



PSInet: a new global water potential network

Ana Maria Restrepo-Acevedo^{1,2,*}, Jessica S. Guo³, Steven A. Kannenberg², Michael C. Benson¹, Daniel Beverly¹, Renata Diaz³, William R. L. Anderegg⁴, Daniel M. Johnson⁵, George Koch⁶, Alexandra G. Konings⁷, Lauren E. L. Lowman⁸, Jordi Martínez-Vilalta^{9,10}, Rafael Poyatos^{9,10}, H. Jochen Schenk¹¹, Ashley M. Matheny¹², Katherine A. McCulloh¹³ , Jesse B. Nippert¹⁴, Rafael S. Oliveira¹⁵, Kimberly Novick¹

¹O'Neill School of Public & Environmental Affairs, Indiana University Bloomington, 702 N Walnut Grove St, Bloomington, IN 47405, USA

²Department of Biology, West Virginia University, Morgantown, VA 26506, USA

³Arizona Experiment Station, University of Arizona, 1140 E. South Campus Dr., Tucson, AZ 85721, USA

⁴School of Biological Sciences and Wilkes Center for Climate Science and Policy, University of Utah, Salt Lake City, UT 84112, USA

⁵Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

⁶Center for Ecosystem Science and Society & Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ 86011, USA

⁷Department of Earth System Science, Stanford University, Stanford, CA 94305, USA

⁸Department of Engineering, Wake Forest University, Winston-Salem, NC 27101, USA

⁹CREAF, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain

¹⁰Universitat Autònoma de Barcelona, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain

¹¹Department of Biological Science, California State University, Fullerton, CA 92831, USA

¹²Department of Earth and Planetary Sciences, Jackson School of Geological Sciences, University of Texas at Austin, Austin, TX 98705, USA

¹³Department of Botany, University of Wisconsin-Madison, Madison, WI 53706, USA

¹⁴Division of Biology, Kansas State University, Manhattan, KA 66506, USA

¹⁵Department of Plant Biology, University of Campinas (UNICAMP), Campinas, SP, Brazil

*Corresponding author: 3330 E Foothill Blvd, Unit 212, Pasadena, CA 91107, USA; Tel: 512-696-8622. Email: anarest@iu.edu

Handling Editor: Sebastian Pfautsch

Given the pressing challenges posed by climate change, it is crucial to develop a deeper understanding of the impacts of escalating drought and heat stress on terrestrial ecosystems and the vital services they offer. Soil and plant water potential play a pivotal role in governing the dynamics of water within ecosystems and exert direct control over plant function and mortality risk during periods of ecological stress. However, existing observations of water potential suffer from significant limitations, including their sporadic and discontinuous nature, inconsistent representation of relevant spatio-temporal scales and numerous methodological challenges. These limitations hinder the comprehensive and synthetic research needed to enhance our conceptual understanding and predictive models of plant function and survival under limited moisture availability. In this article, we present PSInet (PSI—for the Greek letter Ψ used to denote water potential), a novel collaborative network of researchers and data, designed to bridge the current critical information gap in water potential data. The primary objectives of PSInet are as follows. (i) Establishing the first openly accessible global database for time series of plant and soil water potential measurements, while providing important linkages with other relevant observation networks. (ii) Fostering an inclusive and diverse collaborative environment for all scientists studying water potential in various stages of their careers. (iii) Standardizing methodologies, processing and interpretation of water potential data through the engagement of a global community of scientists, facilitated by the dissemination of standardized protocols, best practices and early career training opportunities. (iv) Facilitating the use of the PSInet database for synthesizing knowledge and addressing prominent gaps in our understanding of plants' physiological responses to various environmental stressors. The PSInet initiative is integral to meeting the fundamental research challenge of discerning which plant species will thrive and which will be vulnerable in a world undergoing rapid warming and increasing aridification.

Key words: database, drought, network, plants, plant hydraulics, water potential.

Water potential data are crucial for understanding plant responses to changing environmental conditions

Ecosystem function is strongly controlled by water potential (Ψ) gradients from soil to plants and to the atmosphere. In many ways, Ψ can be imagined as the 'blood pressure' of the ecosystem; in the same way that blood pressure is a key measure of human health, Ψ is a key indicator of plant

performance. Gradients in Ψ —within the soil, between plant roots and leaves, and between leaves and the atmosphere—are the energetic basis for ecosystem water fluxes. Leaf water potential (Ψ_L) directly controls stomatal conductance and photosynthesis (Jarvis 1976; Sperry 2000) and is coupled with branch and stem water potential (Ψ_X), which determine the risk of drought-driven hydraulic failure (Choat et al. 2012). Severely limited access to soil moisture can cause detrimental

Received: February 23, 2024. Accepted: August 26, 2024

© The Author(s) 2024. Published by Oxford University Press.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

declines in plant Ψ_L and Ψ_X , which can in turn induce stomatal closure, cause reductions in photosynthesis and growth, propagate embolism through the xylem network and limit water transport. Consequently, Ψ is a first-order control on how much carbon ecosystems remove from the atmosphere, how much water they move to the atmosphere in the process and the likelihood that plants survive droughts. Over the past decade, there has been a surge of interest in uncovering the relationships between Ψ and physiological traits (Martínez-Vilalta et al. 2017; McCulloh et al. 2019; Li et al. 2020; Flo et al. 2021; Kannenberg et al. 2021), incorporating plant hydraulics into predictive models (Kennedy et al. 2019; Mirfenderesgi et al. 2016; Sperry et al. 2017; Li et al. 2020) and advancing diverse remote-sensing approaches for detecting Ψ (Momen et al. 2017; Konings et al. 2019, 2021).

However, while our understanding of plant Ψ is theory-rich, it is currently data-poor and there exist significant challenges in its study. Despite the abundance of time series data collected in some regions, accessibility remains a considerable hurdle due to the absence of a centralized database. Additionally, published Ψ studies tend to be biased towards ecosystems within North America (USA and Canada) and Europe (Fig. 1), which together comprise ~47% of studies conducted globally even though these regions represent only 24% of the global land area. A major challenge in studying Ψ lies in the absence of a centralized repository that could facilitate the synthesis of essential knowledge and bridge prominent gaps in our comprehension of plants' physiological responses to diverse environmental stressors. The absence of a unified information source, coupled with geographical biases, plays a pivotal role in conspicuously underrepresenting critical ecosystems globally. Furthermore, this deficiency in Ψ data deprives the scientific community of indispensable insights necessary for a holistic comprehension of Earth's interlinked systems and their responses to environmental dynamics.

Plant water potential measurements: status and future needs

The predominant approach for assessing plant Ψ_L and Ψ_X currently involves manual measurements using a Scholander-style 'pressure chamber' (Scholander et al. 1965; Rodríguez-Dominguez et al. 2022). These measurements provide estimates of plant Ψ_L and Ψ_X under specific conditions at a specific moment in time. However, for a more comprehensive understanding of a plant's water stress, it is essential to collect data multiple times during the day and at intervals spanning weeks or longer, to capture gradients in key environmental drivers. While pressure chamber data are temporally discrete, these data are usually collected twice daily (e.g. and pre-dawn and mid-day), often for several weeks or months. Thus, a rich global database would be particularly useful to comprehend Ψ at diurnal timescales and to capture seasonal dynamics and fluctuations in soil moisture. It aids in evaluating the water status and drought responses of vegetation within natural ecosystems. Chamber Ψ can be monitored to optimize water management practices in agriculture and horticulture (Bittelli 2010; Levin and Nackley 2021). Finally, it serves as a reliable reference dataset for the validation of remote sensing techniques used in monitoring vegetation water status (Momen et al. 2017; Holtzman et al. 2021).

