Requires precise insertion depth and stable xylem contact; limited suitability for small stems or saplings; potential displacement by growth; calibration and validation recommended during deployment
Stem water content sensors (dendrometers, TDR/FDR)	Cost-effective; easy deployment; stable under variable environmental conditions; suitable for long-term, large-scale monitoring; provide insights into water storage and carbon–water interactions	Indirect proxy for Ψ; WC–Ψ relationship is nonlinear and species-specific; requires sensor- and tree-specific calibration; sensitive to rainfall, freeze–thaw cycles, and growth effects	Best suited for medium to large stems; installation challenging in irregular or rapidly growing stems; calibration required for each species and sensor type; ancillary environmental data recommended
GNSS/tower-based radiometers	Noncontact, canopy-integrated measurements; representative of whole-plant or ecosystem water status; suitable for long-term monitoring; minimal biological disturbance; scalable	Does not directly measure Ψ or WC; influenced by biomass, species composition, temperature, and canopy structure; limited sensitivity to lower canopy layers; scale mismatch with tissue-level measurements	Requires towers or elevated infrastructure; precise antenna geometry and footprint characterization; co-located meteorological and wetness sensors needed; complex site-specific processing and calibration

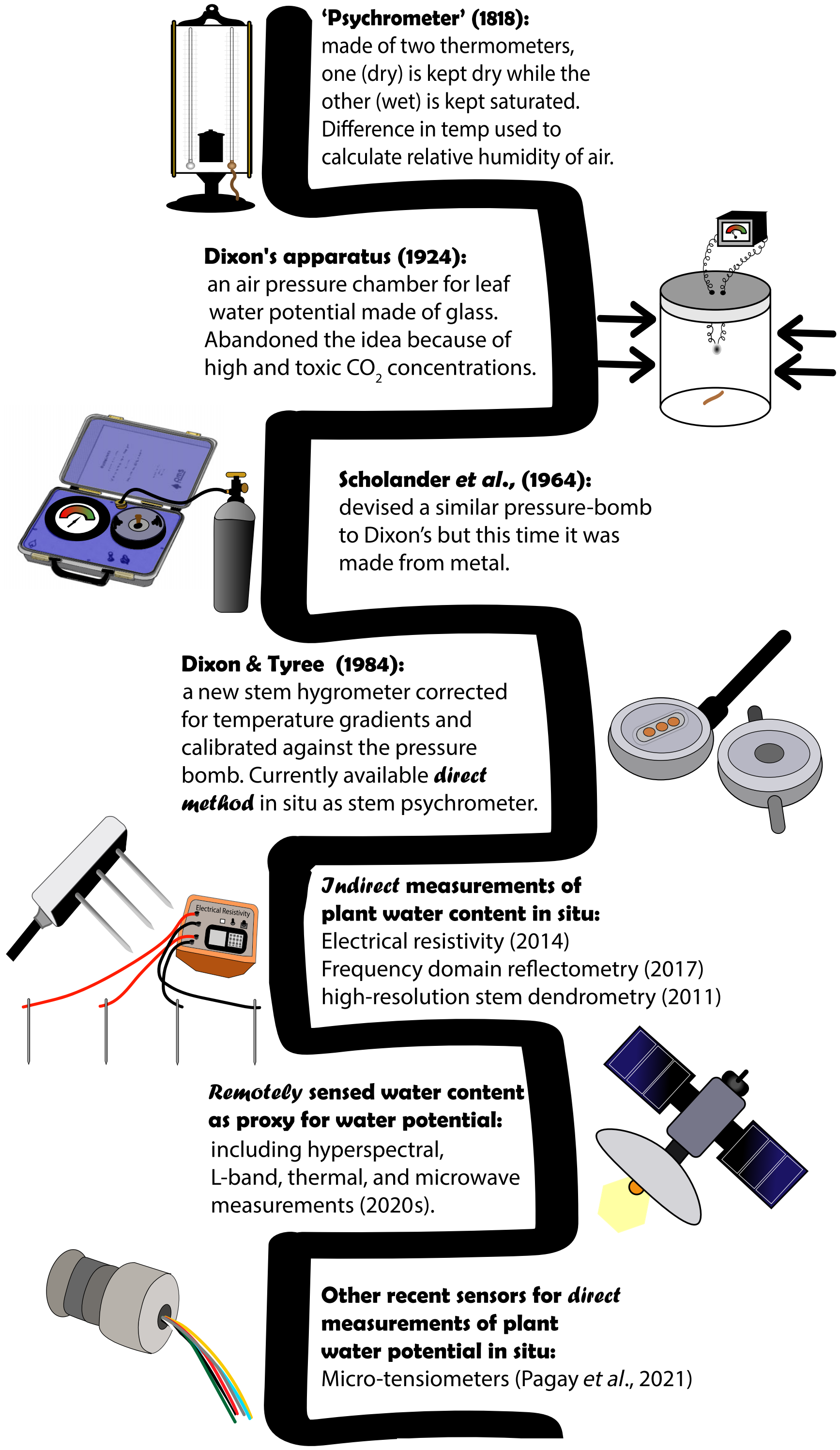
For each sensor type, the table synthesizes key advantages, limitations, and installation and practical constraints discussed in Section Description, facilitating comparison across methods and highlighting trade-offs related to measurement principle, deployment requirements, and applicability across species, environments, and spatial scales.

the chamber will not be contaminated with vacuum grease during the installation period. Finally, as with any automated sensor, manual validation against pressure chamber measurements is strongly recommended. Because psychrometers are typically installed upstream of the leaves used for pressure chamber validation, predawn measurements are recommended for sensor validation. Due to the nature of removing a significant area of living tissue to install a sensor, a sensor installation will not last indefinitely; the duration of a successful installation varies with growth rate and wounding responses of the target species as well as installation technique.

Additionally, using multiple sensors per individual, or even per individual stem, allows for rotation and cross-comparison, supporting continuity of measurements and quality control. Installing multiple sensors is also recommended for latex-producing species (for which pressure chamber measurements are often unreliable due to latex exudation at cut surfaces). In these cases, cross-validation should rely on sensor-to-sensor comparisons, nondestructive *in situ* measurements, and evaluation of physiological and environmental coherence rather than excision-based reference methods. However, it can be challenging to differentiate between installation error and true differences within individual Ψ consistent with hydraulic segmentation (Fig. 2).

Advantages. Psychrometers provide direct measurements of tissue Ψ based on vapor pressure equilibrium, rather than relying on proxies or indirect estimates, enabling long-term, continuous monitoring without the labor-intensive demands of repeated pressure chamber measurements. They can be installed in plant tissues that are largely inaccessible to chamber-based approaches, including trunks, large roots, and sessile leaves of succulents (Nobel & Jordan, 1983; Savage & Cass, 1983; Dixon & Tyree, 1984). Psychrometers are also reusable: sensors can be removed, cleaned, recalibrated, and reinstalled at different locations, allowing their use across multiple experiments and facilitating iterative refinement of experimental setups (ICT International, *PSY-1 Operation and Maintenance Manual*).

Because psychrometers quantify Ψ independently of assumptions related to xylem continuity, sap flow, or pressure transmission, they can be applied across a wide range of plant functional types, wood anatomies, and environmental conditions. Furthermore, psychrometers can measure low water potentials of down to −10 MPa and are therefore suitable for characterizing plant responses to extreme events, such as drought. They have been successfully installed in field-grown angiosperms and gymnosperms (Guo *et al.*, 2020, 2024; Rodriguez-Dominguez & Brodribb, 2020; Kannenberg *et al.*, 2022; Rodriguez-Dominguez *et al.*, 2022; Johnson & Brodribb, 2023), although their performance is poor in resin-producing species. They can also be used *in situ* to measure herbaceous plants and forbs, although in the absence of woody structure, these installations must be closely monitored and short in duration. In addition to *in situ*



‘Psychrometer’ (1818):
made of two thermometers, one (dry) is kept dry while the other (wet) is kept saturated. Difference in temp used to calculate relative humidity of air.

Dixon's apparatus (1924):
an air pressure chamber for leaf water potential made of glass. Abandoned the idea because of high and toxic CO_2 concentrations.

Scholander *et al.*, (1964):
devised a similar pressure-bomb to Dixon’s but this time it was made from metal.

Dixon & Tyree (1984):
a new stem hygrometer corrected for temperature gradients and calibrated against the pressure bomb. Currently available ***direct method*** in situ as stem psychrometer.

***Indirect* measurements of plant water content in situ:**
Electrical resistivity (2014)
Frequency domain reflectometry (2017)
high-resolution stem dendrometry (2011)

***Remotely* sensed water content as proxy for water potential:**
including hyperspectral, L-band, thermal, and microwave measurements (2020s).