Records of pre-dawn and mid-day water potential collected with pressure chambers at weekly (or longer) timescales may be sufficient to link Ψ_L and Ψ_X dynamics to variations in soil water availability within a specific study. However, the time-intensive nature of this sampling approach usually limits the length of these time series. Furthermore, the time intervals at which most pressure chamber data are gathered are not sufficiently fine to capture more rapid sub-diurnal processes, such as stomatal response to changes in vapor pressure deficit (VPD; Novick et al. 2022) and daily fluctuations in plant water storage (Matheny et al. 2017). Moreover, collecting Ψ_L and Ψ_X data involves conducting field work, which presents unique inherent challenges.

The PSInet water potential dataset and community

The PSInet Research Coordination Network (<https://psine.trcn.github.io/>) is a new centralized global dataset of plant and soil water potential measurements that will confront the Ψ information gap and enable the pursuit of previously intractable questions about plant responses to environmental drivers. PSInet will function as a bridge connecting readily available information about environmental variables and eco-physiological responses from other network databases. The latter include continuous flux tower observations of ecosystem-scale carbon and water fluxes (e.g. AmeriFlux and FLUXNET; Baldocchi 2008; Novick et al. 2018), the SAPFLUXNET database of continuous tree water-use observations (Poyatos et al. 2012) and the Xylem Functional Traits database (Choat et al. 2012), which is the primary source of information about plant hydraulic traits within the larger TRY plant traits database (Kattge et al. 2019). While these networks aggregate many important eco-physiological variables and traits, they do not provide the time series of Ψ that are required to mechanistically link environmental drivers and physiological responses, and to benchmark and inform modeling and remote-sensing approaches. This is the gap that PSInet will fill, to accelerate our theoretical and predictive understanding of plant–environment responses, now and for a warmer future.

Importantly, PSInet is not just a network of data but a network of people, organized around coordinated research, training and community-building activities designed to increase the availability, integrity and accessibility of Ψ information to a diverse scientific community. An overarching goal of PSInet is to create a Community of Practice with greater gender balance, racial diversity and geographic diversity than the status quo. We foster a diverse and inclusive network environment with multiple mechanisms to advance the careers of demographically, geographically and intellectually diverse cohorts of early career scientists. Within the scope of PSInet, we will implement multiple mechanisms to support the training of the next generation of ecophysicologists, including multiple early career summer workshops such as Phys-Fest, a forthcoming early career workshop on plant hydraulics, a forthcoming distributed graduate seminar, and numerous opportunities to participate in virtual and in-person workshops, conference sessions and seminars (Fig. 2). Implicit in all PSInet Community of Practice activities is an emphasis on elevating the work and careers of scientists from underrepresented demographics and geographies.

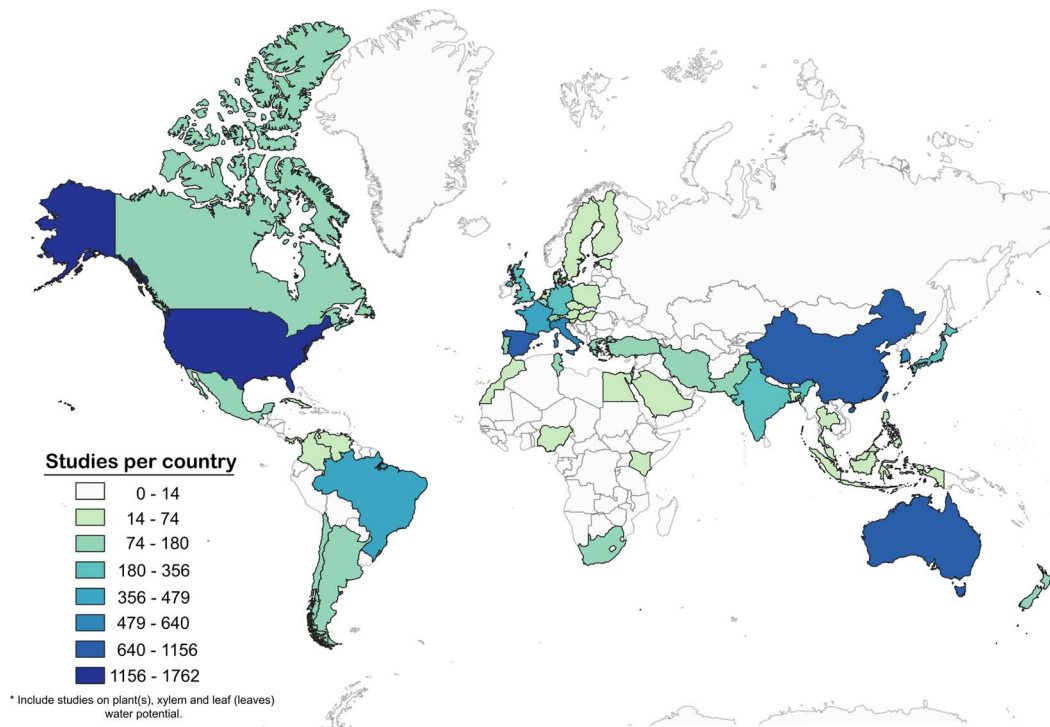


Figure 1. Geographic distribution of studies on plant water potential for both natural and agricultural ecosystems from 1970 to 2023 (including plants, leaves and xylem). Data from a Scopus search of literature (plant[s] water potential' OR 'xylem water potential' OR 'leaf water potential' OR 'stem water potential' in title, abstract or keywords) and visualized by color-coding the number of studies in each country. Notably, the USA stands out with the highest number of studies (1257), followed by China (794) and Australia and Spain (507 each). There is a pronounced underrepresentation in regions such as central and South America, Africa and eastern European countries. These areas exhibit a significant gap in research on Ψ , highlighting the need for more comprehensive global coverage in the field.

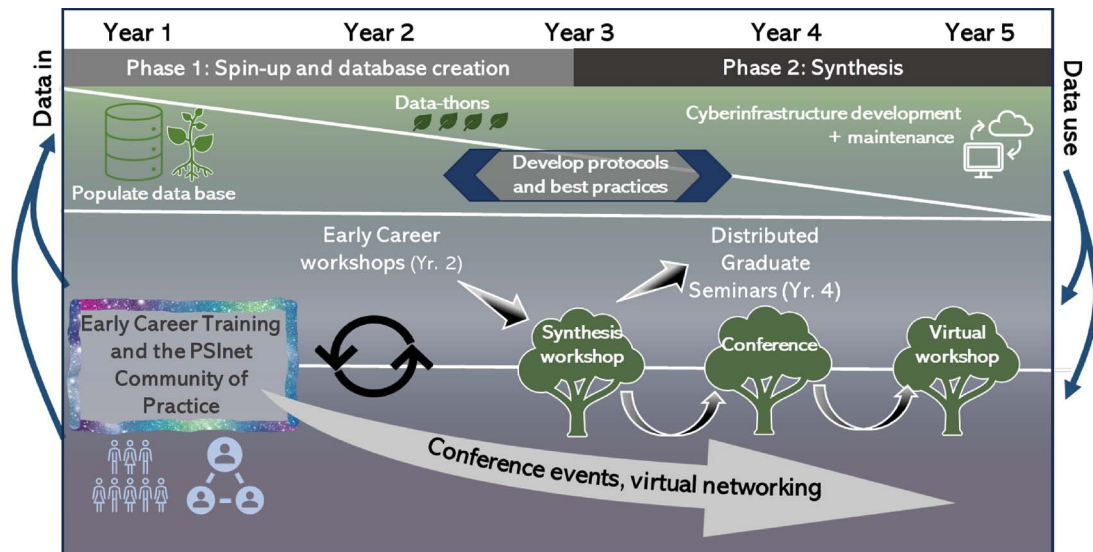


Figure 2. PSInet project activities and timeline.

Figure 2. PSInet project activities and timeline.

In early 2024, we initiated collection of plant water potential data and invite potential data contributors to join the effort. As a benefit to contributing data for free and open dissemination via PSInet, data contributors will receive priority access to the PSInet data for an embargo period of 1 year and opportunities to participate in PSInet networking, career development, and collaborative activities. Up to two contributors associated with each dataset contributed to the PSInet database will have the opportunity to

collaborate on a forthcoming data paper. More information about the PSInet data submission process is available in Fig. 3 and at <https://psinetrcn.github.io/submit.html>. We are also actively seeking volunteer participation in the organization and execution of PSInet networking and outreach activities. Interested participants can indicate their interest by visiting <https://psinetrcn.github.io/join.html>. Our initial focus is on collecting plant water potential data and associated ancillary measurements. In the future, we envision an extension of

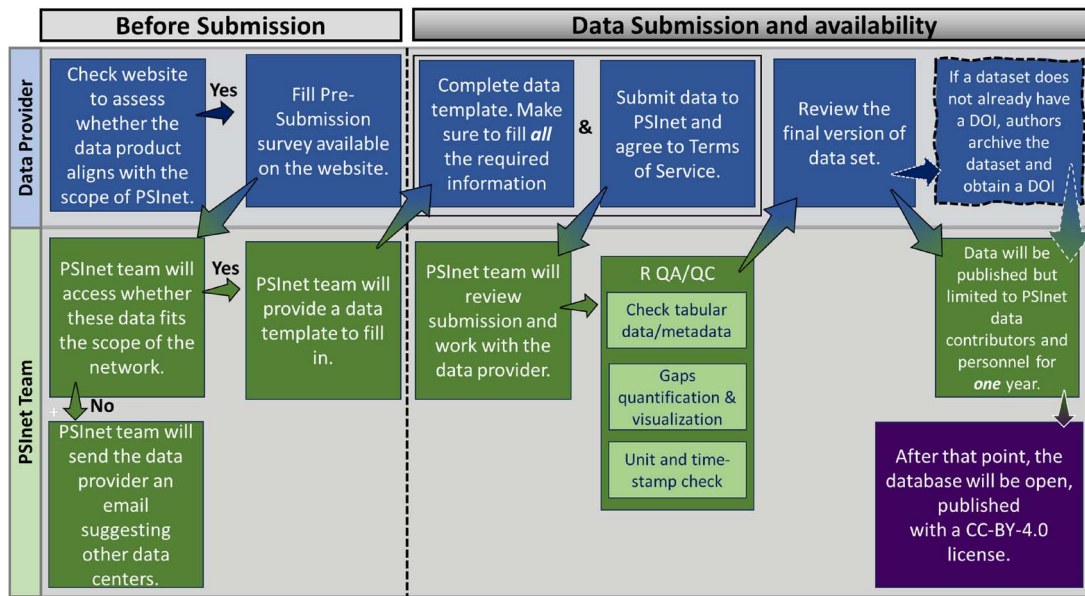


Figure 3. PSInet data flow from submission to publication. The first step is completing the pre-submission survey available on the PSInet website (<https://psinetrcn.github.io/submit.html>). Subsequently, the contributor prepares the data for submission, after which PSInet personnel conduct quality assurance and quality control (QA/QC) checks. Data contributors are then responsible for final approval and the assignment of a unique data identifier (DOI). The data become accessible initially to the contributors and afterwards to the public.

PSInet to collect and aggregate information on soil water potential from sites that do not necessarily monitor plant water potential.

Alternative techniques for measuring Ψ

Over the past three decades, there has been considerable progress in the development of alternative techniques for monitoring Ψ_L and Ψ_X and plant's water status to address the discontinuous and discrete nature of pressure chamber Ψ measurements (Fig. 4). Several techniques offer promising, automated methods to monitor Ψ on the order of days to months. These techniques could be broadly classified as (i) direct sensing of water potential such as psychrometry, and most recently micro-tensimeters and hydrogel nano-reporters, and (ii) indirect measurements such as remote sensing, or geophysical monitoring methods (e.g. capacitance such as time domain reflectometry [TDR], frequency domain reflectometry [FDR] and electrical resistivity). As a network of data and people involved in water potential, PSInet is well-poised to evaluate Ψ data generated with newer techniques, facilitate intercomparisons across methodologies, and promote best practices for collecting and analyzing these data.

These techniques allow estimations and measurements of plant Ψ at timescales that can capture high frequency or large spatial dynamics, and which complement the scales over which water and carbon fluxes are often measured and modeled. However, their practical implementation remains limited due to acknowledged constraints associated with these methods. Overall, the limitations associated with these techniques challenge our ability to synthesize and interpret the water potential 'observations'. Factors include: (i) assessing method selection based on the specific plant tissue under investigation (e.g. Ψ_L vs Ψ_X vs root water potential— Ψ_R), (ii) scaling challenges from individual plants to the ecosystem level, (iii) the essential but often problematic tasks of instrument maintenance under field conditions (e.g. accessing

canopies and the necessity for routine checking due to tree protective mechanisms), (iv) the necessity of species-specific calibration parameters, and (v) potential biases stemming from the sensitivity of instruments to environmental variables. Collectively, these techniques represent valuable resources for bridging the spatial and temporal gaps inherent to pressure chamber data, but we urgently need openly accessible databases and community crafted best practices to overcome these operational difficulties.

For instance, remote sensing, with its potential for broad spatial coverage, appears as the second most common technique used to study and provide information about Ψ (Fig. 2). Several relevant approaches exist, including hyperspectral, L-band, thermal and microwave measurement. Among these methods, microwave remote sensing, as highlighted by Konings et al. (2021), shows promise since it can penetrate clouds and is sensitive to vegetation water content. However, this approach is not currently sufficiently mature to be used for estimation of Ψ without extensive ground calibration and validation data. Furthermore, a substantial portion of the current studies on Ψ utilizing remote sensing techniques tends to focus more on evaluating various methodologies rather than fundamental water potential research. Over the past few decades, alternative techniques like capacitance sensors (TDR, FDR—Matheny et al. 2017), electrical resistivity (Cardenas et al. 2014), hydrogel nanoreporters (Jain et al. 2021) and even high-resolution stem dendrometry (Drew et al. 2011; Eller et al. 2017) have emerged as suitable options for long-term, high-resolution studies across various plant types and specific tissues (particularly for Ψ_R and Ψ_X). However, these methods also rely on indirect measurements since they measure water content and approximate Ψ from this data (much like microwave remote sensing does). Moreover, these techniques require precise, species-specific calibration parameters that may impact measurement accuracy and limit generality to other species or ecosystems.