Other recent sensors for *direct* measurements of plant water potential in situ:
Micro-tensiometers (Pagay *et al.*, 2021)

Fig. 1 Timeline of the history of sensors used to monitor plant Ψ.

applications, psychrometers can be used on excised tissues under laboratory or controlled conditions, enabling mechanistic experiments on Ψ dynamics, wood water retention, hydraulic capacitance, and xylem vulnerability that are difficult to achieve with alternative methods (ICT *International application notes*; Guo *et al.*, 2020; Lakso *et al.*, 2022). Finally, psychrometers provide point-based measurements of Ψ, in contrast to pressure chamber measurements that integrate Ψ across compositionally complex leaves or branches. This distinction is important given the ongoing debate regarding the interpretation of pressure chamber

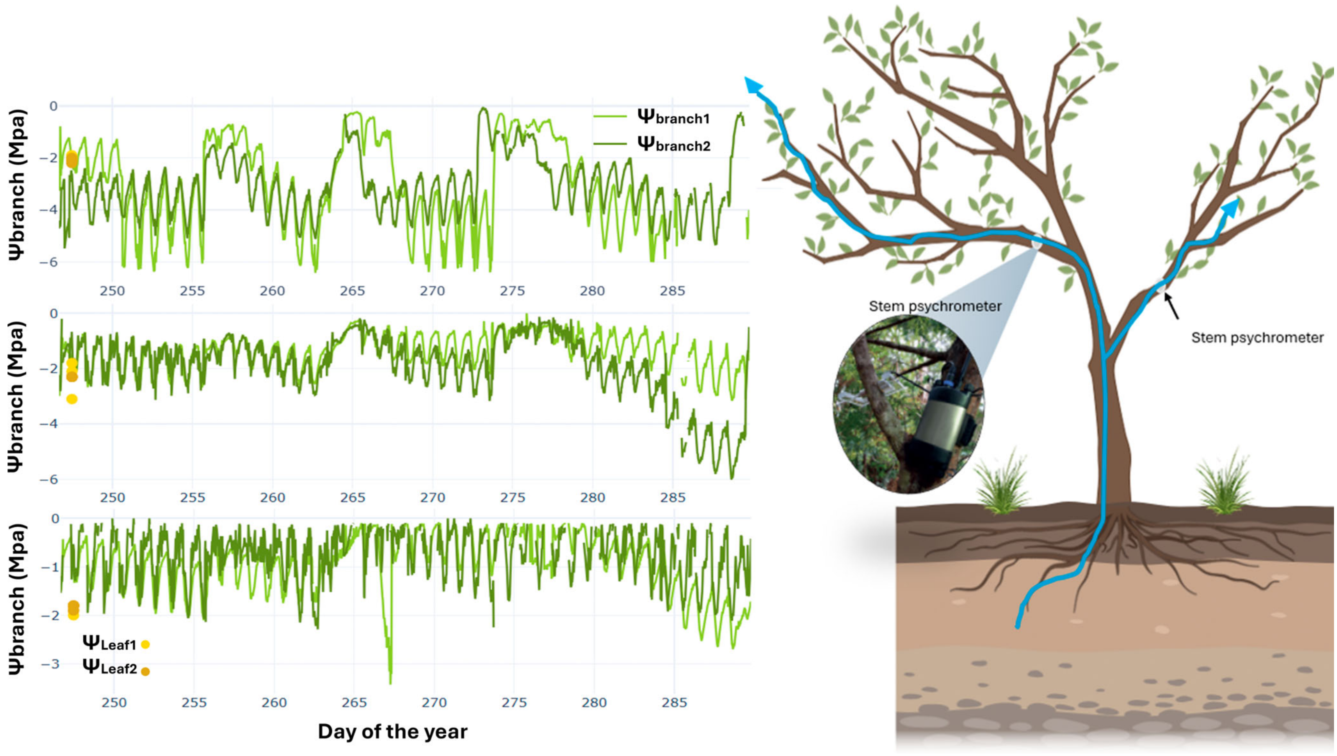


Fig. 2 Significant variation in Ψ measurements was observed when stem psychrometers were installed in different organs of the same *Juniperus osteosperma* (Torr.) Little individual. Continuous data from stem-installed psychrometers (green lines) were compared with point measurements from a Scholander pressure chamber (yellow dots) for validation. The experiment was replicated across three separate trees. Over time, increasing divergence between sensor readings suggested a possible sensor error, wounding response by plants, or hydraulic segmentation. Data from S. Kannenberg are available at doi: 10.5281/zenodo.18856863.

measurements and which hydraulic compartments they represent (Cochard *et al.*, 2001; Roderick & Canny, 2005; Rodriguez-Dominguez *et al.*, 2022).

Limitations. Stem psychrometers require a minimum stem diameter (typically *c.* 10 mm), which restricts their use on small plants, seedlings, and thin stems, while leaf psychrometers require sufficiently robust leaves to allow secure chamber attachment (ICT International, PSY-1 Stem Psychrometer Manual). Installation is technically demanding, particularly on smaller stems, largely due to the size of commercially available sensor heads (typically *c.* 12–15 mm), and measurements are sensitive to improper sealing, mispositioned thermocouples, or residual cambium that interferes with effective sensor contact. Environmental and thermal effects further complicate accuracy: direct solar radiation can induce temperature gradients that bias readings, nocturnal condensation within the chamber can introduce errors, and temperature differences within sapwood – especially in deeply rooted plants – may lead to substantial deviations (Quick *et al.*, 2018). Psychrometers generally perform best under relatively dry conditions (Guo *et al.*, 2024). Their performance can decline under wetter or more mesic environments due to condensation and potential sensor contamination. In particular, measurements near saturation (*c.* 0 MPa) are unreliable, as condensation interferes with accurate signal detection (Barrs, 1964; Campbell *et al.*, 1973; Savage & Cass, 1983; Tyree & Zimmermann, 2002; Clearwater & Goldstein, 2005).

Sensor performance can also be compromised by plants' biological responses. Wound reactions, stem swelling, and exudation can impair sensor function, particularly in resin-producing species, such as pines, spruces, and firs, where resin contamination can invalidate measurements (Rodriguez-Dominguez *et al.*, 2022). Mesic species with strong wound responses may require frequent sensor replacement – sometimes within days – resulting in increased labor and a higher risk of sensor damage, and in extreme cases data quality can deteriorate within hours of deployment. The primary culprit is the fine thermocouples (*c.* 25 μm diameter) within the sensor chamber, which renders psychrometers vulnerable to contamination and mechanical damage. Thick-barked species present additional challenges, as bark removal is required to ensure contact with the xylem and subsequent bark swelling or shrinkage can dislodge sensors (Savage & Cass, 1983; Dixon & Tyree, 1984; Campbell & Norman, 1998; Tyree & Zimmermann, 2002). Moreover, species that develop positive xylem pressure at night (e.g. walnuts, avocados, camphor trees, bamboos, and many herbaceous plants) may accumulate sap within the psychrometer chamber, rendering measurements unreliable (Michaud *et al.*, 2024). Finally, developing the experience to assess data quality, adjust settings, and rotating sensors, when necessary, can take time and be particularly challenging for

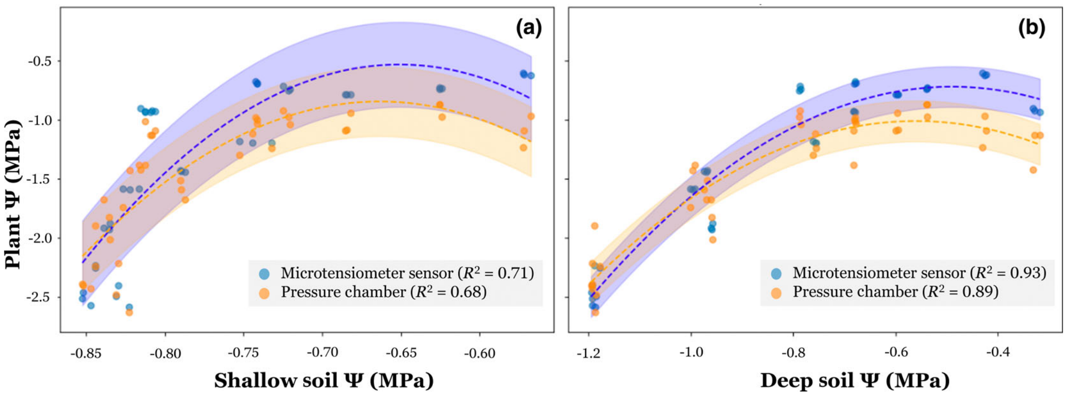


Fig. 3 Relationship between soil Ψ and plant Ψ in *Prunus dulcis* (Mill.) D.A.Webb (almond), measured using stem-installed microtensiometer sensors and leaf pressure chamber measurements. (a) Shallow soil Ψ vs plant Ψ. (b) Deep soil Ψ vs plant Ψ. Data were collected under dry field conditions during the growing season, when soil water availability was low and transpiration demand was present. Soil Ψ is shown as an external reference to provide environmental context and to evaluate whether plant Ψ responses measured by different methods are consistent with expected gradients in soil water availability. Second-order polynomial fits are shown with 95% confidence intervals, and R^2 values indicate goodness-of-fit for each method. This figure is intended to illustrate internal consistency and data plausibility across measurement approaches rather than a mechanistic soil–plant coupling. Data from *J. Knowles* are available at doi: 10.5281/zenodo.18856768.

new users. Together, these limitations highlight the need for species-specific deployment strategies, rigorous quality control, and the graduate development of installation experience to ensure reliable measurements.