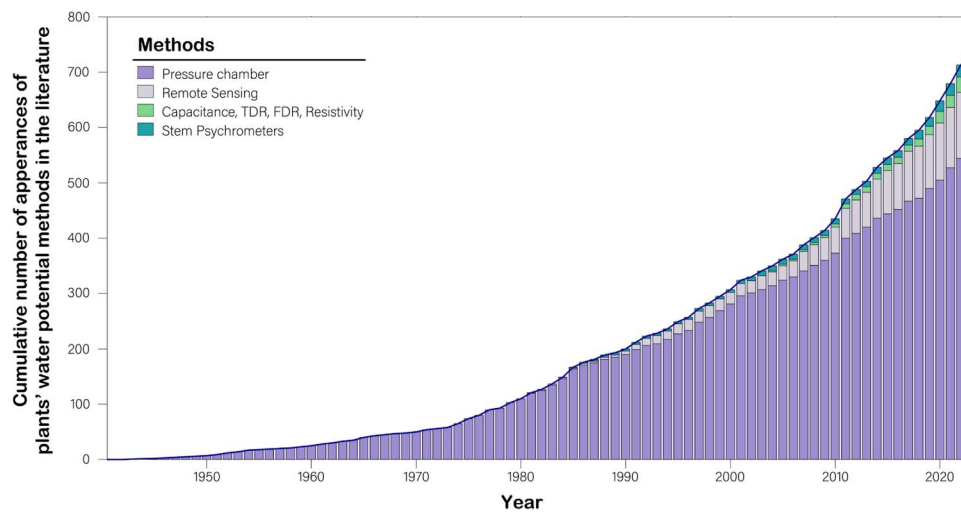


Figure 4. Cumulative count of appearances of different direct and indirect methods for estimating plant water potential in a Scopus search of literature (plant[s] water potential' OR 'xylem water potential' OR 'leaf water potential' OR 'stem water potential' in title, abstract or keywords). Note that counts represent individual appearances of each method, not papers (e.g. a paper can have multiple methods). We found that the pressure chamber method (e.g. Scholander et al. 1965) is historically the most popular (~87%) followed by remote sensing techniques including methodological developments and estimations of plant Ψ (~10%). However, in the last 10 years, the popularity of the different methods has been changing. The pressure chamber method remains the most popular with ~79%, followed by remote sensing (~15%), geophysical techniques such as resistivity, TDR, FDR (~2.7%) and psychrometry (2.6%).

Stem psychrometry has been proven suitable for monitoring Ψ_x directly on individual plants at longer temporal resolutions (Dixon and Tyree 1984; Guo et al. 2019; Kannenberg et al. 2022), but it can present significant limitations, especially concerning the thermocouples in the sensors. High-precision Peltier-style thermocouples within the stem sensor can become occluded due to the plant wounding response, with the severity of this response varying significantly among different species. Moreover, this technique relies on the cooling effect resulting from water evaporation, which can be sensitive to daily and seasonal temperature and humidity fluctuations in natural conditions. To mitigate these limitations, careful calibration and frequent maintenance, as well as strong insulation and shielding to limit temperature gradients, are imperative. Furthermore, data must be corrected to account for temperature-related errors (Quick et al. 2018).

More recently, microtensiometers (Pagay et al. 2014; Pagay 2021; Dainese et al. 2021, 2022; Lakso et al. 2022; Conesa et al. 2023) have emerged as valuable tools for continuously monitoring plant water potential (Ψ) directly at a finer scale. It stands out that microtensiometers offer high-resolution measurements of 0.1 bar with measurements every 20 min. However, it is important to note that, owing to their small-scale nature, both microtensiometers and psychrometers provide localized measurements that may not be reflective of whole-plant dynamics. Achieving a comprehensive understanding of plant water potential may need the use of multiple devices, adding complexity to the study. Additionally, regular maintenance may be required to ensure the continued accuracy and reliability of microtensiometer measurements due to cavitation of water in the sensing system.

We recognize that the challenges discussed are not exclusive to monitoring plant Ψ . For instance, measurements of soil water potential (Ψ_s), which dictates water availability to plant roots, encounter similar hurdles (Martínez-Vilalta et al. 2021; Khare et al. 2022; Novick et al. 2022). Current soil sensors often have limitations, typically providing accuracy only

down to -2 MPa (with a few exceptions like the dielectric now available as TEROS 21 from METER). Additionally, the construction of accurate water retention curves, enabling the conversion of water content to water potential, can be intricate and demanding.

For these reasons, another important objective of PSInet is to facilitate the creation of community-developed best practices and protocols for emerging approaches to measuring water potential along the soil–plant–atmosphere continuum. The diversity of techniques used to measure Ψ emphasizes the necessity for inter-comparison and integration, aiming to streamline sensor choices in future studies. This juncture presents an opportune moment for a renewed emphasis on field data collection and the establishment of new networks, such as PSInet, for aggregating observations across various sites. Coupled with innovative approaches for integrating these observations into Earth system models, such initiatives can significantly advance our understanding of the intricate interplay within the soil–plant–atmosphere continuum.

Scientific questions answerable using data from PSInet

We anticipate that the extensive data and collaborative ethos of PSInet will be instrumental in addressing a wide range of crucial research questions spanning plant-to-ecosystem scales. These questions may include topics such as the following.

How do plants respond to increasing VPD induced by climate change?

Plants independently and interactively respond to water deficits both in the soil (e.g. soil water potential, Ψ_s) and the air (determined by VPD). Climate change is driving substantial increases in VPD almost everywhere (Ficklin and Novick 2017; Grossiord et al. 2020), but the directionality of soil moisture projections varies, increasing in some regions and decreasing in others (Cook et al. 2015). Consequently, the

relationship between Ψ_S and VPD is changing, and understanding how plants respond to each factor is essential for making reliable projections about plant function and survival in the future. Generalizing the role of VPD in governing plant dynamics requires plant Ψ time series collected at diurnal timescales over which VPD varies significantly, but soil moisture does not, necessary to disentangle the relative contribution of soil versus atmospheric drought. Continuous plant Ψ data are especially well-suited for this challenge, though diurnal pressure chamber data are also useful (Koch et al. 2015; Guo and Ogle 2018; Gersony et al. 2020).

What are the mechanisms underlying drought-induced plant mortality and hydraulic failure?

There is broad consensus that hydraulic failure, or the cessation of xylem water transport due to embolism, triggers drought-induced mortality in plants (Adams et al. 2017; Choat et al. 2018; Hammond et al. 2019; McDowell et al. 2022). The risk of hydraulic failure is typically assessed using the hydraulic safety margin (HSM), quantified as the difference between the minimum plant Ψ experienced by the plant and a measure of embolism resistance (e.g. P50, the Ψ causing 50% loss of hydraulic conductivity, Meinzer et al. 2009; Choat et al. 2012). In other words, $HSM = \text{minimum plant } \Psi - P50$. HSM integrates a measure of absolute stress tolerance determined in the laboratory (P50) with a measure of extreme exposure at the tissue level, yielding a promising indicator of mortality risk (Anderegg et al. 2016; Benito Garzón et al. 2018; Venturas et al. 2020). However, determining minimum Ψ is methodologically challenging, and current estimates are known to be biased due to the significant effect of sample size on absolute extremes (Martínez-Vilalta et al. 2021). PSInet will improve the quality and quantity of Ψ data available to assess drought stress exposure in plants.