Microtensiometers ***Operating principles.*** Tensiometers also permit direct measurements of Ψ by linking liquid water to vapor through a wettable porous membrane. Inside of the tensiometer, pure liquid water equilibrates with vapor, which is in turn influenced by the external environment. As water evaporates from the membrane, internal pressure decreases until equilibrium is reached. The resulting pressure difference across the membrane provides a direct measurement of Ψ. Traditional tensiometers, which were primarily developed to measure soil Ψ, struggle at low Ψ due to cavitation in the membrane, where gas bubbles form and disrupt measurements. However, modern sensors (Pagay *et al.*, 2014; Dainese *et al.*, 2021, 2022; Pagay, 2021; Lakso *et al.*, 2022; Conesa *et al.*, 2023) operate by embedding a microelectromechanical system (MEMS) tensiometer directly into the sapwood, where it detects changes in xylem water tension. FloraPulse, (Davis, CA) makes a microtensiometer that uses stainless-steel sleeves with barbs that serve as a drill guide and securely anchor the sensor against the xylem. To ensure optimal liquid contact, a fine clay paste is applied between the sensor edge and the xylem tissue, compensating for surface imperfections left by drilling into wet wood. This design enables real-time tracking of rapid hydrodynamic changes, capturing sub-hourly fluctuations in Ψ without the need for complex calibrations (Pagay *et al.*, 2014). Utilizing silicon-based MEMS technology, the sensor functions similarly to a traditional soil tensiometer but is adapted for the much drier conditions inside of plant tissues than other sensors. Specifically, while traditional tensiometers operate within a narrow range of 0 to −0.16 MPa, offering excellent accuracy ($\pm 5 \times 10^{-4}$ MPa; Delta T-Services, 2009), the micro-scale design of new sensors (e.g. FloraPulse microtensiometers) offers a promising approach for accurately measuring Ψ across a much broader range ($\Psi x > -3.5$ MPa).

Installation and practical constraints. To achieve better results with microtensiometers, proper installation and regular monitoring are essential. Following the manufacturer's installation protocol, along with additional recommendations from recent protocols (Magh & Paligi, 2024), can help minimize errors. It is crucial to reduce air exposure during installation, as prolonged exposure can cause cavitation in the sensor, requiring specialized equipment to refill. For trees with thick bark, measuring bark depth beforehand ensures the sensor reaches the xylem just beneath the cambium, which is especially important for ring-porous species. Tools like a bark gauge, screwdriver, or chisel can help determine the correct depth, while a Forstner drill bit allows precise removal of excess bark with minimal tree damage. Calibration and lab testing before field deployment ensure sensor accuracy and reliability. Using multiple sensors per tree at multiple positions (root, stem, and canopy) or site can improve data reliability by accounting for spatial variability and reducing dependence on a single sensor. Regular biweekly monitoring and cross-checking with leaf Ψ measurements help confirm sensor function and data plausibility, making early detection of sensor failure or inaccurate readings possible (Fig. 3).

Advantages. Microtensiometers provide continuous, nondestructive, direct measurements of plant water status and are embedded directly into the stem or trunk, minimizing excess tissue injury that could affect readings (Pagay *et al.*, 2014; Knipfer *et al.*, 2020). Compared with psychrometers, they are relatively easy to install, monitor, and maintain, with typical installation times in the order of minutes, and offer cost advantages at comparable levels of uncertainty (Pagay *et al.*, 2014; Blackman *et al.*, 2022). Their robust design has demonstrated reliable performance over full growing seasons in some applications, reducing the need for frequent recalibration or replacement (Knipfer *et al*., 2020; Lakso *et al*., 2022). Because microtensiometers do not rely on precise temperature measurements, they are less sensitive to temperature fluctuations or disequilibrium and are theoretically more resilient to contamination by sap, soil particles, or microbial growth (Pagay *et al*., 2014; Blackman *et al*., 2022). Published specifications for commercially available sensors indicate an operational range extending to *c*. −3.5 MPa with equilibration times of *c*. 20 min, and current devices are compatible with dataloggers from multiple manufacturers, facilitating integration into existing monitoring systems (Lakso *et al*., 2022; FloraPulse Inc., technical specifications). Although microtensiometer systems have been shown to theoretically resolve water potentials approaching −10 MPa under controlled conditions (Pagay *et al*., 2014), commercial implementations operate within a more conservative Ψ range to minimize cavitation risk and ensure stable sensor–tissue contact and long-term field robustness.

Limitations. The performance and long-term reliability of microtensiometers can be strongly influenced by species-specific anatomical traits, including bark thickness, resin or mucilage production, and xylem structure. Resin intrusion has been observed to compromise sensor function and can render sensors unusable, while in ring-porous species precise control of installation depth is critical because water conduction is restricted to a limited number of annual rings. Over time, sensor–xylem contact may be lost or probes may be displaced by stem growth, requiring reinstallation to maintain accurate measurements (Magh & Paligi, 2024). Because microtensiometers have been commercially available only since *c*. 2018 and have been deployed predominantly in intensively managed systems like orchards, their limitations are less comprehensively characterized than those of psychrometers, and factors known to affect psychrometric measurements – such as wound responses or positive xylem pressures – may also influence tensiometer performance (Pagay *et al*., 2014; Knipfer *et al*., 2020). As with psychrometers, microtensiometers measure xylem Ψ in woody tissues, which may not directly correspond to leaf or twig Ψ, requiring careful interpretation when compared with pressure chamber measurements. Durability also remains a concern: prolonged deployments can result in probe breakage, cavitation within the sensor, or difficulties in sensor removal without damaging the stem, and some devices may be limited to single-use applications, increasing costs for long-term or large-scale studies (Knipfer *et al*., 2020; Lakso *et al*., 2022). Several studies have reported sensitivity of microtensiometer readings to atmospheric conditions, including potential biases under high VPD and precipitation events (Pagay, 2022; Blanco & Kalcsits, 2023). In addition, a time lag between changes in plant Ψ and sensor response – sometimes approaching 2 h – has been observed, likely reflecting hydraulic equilibration time, thermal sensitivity, and buffering by stem hydraulic capacitance, and may require correction or validation using pressure chamber data (*et al*., 2024; Blanco & Kalcsits, 2023). Finally, application of microtensiometers is constrained by minimum stem size (19 mm, FloraPulse manual recommendation) and tissue integrity, limiting their use primarily to woody species or herbaceous plants with sufficiently developed vascular tissues, as stable hydraulic contact in small or fragile stems remains challenging (Pagay *et al*., 2014; Knipfer *et al*., 2020; Blackman *et al*., 2022).

Indirect *in situ* methods that infer ψ from plant water content dynamics, including TDR, FDR, and dendrometers

Operating principles *In situ* WC measurements, (e.g. from TDR, FDR, and dendrometers) are now increasingly used to quantify the total amount of water present in the plant's tissues, useful for assessing hydration status, estimating irrigation needs, and measuring water storage. Importantly, WC is theoretically related to Ψ, such that WC can be transformed into continuous time series of Ψ (Tyree & Hammel, 1972; Tyree & Zimmermann, 2002; Jones, 2014). The relationship between WC and ψ is complex and not linear. As a plant loses water due to transpiration or environmental stress, both WC and ψ decrease, but at different rates (Zweifel *et al*., 2000), with the specifics of the pressure–volume curve (WC vs ψ) differing substantially by hydration status, species, and method of measurement (Fig. 4). Initially, as the plant loses water, both WC and ψ decrease, but as dehydration continues, WC decreases more slowly while ψ continues to become more negative, indicating increased water deficit and stronger binding of water in the plant's tissues. In practice, the use of continuous *in situ* WC measurements to infer ψ requires that the shape of the pressure–volume curve be independently generated – usually in the laboratory – using excised plant tissues. Species-level variation in thresholds for hydraulic damage, turgor loss – driven by differences in anatomy – regulation of water loss, osmotic adjustment, and turgor pressure can all substantially influence the shape of the curve (Scholz *et al*., 2011; Pratt & Jacobsen, 2017; Xiong & Nadal, 2019; de *et al*., 2022). Therefore, species-specific curves should be generated rather than assuming a universal relationship.

TDR, FDR, and dendrometer sensors each operate based on distinct principles. TDR sensors work by sending an electromagnetic pulse (typically < 1.5 GHz) through a probe and measuring the time it takes for the pulse to return. The travel time of the wave is a function of the apparent or effective permittivity of the bulk material (K_a), which depends on the permittivity of the individual constituents in the matrix (e.g. air, water, solids, and ice), their volumetric fractions, and geometric arrangements (He *et al*., 2021). FDR sensors operate similarly but instead measure the frequency shift of an electromagnetic signal. The frequency shift is influenced by the amount of water in the medium, allowing an estimation of WC by assessing the dielectric permittivity of the matrix (Skierucha & Wilczek, 2010).

High-resolution dendrometry measures tissue expansion or shrinkage due to a change in tissue WC and infers the tissue Ψ from change in WC. While dendrometer data have traditionally been used to quantify long-term trends in stem growth, subdaily, micrometer-scale measurements can also capture cycles of stem expansion and shrinkage, which serve as a proxy for plant water status (Zweifel *et al*., 2005; Peters *et al*., 2025). In this context, decreases in diameter are attributable primarily to water-

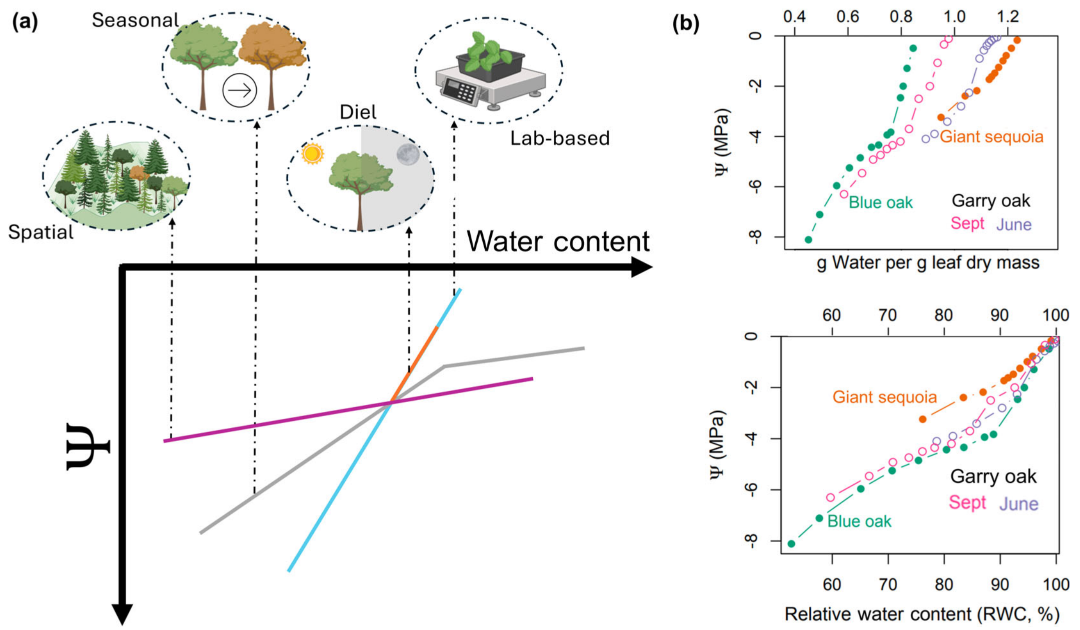


Fig. 4 Conceptual and empirical variation in the relationship between water potential (Ψ) and water content (WC) across spatial and temporal scales for *Quercus douglasii* Hook. & Arn. (blue oak, green), *Sequoiadendron giganteum* (Lindl.) J. Buchholz. (giant sequoia, orange), and *Quercus garryana* Douglas ex Hook (garry oak, pink, and gray). (a) Conceptual illustration showing how the Ψ–WC relationship may differ depending on the scale of observation and experimental context, including spatial heterogeneity (within-plant to ecosystem), seasonal dynamics (for *Quercus garryana*; pink – September, and gray – June), diel cycles, and controlled laboratory measurements. These differences reflect variation in tissue properties, hydraulic storage, and the degree of environmental forcing rather than a single, universal Ψ–WC relationship. (b) Empirical examples of leaf-level Ψ–WC relationships illustrating species-specific differences and seasonal shifts, using pressure–volume curve data. Conceptual elements adapted from Boving *et al*. (2025a, 2025b) and leaf pressure–volume data from Williams *et al*. (2017) and Hahm *et al*. (2018).

stress–induced shrinkage. Similarly, physical or optical dendrometers applied to other tissues (e.g. monocot stems and petioles) measure linear tissue shrinkage and swelling, providing an additional proxy for water status (Bourbia & Brodribb, 2023; Gleason *et al.*, 2024). The concept of dendrometry is based on the cohesion–tension theory (Dixon & Joly, 1894; Zimmerman, 1983) and the physical principles of a closed hydraulic system, where water is stored in living, elastic tissues along the water transport pathway (Zweifel *et al.*, 2001, 2016, 2021; Steppe & Lemeur, 2004; Steppe *et al.*, 2005, 2015; De Swaef *et al.*, 2015). In essence, reductions in stem diameter are attributable exclusively to shrinkage resulting from water stress, and established protocols exist for disentangling stem growth from hydraulic dynamics (Zweifel *et al.*, 2016, 2021). While TDR and FDR provide more direct measurements of WC, dendrometers offer insights into plant water dynamics and are useful for tracking overall water status (Zweifel *et al.*, 2005, 2016; Dietrich *et al.*, 2018b; Salomón *et al.*, 2022; Ziegler *et al.*, 2024; Bloom *et al.*, 2025). However, none of these methods directly estimates Ψ.

Installation and practical constraints Proper calibration under controlled conditions is critical to account for species-specific, or even individual or phenological stage-specific, differences in WC changes and Ψ relationships, with periodic recalibration recommended for long-term accuracy. Sensors should be strategically placed to avoid irregular stem structures, bark roughness, or mechanical disturbances that may affect readings. Using high-resolution data loggers (24-bit resolution) improves data quality by capturing subtle changes in stem diameter. Complementing dendrometers or WC sensors with sap flow sensors or direct Ψ *in situ* measurements can enhance data validation and provide a more comprehensive understanding of plant water dynamics. Additionally, for dendrometry, distinguishing between growth-related and water-related diameter changes is critical for interpretation, requiring long-term monitoring and hydraulic models. Finally, conducting comparative studies across different conditions and species can help refine best practices and optimize sensor deployment for specific applications.

Advantages WC measurements are well suited for large-scale environmental monitoring, precision agriculture, and ecosystem modeling due to their relative ease of deployment, automation, and ability to provide continuous data streams (Zweifel *et al.*, 2005; Matheny *et al.*, 2017; Peters *et al.*, 2018). WC sensors are generally more cost-effective and simpler to install, calibrate, and maintain than Ψ sensors, and they tend to function reliably across a wide range of environmental conditions, making them particularly attractive for long-term and spatially extensive studies. High-resolution dendrometers offer additional advantages by capturing tissue shrinkage and swelling with minimal disturbance – typically requiring only small mounting points – allowing simultaneous insights into plant water status and carbon dynamics across diel to seasonal timescales and at multiple positions within the tree (Zweifel *et al.*, 2005; Ehrenberger *et al.*,