What can nocturnal water potential data reveal about pre-dawn equilibrium throughout the soil–plant–atmosphere continuum?

It is often assumed that Ψ_L , Ψ_X and Ψ_S equilibrate during pre-dawn hours (Donovan et al. 2001; Fisher et al. 2006). This assumption has allowed eco-physiologists to use pre-dawn observations of plant water potential (Ψ) as a proxy for root-zone Ψ_S , circumventing the need for direct soil Ψ measurements. However, important eco-physiological processes such as nocturnal transpiration (Novick et al. 2009) and nocturnal refilling of water storage pools (Matheny et al. 2015) can prevent pre-dawn equilibrium (Bucci et al. 2005; Caird et al. 2007; Dawson et al. 2007). Understanding what drives disequilibrium is crucial, as it lowers pre-dawn Ψ_L and complicates assessments of species-specific rooting depths. Continuous plant Ψ data will be a valuable source of insight because equilibrium should be evident in the stationarity of pre-dawn plant Ψ time series.

How can we improve model predictions including plant hydraulics?

Feedback mechanisms linked to increasing drought frequency and intensity are a major source of uncertainty in land surface models (Reichstein et al. 2013, Mencuccini et al. 2019). Explicit representation of plant hydraulic processes can substantially reduce this uncertainty. Over the past 5–10 years,

hydrologic and Earth system models have increasingly incorporated improved representations of plant hydraulic dynamics (Mackay et al. 2015; Sperry et al. 2017; Kennedy et al. 2019; Mirfenderesgi et al. 2016; De Cáceres et al. 2021; Xu and Trugman 2021). Site-level tests of these models show enhanced prediction accuracy (Eller et al. 2020; Lowman and Godoy 2020; Sabot et al. 2019). However, fundamental questions remain, such as: (i) the optimal structure of hydraulic models for accurately reflecting and predicting carbon and water balance (Sabot et al. 2022) and (ii) the best methods for parameterizing these models, whether through model-data fusion (Li et al. 2020) or parameterization schemes based on theoretical principles (Sperry et al. 2016; Sabot et al. 2019; Eller et al. 2020). Addressing these knowledge gaps requires a comprehensive database like PSInet.

Can remotely sensed estimates of canopy water content capture plant and soil water potential across space and time?

One of the biggest challenges in studying Ψ is that this variable is difficult to measure even at the individual plant level. Moreover, to make informed decisions about the health of our ecosystems, it is imperative to explore strategies for linking Ψ to larger-scale observations derived from plot-level measurements or even from space (Novick et al. 2022).

Microwave remote sensing is among the most promising approaches for understanding Ψ dynamics at these scales (Konings et al. 2021). These microwave observations can be used to determine vegetation optical depth (VOD), which is sensitive to plant water content (Jackson and Schmugge 1991) and is related to Ψ (Momen et al. 2017; Konings et al. 2019; Holtzman et al. 2021; Humphrey and Frankenberg 2023; Yao et al. 2024). However, the exact relationship between VOD and Ψ can be influenced by various factors such as spatial and temporal resolution (VOD observations derived from satellite data), vegetation heterogeneity (Konings et al. 2019) and species-specific responses. Ground validation measurements are essential to improve the accuracy and reliability of studies on the relationship between Ψ and VOD data. Our centralized Ψ data from diverse ecosystems in PSInet will facilitate linking between Ψ measurements and these larger-scale techniques.

How much is our understanding of plant drought responses limited by lack of information about soil water potential?

The relationship between soil water potential (Ψ_s) and soil moisture content (θ)—often called the ‘water retention curve’ or ‘moisture release curve’—is highly non-linear and strongly dependent on soil texture and structure (Clapp and Hornberger 1978; van Genuchten 1980). Unfortunately, in-situ observations of Ψ_s are scarce in ecohydrological and ecological field settings, and site-specific information on water retention curves is largely absent from environmental observation networks (Novick et al. 2022). Because θ is widely measured while Ψ_s is not, θ is often used as a proxy for plant-available water (Green et al. 2019; Humphrey et al. 2021; Novick et al. 2016; Stocker et al. 2018). However, Ψ_s is a more physiologically relevant driver and better predicts ecosystem carbon fluxes compared with θ within and across sites (Baldocchi et al. 2004; Ghezzehei et al. 2019; Novick et al. 2022). Even if Ψ_s data were plentiful, modeling strategies to transform Ψ_s into θ would be necessary to

connect water balance equations with water potential-driven flows. Most land surface models rely on retention curve models parameterized with pedotransfer functions (conversion from moisture content to water potential) driven primarily by soil texture (Schaap et al. 2001). Although pedotransfer function development is an active field (Van Looy et al. 2017), most are characterized by large uncertainties that propagate through ecosystem models (Fatichi et al. 2020; Novick et al. 2022; Weihermüller et al. 2021). Site-level water retention curves and/or in-situ Ψ s data, which will be part of the PSInet database, may eliminate the need to rely on pedotransfer functions for site-level simulations, allowing other sources of model uncertainty to become more discernible.

Conclusion

Understanding which species will thrive and which will falter in a warmer and drier world is a fundamental research challenge informing many applications with societal value, including agro-ecosystem management and decisions about when and where ecosystems can be leveraged to mitigate climate change. PSInet is prepared to catalyze progress in areas that have been impacted by the scarcity of Ψ information. Moreover, our network of data and people will empower eco-physiological scientists by providing essential data, tools and a collaborative community for translational science. We aim to foster connections between research communities tackling plant responses to climate change, while fostering inclusivity and providing support to scientists in diverse regions.

Supplementary data

Supplementary data are available at *Tree Physiology* Online.

Funding

The authors recognize support from the National Science Foundation—Division of Integrative Organismal Biology via a Research Coordination Grant (#2243900). K.N. acknowledges additional support from the US (United States) Department of Energy via the Environmental System Science Program (grant number DE-SC0021980). D.B. acknowledges support from the USDA (United States Department of Agriculture)—National Institute of Food and Agriculture (NIFA, grant number 2023-67012-40083).

Conflict of interest

All authors declare that they have no conflicts of interest to report.

Data availability

The data that support the findings of this study were derived from the resources available in the public domain: [<https://www.scopus.com/>].