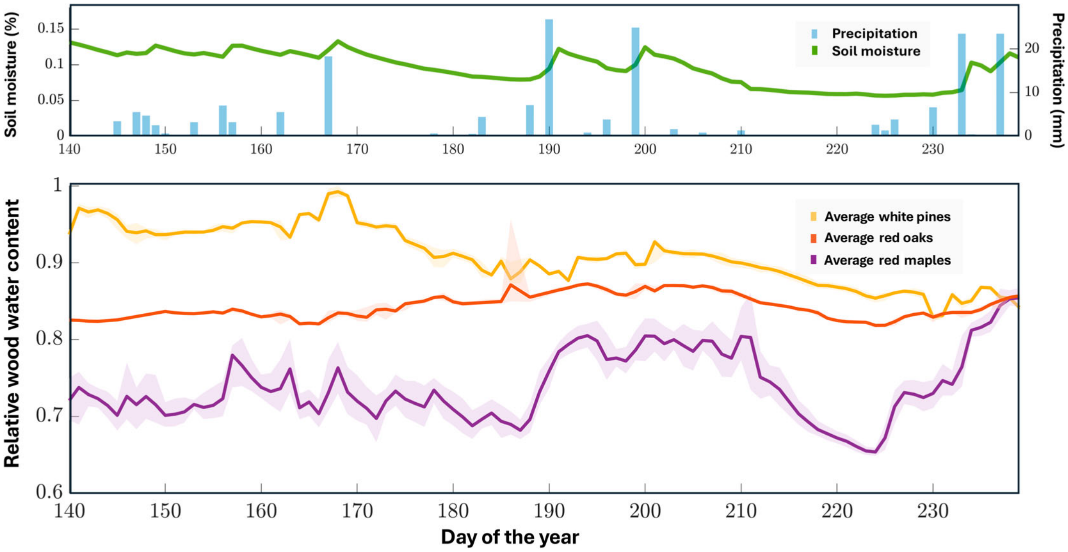


Fig. 5 Seasonal dynamics of stem water content (WC) in tree species exhibiting contrasting hydraulic strategies, measured using time-domain reflectometry (TDR) sensors. Data show averaged relative stem WC for eight individuals per species. White pine displays relatively dampened variability consistent with more conservative water-use behavior; red oak exhibits intermediate dynamics, and red maple shows larger fluctuations indicative of greater reliance on internal water storage. The temporal resolution emphasizes seasonal trends and responses to changes in soil moisture following precipitation events, while sub-daily depletion–recharge cycles present in the underlying high-frequency data are not resolved in this aggregated representation. Data from A. M. Restrepo-Acevedo are available at doi: 10.18738/T8/YZTCC2.

2012; Dietrich *et al*., 2018a; Peters *et al*., 2025). These sensors can operate autonomously for years and are readily compatible with many commercially available data loggers. TDR and FDR sensors further enable *in situ*, real-time monitoring of WC with high temporal resolution and precision (on the order of 0.001 $m^3\ m^{-3}$). While these instruments are widely used for soil WC measurements, calibration for plant structural properties allows trunk-installed TDR/FDR sensors to provide valuable insights into tree water dynamics at fine temporal scales (Matheny *et al*., 2017; Fig. 5). Overall, WC sensors are generally more stable than Ψ sensors under fluctuating environmental conditions, as they are less sensitive to temperature variations, solar radiation, and atmospheric humidity. Nonetheless, shielding from extreme temperature fluctuations and environmental contamination remains recommended to ensure optimal accuracy and long-term performance in field applications.

Limitations WC sensors do not measure Ψ directly, but instead quantify changes in tissue dimensions (e.g. stem radius variations) or volumetric WC that are assumed to correlate with Ψ. However, the relationship between WC, tissue volume changes, and Ψ is complex and often–nonlinear, and can vary with species-specific traits, plant water status, tissue development and phenology, and internal water storage dynamics, complicating direct comparisons across sensors, species, or conditions. Consequently, all WC-based approaches require species- and/or sensor-specific calibration, which represents a fundamental limitation by increasing methodological complexity, reducing transferability across sites and species, and necessitating ongoing maintenance to ensure reliable long-term measurements (Matheny *et al*., 2017; Bourbia *et al*., 2021; Peters *et al*., 2025).

WC measurements are also sensitive to environmental factors that can obscure underlying water status signals. Rainwater infiltration and freeze–thaw cycles can alter stem dimensions independently of plant water status or influence dielectric permittivity readings in TDR/FDR sensors, making it difficult to isolate Ψ-related dynamics without additional correction or ancillary data (Zweifel *et al*., 2000). Importantly, dendrometers should not be interpreted as providing direct estimates of Ψ; instead, they capture tissue deformation – integrated across cambium, phloem and xylem – driven by both hydraulic and nonhydraulic processes, including growth, phenology, and carbon allocation, which can decouple stem diameter variations from water potential, particularly over seasonal timescales (Downes *et al*., 1999; Zweifel *et al*., 2005; Oberhuber *et al*., 2015). In terms of applicability, most commercially available WC sensors and high-precision dendrometers are best suited for medium to large trees, with exceptions including point dendrometers that can be installed on stems >1 cm in diameter and optical dendrometers that can be deployed on petioles, albeit with increased sensitivity to field conditions. As a result, these techniques are generally not applicable to grasses, field-grown crops, or seedlings with thin stems. Furthermore, installation can be challenging in species with irregular stem morphology, rough bark, or rapid growth rates, which may compromise measurement accuracy, long-term stability, or sensor integrity.

Remotely sensed measurements of water content, which serve as proxies for plant ψ, including GNSS and tower-based radiometers

Operating principles Vegetation optical depth (VOD) is a RS metric that quantifies aboveground plant WC by measuring the attenuation of electromagnetic microwaves as they pass through the canopy. The working principle relies on measuring changes in signal strength (electromagnetic wave amplitude) and phase caused by vegetation. Based on theoretical considerations and experimental findings in grasslands and shrublands (cf. Konings *et al*., 2019, and references therein), VOD has been found to be approximately linearly proportional to the total liquid water stored in aboveground vegetation, effectively summing WC along a vertical column through the canopy. This quantity reflects both the amount of vegetative material present (biomass) and its hydration state. Consequently, tower-based VOD estimates have been shown to co-vary with plant Ψ (Holtzman *et al*., 2021; Yao *et al*., 2024).

Global Navigation Satellite System (GNSS) based VOD measurements rely on the attenuation and scattering of GNSS radio signals as they pass through the canopy, which affects signal transmission and reflection at L-band frequencies (*c.* 1.2–1.6 GHz). These frequencies are ideal for vegetation studies because they can penetrate canopy layers and are particularly sensitive to vegetation's WC. There are three main approaches to GNSS-based VOD estimation: GNSS reflectometry (GNSS-R), ground-based GNSS interference (GNSS-IR), and GNSS-Transmissometry (GNSS-T). In GNSS-R, signals emitted by GNSS satellites reflect the Earth's surface and are received by low-altitude satellites or airborne instruments. Vegetation affects the amplitude, coherence, and polarization of reflected signals. By comparing the direct and reflected signal properties and applying radiative transfer models, it is possible to infer vegetation structure and WC, which are expressed as VOD. In GNSS-IR, stationary ground-based receivers detect both the direct GNSS signal from the satellite and its multipath reflections from nearby surfaces, including vegetation. As vegetation grows or accumulates in water, it alters the phase and amplitude of the nondirect reflected signals, changing the observed interference patterns – particularly the signal-to-noise ratio (SNR) over time. These SNR variations can be modeled as a function of canopy height, density, and WC (Ulaby & El-rayes, 1987; Humphrey & Frankenberg, 2023). Finally, GNSS-T relies on pairs of ground-based receivers and focuses on how vegetation attenuates the direct GNSS signal (Humphrey & Frankenberg, 2023). Because VOD quantifies the attenuation of microwave radiation through vegetation, it integrates both the amount of biomass and its WC, providing a physically meaningful proxy for Ψ under conditions when biomass changes are minimal.

Similarly, tower-based microwave radiometers estimate VOD by passively measuring the natural thermal microwave emission (brightness temperature) from the Earth's surface or the sky – depending on the specific site setup – at specific frequencies, typically in the L-band (1–2 GHz), C-band (4–8 GHz), or X-band (8–12 GHz) (Frappart *et al*., 2020). The principle is based on the fact that vegetation attenuates and emits microwave radiation as a function of its structure and WC. As microwaves interact with the canopy, they are partially absorbed and scattered, reducing the brightness temperature observed by the radiometer. The level of attenuation is directly related to VOD, which serves as a proxy for the total water mass and biomass within the vegetation column. L-band frequencies are particularly advantageous for estimating VOD because they penetrate deeper into the canopy and are more sensitive to changes in woody biomass and vegetation WC compared with higher frequencies.

Installation and practical constraints Tower-based GNSS-T VOD measurements require stable mounting of GNSS receivers and antennas above the canopy to ensure a clear line of sight between satellites, vegetation, and the receiving system, typically necessitating permanent towers or existing infrastructure (Holtzman *et al*., 2021; Humphrey & Frankenberg, 2023). Accurate installation depends on precise antenna orientation, stable geometry, and careful characterization of the antenna footprint, which can vary with satellite constellation, elevation angle, and canopy structure. Co-located ancillary measurements (e.g. soil moisture, precipitation, temperature, and canopy wetness) are essential to support signal interpretation and quality control, particularly during rainfall or freeze–thaw events that affect VOD retrievals (Humphrey & Frankenberg, 2023; Yao *et al*., 2024). Long-term deployments also require consistent calibration and monitoring of instrumental stability, as well as site-specific processing choices to separate vegetation and soil contributions. These practical requirements currently limit GNSS-T VOD applications primarily to well-instrumented sites, such as flux towers or research observatories.