References

- Adams HD, Zeppel MJB, Anderegg WRL, Hartmann H, Landhäusser SM, Tissue DT, Huxman TE, Hudson PJ, Franz TE, Allen CD et al. 2017. A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nat Ecol Evol.* 1(9):1285–1291. <https://doi.org/10.1038/s41559-017-0248-x>.
- Anderegg WRL, Klein T, Bartlett M, Jansen S. 2016. Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. *Proc Natl Acad Sci USA.* 113(18):5024–5029. <https://doi.org/10.1073/pnas.1525678113>.
- Baldocchi D. 2008. ‘Breathing’ of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Aust J Bot.* 56(1):1–26. <https://doi.org/10.1071/BT07151>.
- Baldocchi DD, Xu L, Kiang N. 2004. How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. *Agric For Meteorol.* 123(1–2):13–39. <https://doi.org/10.1016/j.agrformet.2003.11.006>.
- Benito Garzón M, Robson TM, Hampe A. 2019. Δ TraitSDMs: species distribution models that account for local adaptation and phenotypic plasticity. *New Phytol.* 222(4):1757–1765. <https://doi.org/10.1111/nph.15716>.
- Bittelli M. 2010. Measuring soil water potential for water management in agriculture: a review. *Sustainability.* 2(5):1226–1251. <https://doi.org/10.3390/su2051226>.
- Bucci SJ, Goldstein G, Meinzer FC, Franco AC, Campanello P, Scholz FG. 2005. Mechanisms contributing to seasonal homeostasis of minimum leaf water potential and predawn disequilibrium between soil and plant water potential in neotropical savanna trees. *Trees.* 19(3):296–304. <https://doi.org/10.1007/s00468-004-0391-2>.
- Caird MA, Richards JH, Donovan LA. 2007. Nighttime stomatal conductance and transpiration in C3 and C4 plants. *Plant Physiol.* 143(1):4–10. <https://doi.org/10.1104/pp.106.092940>.
- Cardenas MB, Kanarek MR. 2014. Soil moisture variation and dynamics across a wildfire burn boundary in a loblolly pine (*Pinus taeda*) forest. *J Hydrol.* 519:490–502. <https://doi.org/10.1016/j.jhydrol.2014.07.016>.
- Choat B, Jansen S, Brodribb T, Cochard H, Delzon S, Bhaskar R, Bucci SJ, Feild TS, Gleason SM, Hacke UG et al. 2012. Global convergence in the vulnerability of forests to drought. *Nature.* 491(7426):752–755. <https://doi.org/10.1038/nature11688>.
- Choat B, Brodribb TJ, Brodersen CR, Duursma RA, López R, Medlyn BE. 2018. Triggers of tree mortality under drought. *Nature.* 558(7711):531–539. <https://doi.org/10.1038/s41586-018-0240-x>.
- Clapp RB, Hornberger GM. 1978. Empirical equations for some soil hydraulic properties. *Water Resour Res.* 14(4):601–604. <https://doi.org/10.1029/WR014i004p00601>.
- Conesa MR, Conejero W, Vera J, Ruiz-Sánchez MC. 2023. Assessment of trunk microtensiometer as a novel biosensor to continuously monitor plant water status in nectarine trees. *Front Plant Sci.* 14:1123045. <https://doi.org/10.3389/fpls.2023.1123045>.
- Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American southwest and Central Plains. *Sci Adv.* 1(1):e1400082. <https://doi.org/10.1126/sciadv.1400082>.
- Dainese R, de CFL Lopes B, Tedeschi G, Lamarque LJ, Delzon S, Fourcaud T, Tarantino A. 2022. Cross-validation of the high-capacity tensiometer and thermocouple psychrometer for continuous monitoring of xylem water potential in saplings. *J Exp Bot.* 73(1):400–412. <https://doi.org/10.1093/jxb/erab412>.
- Dainese R, Lopes BDCFL, Fourcaud T, Tarantino A. 2021. Evaluation of instruments for monitoring the soil–plant continuum. *Geomech Energy Environ.* 100256.
- Dawson TE, Burgess SSO, Tu KP, Oliveira RS, Santiago LS, Fisher JB, Simonin KA, Ambrose AR. 2007. Nighttime transpiration in woody plants from contrasting ecosystems. *Tree Physiol.* 27(4):561–575. <https://doi.org/10.1093/treephys/27.4.561>.
- De Cáceres M, Mencuccini M, Martin-StPaul N, Limousin J-M, Coll L, Poyatos R, Cabon A, Granda V, Forner A, Valladares F et al. 2021. Unravelling the effect of species mixing on water use and drought stress in Mediterranean forests: a modelling approach. *Agric For Meteorol.* 296:108233. <https://doi.org/10.1016/j.agrformet.2020.108233>.
- Dixon MA, Tyree MT. 1984. A new stem hygrometer, corrected for temperature gradients and calibrated against the pressure bomb. *Plant Cell Environ.* 7(9):693–697. <https://doi.org/10.1111/1365-3040.e11572454>.