Advantages GNSS VOD and tower-based microwave radiometers provide spatially integrated measurements of canopy WC by capturing signal attenuation across entire canopies, including sunlit and shaded leaves, branches, and multiple canopy layers. This integration yields a more representative estimate of whole-plant or ecosystem-scale water status than is typically achievable by scaling point-based pressure chamber or *in situ* sensor measurements (Frappart *et al*., 2020; Humphrey & Frankenberg, 2023; Feldman, 2024). GNSS receivers are ground-based, require no physical contact with vegetation, and are robust, low-maintenance tools suitable for long-term deployment without disturbing plant function. Compared with microwave radiometers, GNSS-T VOD retrievals generally require fewer complex algorithms to separate soil moisture and vegetation signals, simplifying data processing and reducing uncertainty (Feldman, 2024). In addition, L-band microwave signals (*c.* 1.4 GHz) are sensitive to water stored in stems and branches as well as leaves, enhancing their ability to capture total canopy WC (Wigneron *et al*., 2017; Frappart *et al*., 2020; Konings *et al*., 2021). Radiometer observations at multiple frequencies and viewing angles further improve the separation of soil and vegetation contributions, strengthening interpretation of canopy-scale water dynamics (Kerr *et al*., 2010; Wigneron *et al*., 2017; Konings *et al*., 2021).

Limitations VOD is sensitive to the dielectric properties of water within vegetation but does not directly measure plant Ψ or even vegetation WC. Consequently, VOD-derived metrics should not be interpreted as substitutes for traditional physiological measurements. Meaningful interpretation of VOD in relation to Ψ requires site-specific calibration and integration with complementary datasets, and VOD cannot currently replace direct Ψ measurements. Moreover, VOD signals are influenced by multiple biophysical and environmental factors beyond water status, including species composition, biomass, and ambient temperature, all of which affect vegetation dielectric properties and complicate interpretation (Konings & Gentine, 2017; Frappart *et al.*, 2020; Feldman *et al.*, 2021; Konings *et al.*, 2021).

Tower-based VOD measurements are typically weighted toward signal attenuation from upper canopy layers, reducing sensitivity to lower strata, stems, or woody tissues and limiting the attribution of signals to individual species or organs. These scale mismatches between canopy-integrated signals and tissue-level measurements constrain the transferability of VOD–Ψ relationships across ecosystems without local calibration. VOD is also sensitive to transient environmental conditions: rainfall interception, freeze–thaw cycles, and dew formation can induce short-term fluctuations unrelated to internal plant water dynamics, necessitating co-located wetness sensors, ancillary meteorological data, or signal-filtering approaches. Over longer timescales, VOD additionally responds to changes in vegetation biomass, requiring complementary structural information (e.g. LiDAR- or leaf area index (LAI)-based estimates) to disentangle water-related signals from growth or phenological effects (Konings & Gentine, 2017; Frappart *et al.*, 2020; Holtzman *et al.*, 2021; Humphrey & Frankenberg, 2023; Feldman, 2024).

Given these constraints, VOD-based approaches are best suited for capturing relative changes and spatial patterns in canopy water status at stand to ecosystem scales, particularly in forested systems where long-term, noninvasive monitoring is desired. Their greatest value lies in integration with ground-based physiological measurements and structural datasets, rather than in direct comparison with tissue-level Ψ observations. In this context, Konings & Gentine (2017) demonstrated that diurnal VOD dynamics can be used to infer ecosystem-scale hydraulic regulation (isohydricity), while Holtzman *et al.* (2021) further formalized a semi-physical pathway linking VOD to plant water potential by combining the proportionality between VOD and vegetation water content (VWC) with a linearized pressure–volume relationship, which can be inverted to estimate Ψ when structural parameters are constrained.

Research frontiers that can be explored with continuously monitored water potential data

The following examples represent a few key research questions that can be addressed using continuous Ψ measurements. This is by no means an exhaustive list, and many other important and innovative questions remain to be explored with continuous Ψ data.

How can we improve plant hydraulic modeling with continuous measurements of ψ?

A fundamental need in land surface models' validation and parameterization is the availability of continuous, high-frequency Ψ data – ideally at sub-daily or hourly resolution. Many modern hydraulic and vegetation models (e.g. CLM, Noah-MP, and SPA) operate on short time steps to capture diurnal transpiration cycles, stomatal responses, and rapid changes in plant water status.

A critical aspect of incorporating Ψ into hydrological and climate models involves accurately representing vegetation hydrodynamics. The physics of xylem water flow and plant water storage dynamics form the mechanistic link between soil moisture availability, transpiration, and stomatal conductance (Kennedy *et al.*, 2019; Yao *et al.*, 2022). Models that omit or oversimplify these processes cannot realistically simulate Ψ or its feedback on ecosystem fluxes. Continuous Ψ data offer opportunities to fill physiological knowledge gaps related to plant water relations, including nocturnal transpiration dynamics, hydraulic disequilibrium between plant compartments, and temporally variable water-use strategies (Tardieu & Simonneau, 1998; Caird *et al.*, 2007; Meinzer *et al.*, 2008; Martínez-Vilalta *et al.*, 2014; Dawson & Fisher, 2015; Hentschel *et al.*, 2021; Novick *et al.*, 2022). These processes are critical for understanding plant responses to environmental stress and improving model parameterizations.

Although continuous Ψ data can significantly advance hydraulic model development – now increasingly integrated into Earth system models (e.g. Noah-MP, Niu *et al.*, 2011; JULES, Best *et al.*, 2011) – direct assimilation of Ψ data remains difficult. Key challenges include scale mismatches, limited field data on species composition and canopy structure, and high inter-individual variability. Scaling Ψ measurements from individual branches to plot- or ecosystem-scale remains a major source of uncertainty. This limitation underscores the importance of developing canopy-level observations of vegetation WC – such as those derived from GNSS or radiometric techniques – which integrate over larger spatial footprints. When combined with species- or ecosystem-specific pressure–volume relationships, empirical calibration, or hydraulic modeling frameworks, these observations can provide indirect constraints on canopy-scale Ψ and support evaluation of stand- to regional-scale hydraulic models.

Systematic studies comparing Ψ across spatial scales – from plant organs to full canopies and satellite footprints – are needed to resolve these uncertainties and unlock the full potential of continuous Ψ observations in ecosystem modeling.

From continuous time to continuous space: How can we use continuous ψ measurements to validate satellite remote-sensing estimations, such as VOD?

Continuous measurements of plant Ψ hold significant promise for validating satellite RS estimations of vegetation water status, such as VOD derived from microwave sensors. However, translating these RS observations – which are fundamentally sensitive to plant WC – into meaningful estimates of Ψ presents multiple challenges, stemming from both physical measurement complexities and biological uncertainties.

A primary difficulty lies in understanding the exact canopy components contributing to the RS signal (Yang *et al.*, 2025). Microwave sensors theoretically respond to water contained in leaves, small stems, and medium-sized branches, but the proportional influence of each tissue type remains unclear, especially in dense, multilayered canopies. Furthermore, biological variability in tissue capacitance – the relationship between WC and Ψ –