- Donovan LA, Linton MJ, Richards JH. 2001. Predawn plant water potential does not necessarily equilibrate with soil water potential under well-watered conditions. *Oecologia*. 129(3):328–335. <https://doi.org/10.1007/s004420100738>.
- Drew DM, Richards AE, Downes GM, Cook GD, Baker P. 2011. The development of seasonal tree water deficit in *Callitris intratropica*. *Tree Physiol*. 31(9):953–964. <https://doi.org/10.1093/treephys/tpz031>.
- Eller CB, Barros F D V, Bittencourt PRL, Rowland L, Mencuccini M, Oliveira RS. 2017. Xylem hydraulic safety and construction costs determine tropical tree growth. *Plant Cell Environ*. 41(3):548–562. <https://doi.org/10.1111/pce.13106>.
- Eller CB, Rowland L, Mencuccini M, Rosas T, Williams K, Harper A, Medlyn BE, Wagner Y, Klein T, Teodoro GS et al. 2020. Stomatal optimization based on xylem hydraulics (SOX) improves land surface model simulation of vegetation responses to climate. *New Phytol*. 226(6):1622–1637. <https://doi.org/10.1111/nph.16419>.
- Fatichi S, Or D, Walko R, Vereecken H, Young MH, Ghezzehei TA, Hengl T, Kollet S, Agam N, Avissar R. 2020. Soil structure is an important omission in earth system models. *Nat Commun*. 11(1):522. <https://doi.org/10.1038/s41467-020-14411-z>.
- Ficklin DL, Novick KA. 2017. Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere. *J Geophys Res Atmos*. 122(4):2061–2079. <https://doi.org/10.1002/2016JD025855>.
- Fisher RA, Williams M, Lobo do Vale R, Lola da Costa A, Meir P. 2006. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. *Plant Cell Environ*. 29(2):151–165. <https://doi.org/10.1111/j.1365-3040.2005.01407.x>.
- Flo V, Martínez-Vilalta J, Mencuccini M, Granda V, Anderegg WRL, Poyatos R. 2021. Climate and functional traits jointly mediate tree water-use strategies. *New Phytol*. 231(2):617–630. <https://doi.org/10.1111/nph.17404>.
- Gersony JT, Hochberg U, Rockwell FE, Park M, Gauthier PPG, Holbrook NM. 2020. Leaf carbon export and nonstructural carbohydrates in relation to diurnal water dynamics in mature oak trees. *Plant Physiol*. 183(4):1612–1621. <https://doi.org/10.1104/pp.20.00426>.
- Ghezzehei TA, Sulman B, Arnold CL, Bogie NA, Berhe AA. 2019. On the role of soil water retention characteristic on aerobic microbial respiration. *Biogeosciences*. 16(6):1187–1209. <https://doi.org/10.5194/bg-16-1187-2019>.
- Green JK, Seneviratne SI, Berg AM, Findell KL, Hagemann S, Lawrence DM, Gentile P. 2019. Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*. 565(7740):476–479. <https://doi.org/10.1038/s41586-018-0848-x>.
- Grossiord C, Buckley TN, Cernusak LA, Novick KA, Poulter B, Siegwolf RTW, Sperry JS, McDowell NG. 2020. Plant responses to rising vapor pressure deficit. *New Phytol*. 226(6):1550–1566. <https://doi.org/10.1111/nph.16485>.
- Guo JS, Ogle K. 2018. Antecedent soil water content and vapor pressure deficit interactively control water potential in *Larrea tridentata*. *New Phytol*. 221(1):218–232. <https://doi.org/10.1111/nph.15374>.
- Guo JS, Hultine KR, Koch GW, Kropp H, Ogle K. 2019. Temporal shifts in iso/anisohydry revealed from daily observations of plant water potential in a dominant desert shrub. *New Phytol*. 225(2):713–726. <https://doi.org/10.1111/nph.16196>.
- Hammond WM, Yu K, Wilson LA, Will RE, Anderegg WRL, Adams HD. 2019. Dead or dying? Quantifying the point of no return from hydraulic failure in drought-induced tree mortality. *New Phytologist*. 223(4), 1834–1843. <https://doi.org/10.1111/nph.15922>.
- Holtzman NM, Anderegg LDL, Kraatz S, Mavrovic A, Sonnentag O, Pappas C, Cosh MH, Langlois A, Lakhankar T, Tesser D et al. 2021. L-band vegetation optical depth as an indicator of plant water potential in a temperate deciduous forest stand. *Biogeosciences*. 18(2):739–753. <https://doi.org/10.5194/bg-18-739-2021>.
- Humphrey V, Berg A, Ciais P et al. 2021. Soil moisture–atmosphere feedback dominates land carbon uptake variability. *Nature*. 592, 65–69. <https://doi.org/10.1038/s41586-021-03325-5>.
- Humphrey V, Frankenberg C. 2023. Continuous ground monitoring of vegetation optical depth and water content with GPS signals. *Biogeosciences*. 20(8), 1789–1802. <https://doi.org/10.5194/bg-20-1789-2023>.
- Jackson TJ, Schmugge TJ. 1991. Vegetation effects on the microwave emission of soils. *Remote Sensing of Environment*. 36(3), 203–212. [https://doi.org/10.1016/0034-4257\(91\)90057-D](https://doi.org/10.1016/0034-4257(91)90057-D).
- Jain P, Liu W, Zhu S, Chang CYY, Melkonian J, Rockwell FE, Pauli D, Sun Y, Zipfel WR, Holbrook NM et al. 2021. A minimally disruptive method for measuring water potential in planta using hydrogel nanoreporters. *Proc Natl Acad Sci USA*. 118(23):e2008276118. <https://doi.org/10.1073/pnas.2008276118>.
- Jarvis PG. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philos Trans R Soc Lond B Biol Sci*. 273(927):593–610. <http://www.jstor.org/stable/2417554>.
- Kannenberg SA, Guo JS, Novick KA, Anderegg WRL, Feng X, Kennedy D, Konings AG, Martínez-Vilalta J, Matheny AM. 2021. Opportunities, challenges and pitfalls in characterizing plant water-use strategies. *Funct Ecol*. 35(12):2752–2765. <https://doi.org/10.1111/1365-2435.13945>.
- Kannenberg SA, Barnes ML, Bowling DR, Driscoll AW, Guo JS, Anderegg WRL. 2022. Quantifying the drivers of ecosystem fluxes and water potential across the soil-plant-atmosphere continuum in an arid woodland. *Agric For Meteorol*. 329:109269. <https://doi.org/10.1016/j.agrformet.2022.109269>.
- Kattge J, Bönsch G, Díaz S, Lavorel S, Prentice IC, Leadley P, Wirth C. 2019. TRY plant trait database – enhanced coverage and free access. *Glob Chang Biol*. 26(1):119–188. <https://doi.org/10.1111/gcb.14904>.
- Kennedy D, Swenson S, Oleson KW, Lawrence DM, Fisher R, da Costa ACL, Gentile P. 2019. Implementing plant hydraulics in the community land model, version 5. *J Adv Model Earth Syst*. 11(2): 485–513. <https://doi.org/10.1029/2018MS001500>.
- Khare D, Selzner T, Leitner D, Vanderborght J, Vereecken H, Schnepf A. 2022. Root system scale models significantly overestimate root water uptake at drying soil conditions. *Front Plant Sci*. 13:Article 798741. <https://doi.org/10.3389/fpls.2022.798741>.
- Koch GW, Sillett SC, Antoine ME, Williams CB. 2015. Growth maximization trumps maintenance of leaf conductance in the tallest angiosperm. *Oecologia*. 177(2):321–331. <https://doi.org/10.1007/s00442-014-3181-6>.
- Konings AG, Rao K, Steele-Dunne SC. 2019. Macro to micro: microwave remote sensing of plant water content for physiology and ecology. *New Phytol*. 223(3):1166–1172. <https://doi.org/10.1111/nph.15808>.
- Konings AG, Saatchi SS, Frankenberg C, Keller M, Leshyk V, Anderegg WRL, Humphrey V, Matheny AM, Trugman A, Sack L et al. 2021. Detecting forest response to droughts with global observations of vegetation water content. *Glob Chang Biol*. 27(23):6005–6024. <https://doi.org/10.1111/gcb.15872>.
- Lakso AN, Santiago M, Stroock AD. 2022. Monitoring stem water potential with an embedded microtensiometer to inform irrigation scheduling in fruit crops. *Horticulturae*. 8(12):1207. <https://doi.org/10.3390/horticulturae8121207>.
- Levin A, Nackley L. 2021. Principles and practices of plant-based irrigation management. *HortTechnology*. 31(6):650–660. <https://doi.org/10.21273/HORTTECH04862-21>.
- Li L, Yang Z-L, Matheny AM, Zheng H, Swenson SC, Lawrence DM, Barlage M, Yan B, McDowell NG, Leung LR. 2020. Representation of plant hydraulics in the Noah-MP land surface model: model development and multiscale evaluation. *J Adv Model Earth Syst*. 13(2):e2020MS002214. <https://doi.org/10.1029/2020MS002214>.
- Lowman LEL, Godoy LD. 2020. Simulating stomatal response to cloud immersion for montane cloud forests in the southern Appalachians. *Agric For Meteorol*. 295:108165. <https://doi.org/10.1016/j.agrformet.2020.108165>.
- Mackay DS, Roberts DE, Ewers BE, Sperry JS, McDowell NG, Pockman WT. 2015. Interdependence of chronic hydraulic dysfunction