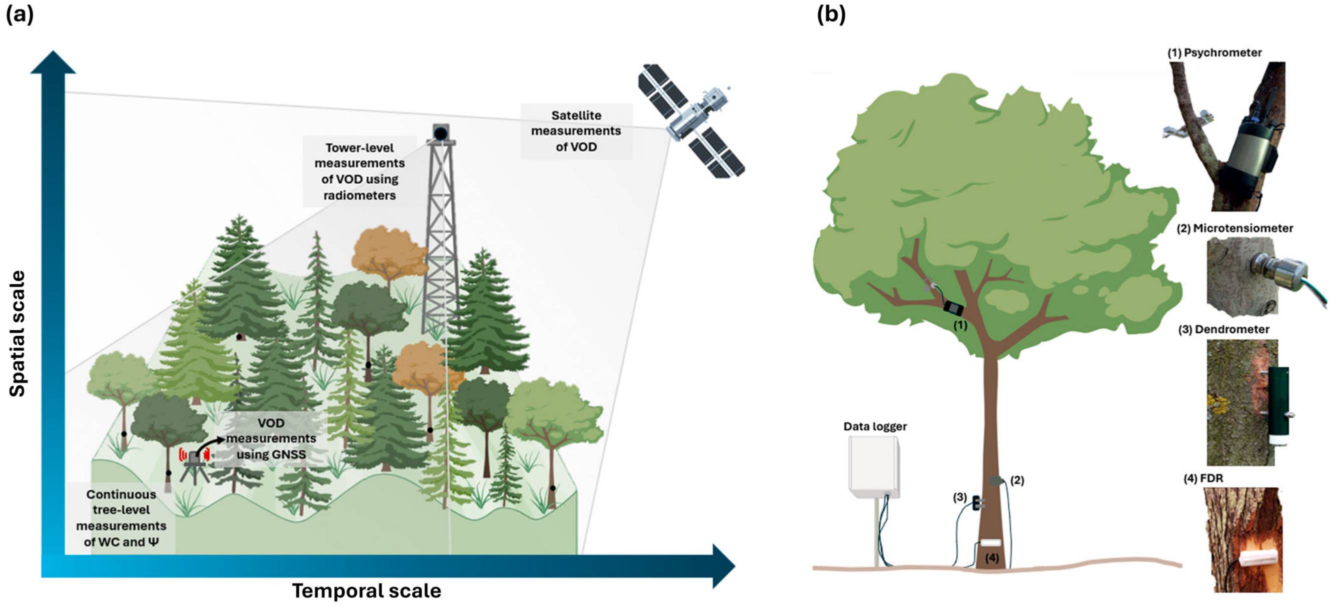


Fig. 6 Integrating continuous plant water potential (Ψ) measurements with remote sensing observations across scales. (a) Continuous *in situ* Ψ measurements provide high-frequency, localized data critical for calibrating and validating Global Navigation Satellite System (GNSS) vegetation optical depth (VOD) data and remote-sensing products. Coordinated campaigns using stand-scale microwave sensors co-located with (b) Ψ and other ground-level measurements help bridge scale mismatches and disentangle the effects of biomass and Ψ on VOD signals, improving remote-sensing (RS) algorithm development and model validation.

varies across species, tissue types, spatial scales, and seasons, complicating efforts to link RS-derived WC to actual Ψ (Wood *et al.*, 2024; Boving *et al.*, 2025b).

Continuous *in situ* Ψ data offer a valuable pathway to overcome challenges in RS of vegetation water status by providing localized, high-frequency measurements essential for calibrating and validating RS products (Fig. 6). These data enable detailed characterization of diurnal and seasonal plant hydraulic dynamics, bridging the temporal and spatial gaps inherent between localized ground observations and broader-scale RS datasets. However, scale mismatches remain a key issue: RS measurements typically represent footprints spanning tens of kilometers for microwave-range to tens of meters for visible-range, while field measurements are restricted to individual plants or small plots. Addressing this mismatch requires coordinated campaigns deploying stand-scale GNSS or microwave sensors co-located with multiple Ψ and LAI measurements to disentangle the intertwined effects of biomass and Ψ on VOD signals. This multi-scale, multi-sensor approach is critical for improving RS algorithm development and model validation. Airborne RS campaigns can also serve as intermediate validation steps bridging ground and satellite scales (e.g. Chadwick *et al.*, 2025; Colliander *et al.*, 2025).

Using continuous ψ measurements to disentangle the impact of soil moisture vs vapor pressure deficit on plant health

Continuous measurements of Ψ provide a valuable tool for disentangling the effects of soil moisture and atmospheric demand, particularly VPD, on plant water status and health. At timescales of weeks or longer, periods of high VPD tend to co-occur with low soil water. This coupling between soil and atmospheric drought has historically made it difficult to disentangle their impact on plant function (Novick *et al.*, 2024). High-frequency monitoring of plant physiological variables is one way to surmount this difficulty. While soil water and VPD are closely coordinated at long timescales, they tend to be decoupled at hourly-to-daily timescales over which soil water is relatively constant, but VPD varies considerably (Lin *et al.*, 2018; Novick *et al.*, 2024). Thus, statistical approaches can be applied to high-resolution data to achieve an empirical disentanglement of VPD vs soil water impacts (Novick *et al.*, 2016; Flo *et al.*, 2022; Guo *et al.*, 2022).

A key uncertainty for predicting vegetation responses to climate change is the extent to which increasing VPD – driven primarily by rising temperatures – will push plants closer to hydraulic failure independently of soil moisture availability (Adams *et al.*, 2017; Anderegg *et al.*, 2018; Massmann *et al.*, 2019; Grossiord *et al.*, 2020; Novick *et al.*, 2024). Existing hydraulic cost-based stomatal optimization algorithms (Sperry *et al.*, 2017; Wang *et al.*, 2020) in principle capture the simultaneous consequences of soil matric potential and VPD. However, the predictions of existing models can differ substantially at environmental extremes (Wang *et al.*, 2020) and may not accurately capture the dynamics of extreme stress (particularly thermal stress, for example Marchin *et al.*, 2021). This question of what happens at the extremes is especially relevant in mesic ecosystems, where plants may not be adapted to cope with prolonged periods of high evaporative demand. While some species may maintain hydraulic function under moderate VPD increases, others may reach critical thresholds, especially during compounding events, such as heatwaves or multi-day droughts.

As climate change progresses, shifts in the relative importance of soil moisture and VPD are expected to reshape plant hydraulic strategies. In regions where soil drought becomes more frequent, plants may reduce their sensitivity to VPD through structural or physiological adaptations (Novick *et al.*, 2024; Grossiord *et al.*, 2020; Anderegg *et al.*, 2016; Li *et al.*, 2023; Martínez-Vilalta *et al.*, 2009). Conversely, in regions with relatively stable soil moisture, rising VPD could become the dominant driver of hydraulic stress. These shifts may result in long-term changes in biomass allocation – such as deeper rooting systems, changes in stem hydraulic architecture, or altered stomatal regulation – that reflect new trade-offs between hydraulic safety and carbon gain. However, the pace and extent of such adaptations remain uncertain and are likely to vary across ecosystems and plant types. Challenging mechanistic plant hydraulic models with high-resolution Ψ and environmental forcing data can help us better untangle both the short- and long-term impacts of soil water and VPD and also reveal how well (or poorly) existing stomatal theory can integrate evaporative vs supply limitations on plant function.

Additional knowledge gaps pertain to the physiological regulation of plant responses to VPD. For instance, the trade-off between stomatal regulation for leaf cooling and hydraulic safety is poorly understood, especially under extreme heat (McDowell *et al.*, 2008; Sperry & Love, 2015; Anderegg *et al.*, 2016; Urban *et al.*, 2017; Grossiord *et al.*, 2020; Posch *et al.*, 2024). Hormonal signaling, particularly the role of abscisic acid, may also influence VPD sensitivity and recovery dynamics following drought (Tardieu & Simonneau, 1998; Zhang *et al.*, 2006; McAdam & Brodribb, 2015; Sperry & Love, 2015). These processes vary across species and life histories, further complicating predictions of ecosystem responses to climate extremes. Ultimately, continuous Ψ monitoring provides a powerful lens for investigating plant responses to both soil water supply and atmospheric demand. By integrating these measurements with detailed environmental data and novel analytical frameworks, researchers can clarify the mechanistic underpinnings of hydraulic stress and improve predictions of plant vulnerability under future climate scenarios.

Unraveling plant drought strategies through continuous monitoring

At the ecological scale, continuous measurements of Ψ enhance our understanding of plant water-use strategies along the spectrum from conservative (isohydric) to liberal (anisohydric) behaviors, and how these strategies respond dynamically to environmental drivers, such as VPD and soil moisture. Such measurements also shed light on the complex interactions among hydraulic vulnerability, safety margins, and drought-induced mortality. However, extrapolating these insights across diverse species and ecosystems introduces biases and uncertainties, underscoring the need for careful validation and context-specific interpretation. Notably, evidence from both natural and managed systems indicates that drought-driven declines in root hydraulic conductance are not confined to woody species: Bourbia *et al.* (2021) observed similarly high sensitivity of whole-root hydraulic conductance to water deficit in a herb and a conifer, while field-scale work in maize shows that soil–plant water relations (including leaf Ψ) depend strongly on root–soil hydraulic properties under drought (e.g. Jorda *et al.*, 2022). Continuous data are crucial to filling persistent knowledge gaps regarding hydraulic conductivity and capacitance. The temporal dynamics of hydraulic conductivity – its decline, recovery, and ultimate failure in response to rising VPD, decreasing soil Ψ, or their combined effects – remain poorly understood due to limited availability of continuous pressure measurements. Similarly, hydraulic capacitance, an essential trait that buffers hydraulic damage and supports photosynthetic function under stress, has been insufficiently studied in natural field conditions. Integrating continuous measurements of both Ψ and storage could unlock new insights into these processes, advancing our understanding of plant drought resilience and recovery mechanisms.

In addition to stomatal regulation, plants can restrict water loss through nonstomatal mechanisms, including dynamic changes in leaf hydraulic properties, such as reduced plasma membrane permeability and altered cell-to-cell water transport. These responses may involve regulation of aquaporin activity, membrane restructuring, or shifts in hydraulic compartmentalization within leaf tissues, allowing plants to decouple transpiration from Ψ gradients under stress conditions (e.g. Jain *et al.*, 2024). Because these processes operate independently of stomatal conductance and can vary rapidly in time, they are difficult to infer from gas exchange measurements alone. Continuous and tissue-specific Ψ measurements, therefore provide a valuable tool for investigating such dynamic adaptations of the hydraulic pathway.

Water potential as a key regulator of plant growth

Plant growth fundamentally results from water accumulation in expanding tissues, driven by gradients in Ψ between the soil, vascular system, and growing cells. Cell expansion occurs when water uptake, governed by Ψ gradients, generates turgor pressure sufficient to overcome cell wall resistance, linking plant hydraulics directly to growth processes (Lockhart, 1965; Cosgrove, 1993). As a result, variability in Ψ is not only a signal of plant water status but also a mechanistic control on growth rates across organs and timescales.

Continuous Ψ measurements provide a unique opportunity to investigate growth dynamics at temporal resolutions that were previously inaccessible. Diurnal fluctuations in Ψ influence the timing and magnitude of growth, often leading to growth pulses during periods of reduced transpiration demand (e.g. nighttime or early morning), when Ψ gradients favor water uptake into expanding tissues (e.g. Cosgrove, 1993). High-frequency Ψ data therefore enable direct examination of how environmental drivers, such as VPD, soil moisture availability, and atmospheric conditions regulate growth through their effects on plant water status.

When combined with complementary measurements of growth – such as stem diameter variations, leaf expansion, or fruit growth – continuous Ψ observations can help disentangle reversible changes in tissue WC from irreversible growth (Zweifel

Table 2 Comparison of plant water sensing methods across five attributes: measurement type, scale, price, applications, and validation.

	Measurement type	Direct/indirect	Continuous/discontinuous	Scale	Price	Applications	Validation
Pressure chamber 	Water potential (Ψ)	Direct	Discontinuous	Point (leaf, small stems)	$$	Field campaigns, calibration/ validation of sensors	‘Gold’ standard for Ψ
Psychrometers 	Water potential (Ψ)	Direct	Continuous	Point (leaf, stems)	$$$	Detailed physiological studies, better performed under laboratory or controlled environments	Requires careful calibration and validations against pressure chamber
Microtensiometer	Water potential (Ψ)	Direct	Continuous	Point (stem)	$$	Continuous *in situ* Ψ measurements in field trees	Requires careful calibration and validations against pressure chamber
TDR/FDR 	Water Content (WC)	Indirect	Continuous	Organ (stem)	$$–$$$	Potential for wood moisture dynamics, trees response to changes in water availability, modeling inputs	Indirect Ψ via pedotransfer with Soil Moisture or continuous water potential measurements
GNSS	Trunk/Stem swelling	Indirect	Continuous	Whole tree/ecosystem	$$$ - $$$$	Long-term water status via stem shrinkage. validation for remote-sensing measurements	Indirect validation via Ψ measurements
Dendrometers 	Stem diameter	Indirect	Continuous	Organ (stem)	$$	Growth dynamics, plant water status via shrinkage	Requires separation of growth and water-related signals to isolate plant water dynamics
Tower-based radiometers	Trunk/Stem swelling	Indirect	Continuous	Whole tree/ecosystem	$$$$	Long-term measurements of water status, for example through continuous canopy temperature monitoring as a proxy for plant stress	Indirect validation via Ψ measurements

Price is represented qualitatively: $ = low cost, $$$$ = high cost. Scale refers to spatial or biological resolution. ‘Direct’ methods measure water potential or water volume explicitly; ‘Indirect’ methods rely on validation or modeling.

et al., 2001; Steppe *et al.*, 2005). This integration offers a powerful framework for linking hydraulic constraints, water storage dynamics, and growth regulation, and for testing theoretical models that describe growth as a balance between hydraulic supply and cell wall properties (Lockhart, 1965; Cosgrove, 2016). More broadly, incorporating continuous Ψ measurements into growth studies has the potential to improve our understanding of how water availability constrains productivity under variable and changing climates. By explicitly connecting hydraulic dynamics to growth processes, Ψ-based approaches can help bridge plant physiology, ecohydrology, and ecosystem productivity, representing a critical research frontier for both experimental and modeling efforts.

Conclusions

Continuous plant water potential (Ψ) measurements represent a powerful tool for advancing our understanding of plant physiology, ecosystem function, and vegetation responses to environmental change. As a direct indicator of plant water status, Ψ provides mechanistic insight into plant responses to both soil water availability and atmospheric demand and offers critical context for interpreting RS observations and model outputs. Importantly, extending Ψ measurements beyond individual organs to stands and ecosystems is scientifically necessary to capture spatial heterogeneity in water availability, species composition, and atmospheric forcing, and to link plant hydraulics with land–atmosphere exchange and ecosystem-scale processes. To fully realize this potential, shared best practices and harmonized, context-specific protocols are needed for sensor deployment, data collection, calibration, and quality control. Without such guidance, methodological inconsistencies can introduce systematic biases that limit the comparability and synthesis of Ψ measurements across species, ecosystems, and timescales.

Choosing an appropriate sensor for continuous Ψ monitoring requires balancing trade-offs among accuracy, durability, suitability for different wood anatomies, spatial and temporal coverage, and cost. Although recent advances in direct Ψ sensors have expanded measurement capabilities, no single technology currently meets all experimental needs. In this context, WC–based approaches should not be viewed as substitutes for direct Ψ measurements, but rather as complementary tools with distinct strengths and limitations that remain valuable where direct methods are impractical, cost-prohibitive, or logistically constrained. Together, these considerations highlight the need for continued development of versatile sensor designs capable of functioning across diverse species, environments, and research scales.

Across both direct and indirect approaches, several common pitfalls repeatedly limit data quality and comparability. These include suboptimal installation (e.g. poor xylem contact, inadequate insulation, or placement in rapidly growing tissues), insufficient calibration across relevant pressure or moisture ranges, and failure to account for environmental confounders, such as temperature, rainfall interception, or VPD. Long-term deployments are particularly vulnerable to sensor drift, biological interference, and data gaps, underscoring the importance of redundancy, routine quality control, and periodic validation against independent measurements. Meaningful calibration and interpretation therefore require (1) species- and site-specific calibration strategies for WC-based sensors, (2) co-located environmental measurements to correct for nonhydraulic effects, and (3) explicit consideration of scale mismatches when linking tissue-level observations with canopy- or ecosystem-scale RS products. Integrating Ψ measurements with complementary observations – such as stem WC, sap flux, and environmental variables – can further strengthen inference and help bridge methodological limitations, analogous to approaches used in soil water retention studies. Comparative summaries of sensor attributes and trade-offs are provided in Table 2. In addition, collaborative data networks and repositories, such as PSInet (Restrepo-Acevedo *et al.*, 2024), will be essential to ensure that Ψ data are reliable, accessible, and interoperable with meteorological, hydrological, and RS datasets.

Ultimately, Ψ data provide more than a snapshot of plant stress; they offer a dynamic view of how vegetation interacts with its environment across scales. As ecosystems face increasing pressures from climate extremes, rising VPDs, and shifting precipitation regimes, continuous Ψ monitoring will become increasingly important for identifying vulnerable systems, informing adaptive management strategies, and improving predictions of ecosystem productivity and resilience. Achieving this potential will require continued methodological refinement, interdisciplinary collaboration, and investment in robust monitoring infrastructure so that Ψ observations can inform science, policy, and conservation at scale.

Acknowledgements

The authors recognize support from the U.S. National Science Foundation (NSF), Division of Integrative Organismal Systems (IOS) via IOS-2243900 IOS-2006196. K. Novick acknowledges additional support from the US (United States) Department of Energy, Office of Science, Biological and Environmental Research, Environmental System Science program (grant no.: DE-SC0021980). D. Beverly acknowledges support from the USDA (United States Department of Agriculture) – National Institute of Food and Agriculture (NIFA, grant no.: 2023-67012-40083).A.G Konings acknowledges support from the Alfred P. Sloan Foundation, from the National Aeronautics and Space Administration, Soil Moisture Active Passive (SMAP) Science Team, and by the National Aeronautics and Space Administration (NASA), Carbon Cycle Science (CARBON) Program through Grant 80NSSC21K1712.

Competing interests

None declared.

Author contributions

AMRA, SK, KN and JG developed the concept for this paper. AMRA, SK, JK and LA analyzed and provided the data for the figures. AMRA wrote the manuscript. VH, RZ, AGK, GK, LA, JP, SSP, JHS, DPB, RKM, YY, CH, GB, MB and AC assisted with the drafting of the final manuscript.

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Data availability

The datasets used to generate Fig. 2 are available at https://doi.org/10.5281/zenodo.18856863. The dataset for Fig. 3 is available at https://doi.org/10.5Figureodo.18856768. The dataset used for Fig. 4 is available at https://doi.org/10.18738/T8/YZTCC2. Data for all other figures are publicly available in the cited references and on the websites of the respective sensor manufacturers.

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