- and canopy processes can improve integrated models of tree response to drought. *Water Resour Res.* 51(8):6156–6176. <https://doi.org/10.1002/2015WR017244>.
- Martínez-Vilalta J, García-Forner N. 2017. Water potential regulation, stomatal behaviour and hydraulic transport under drought: deconstructing the iso/anisohydric concept. *Plant Cell Environ.* 40(6): 962–976. <https://doi.org/10.1111/pce.12846>.
- Martínez-Vilalta J, Santiago LS, Poyatos R, Badiella L, de Cáceres M, Aranda I, Delzon S, Vilagrosa A, Mencuccini M. 2021. Towards a statistically robust determination of minimum water potential and hydraulic risk in plants. *New Phytol.* 232(1):404–417. <https://doi.org/10.1111/nph.17571>.
- Matheny AM, Bohrer G, Garrity SR, Morin TH, Howard CJ, Vogel CS. 2015. Observations of stem water storage in trees of opposing hydraulic strategies. *Ecosphere.* 6(10), Article 165. <https://doi.org/10.1890/ES15-00170.1>.
- Matheny AM, Garrity SR, Bohrer G. 2017. The calibration and use of capacitance sensors to monitor stem water content in trees. *J Vis Exp.* 130:e57062.
- McCulloh KA, Domec JC, Johnson DM, Smith DD, Meinzer FC. 2019. A dynamic yet vulnerable pipeline: integration and coordination of hydraulic traits across whole plants. *Plant Cell Environ.* 42(10): 2789–2807. <https://doi.org/10.1111/pce.13607>.
- McDowell NG, Sapes G, Pivovarov A, Adams HD, Allen CD, Anderegg WRL, Arend M, Breshears DD, Brodribb T, Choat B et al. 2022. Mechanisms of woody-plant mortality under rising drought, CO₂ and vapour pressure deficit. *Nat Rev Earth Environ.* 3(5):294–308. <https://doi.org/10.1038/s43017-022-00272-1>.
- Meinzer FC, Johnson DM, Lachenbruch B, McCulloh KA, Woodruff DR. 2009. Xylem hydraulic safety margins in woody plants: coordination of stomatal control of xylem tension with hydraulic capacitance. *Funct Ecol.* 23(5):922–930. <https://doi.org/10.1111/j.1365-2435.2009.01577.x>.
- Mencuccini M, Rosas T, Rowland L, Choat B, Cornelissen H, Jansen S, Kramer K, Lapenis A, Manzoni S, Niinemets Ü et al. 2019. Leaf economics and plant hydraulics drive leaf : wood area ratios. *New Phytol.* 224(4):1544–1556. <https://doi.org/10.1111/nph.15998>.
- Mirfenderesgi G, Bohrer G, Matheny AM, Fatichi S, de Moraes P, Frasson R, Schäfer KVR. 2016. Tree level hydrodynamic approach for resolving aboveground water storage and stomatal conductance and modeling the effects of tree hydraulic strategy. *J Geophys Res Biogeogr.* 121(6):1709–1725. <https://doi.org/10.1002/2016JG003467>.
- Momen M, Wood JD, Novick KA, Pangle R, Pockman WT, McDowell NG, Konings AG. 2017. Interacting effects of leaf water potential and biomass on vegetation optical depth. *J Geophys Res Biogeogr.* 122(11):3031–3046. <https://doi.org/10.1002/2017JG004145>.
- Novick KA, Oren R, Stoy PC, Siqueira MBS, Katul GG. 2009. Nocturnal evapotranspiration in eddy-covariance records from three co-located ecosystems in the Southeastern U.S.: implications for annual fluxes. *Agric For Meteorol.* 149(9):1491–1504. <https://doi.org/10.1016/j.agrformet.2009.04.005>.
- Novick, K, Ficklin, D, Stoy, P, Williams CA, Bohrer G, Oishi AC, Papuga SA, Blanken PD, Noormets A, Sulman BN, Scott RL, Wang L, Phillips RP, & others. 2016. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nat Clim Change.* 6:1023–1027. <https://doi.org/10.1038/nclimate3114>, 11.
- Novick KA, Biederman JA, Desai AR, Litvak ME, Moore DJP, Scott RL, Torn MS. 2018. The AmeriFlux network: a coalition of the willing. *Agric For Meteorol.* 249:444–456. <https://doi.org/10.1016/j.agrformet.2017.10.009>.
- Novick KA, Ficklin DL, Baldocchi D, Davis KJ, Ghezzehei TA, Konings AG, MacBean N, Raoult N, Scott RL, Shi Y et al. 2022. Confronting the water potential information gap. *Nat Geosci.* 15(3):158–164. <https://doi.org/10.1038/s41561-022-00909-2>.
- Pagay V. 2021. Dynamic aspects of plant water potential revealed by a microtensiometer. *Irrig Sci.* 40(1):45–54. <https://doi.org/10.1007/s00271-021-00758-8>.
- Pagay V, Santiago M, Sessoms DA, Huber EJ, Vincent O, Pharkya A, Corso TN, Lakso AN, Stroock AD. 2014. A microtensiometer capable of measuring water potentials below –10 MPa. *Lab Chip.* 14(15):2806–2817. <https://doi.org/10.1039/C4LC00342J>.
- Poyatos R, Granda V, Flo V, Adams MA, Adorján B, Aguadé D, Martínez-Vilalta, J. 2012. Global transpiration data from sap flow measurements: the SAPFLUXNET database. *Earth Syst Sci Data.* 13(6):2607–2649. <https://doi.org/10.5194/essd-13-2607-2021>.
- Quick DD, Espino S, Morua MG, Schenk HJ. 2018. Effects of thermal gradients in sapwood on stem psychrometry. *Acta Hort.* 1197(1197):23–30. <https://doi.org/10.17660/ActaHortica.2018.1197.4>.
- Reichstein M, Bahn M, Ciais P, Frank D, Mahecha MD, Seneviratne SI, Zscheischler J, Beer C, Buchmann N, Frank DC et al. 2013. Climate extremes and the carbon cycle. *Nature.* 500(7462):287–295. <https://doi.org/10.1038/nature12350>.
- Rodríguez-Domínguez CM, Forner A, Martorell S, Choat B, Lopez R, Peters JMR, Pfautsch S, Mayr S, Carins-Murphy MR, McAdam SAM et al. 2022. Leaf water potential measurements using the pressure chamber: synthetic testing of assumptions towards best practices for precision and accuracy. *Plant Cell Environ.* 45(7): 2037–2061. <https://doi.org/10.1111/pce.14330>.
- Sabot MEB, De Kauwe MG, Pitman AJ, Medlyn BE, Verhoef A, Ukkola AM, Abramowitz G. 2019. Plant profit maximization improves predictions of European forest responses to drought. *New Phytol.* 226(6):1638–1655. <https://doi.org/10.1111/nph.16376>.
- Sabot MEB, De Kauwe MG, Pitman AJ, Ellsworth DS, Medlyn BE, Caldararu S, Zaehle S, Crous KY, Gimeno TE. 2022. Predicting resilience through the lens of competing adjustments to vegetation function. *Plant Cell Environ.* 45(9):2744–2761. <https://doi.org/10.1111/pce.14376>.
- Schaap MG, Leij FJ, Van Genuchten MT. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J Hydrol.* 251(3–4):163–176. [https://doi.org/10.1016/S0022-1694\(01\)00466-8](https://doi.org/10.1016/S0022-1694(01)00466-8).
- Scholander PF, Bradstreet ED, Hemmingsen EA, Hammel HT. 1965. Sap pressure in vascular plants: negative hydrostatic pressure can be measured in plants. *Science.* 148(3668):339–346. <https://doi.org/10.1126/science.148.3668.339>.
- Shi Z, Yang Y, Zhou X, Weng E, Finzi AC, Luo Y. 2016. Inverse analysis of coupled carbon–nitrogen cycles against multiple datasets at ambient and elevated CO₂. *J Plant Ecol.* 9(3):285–295. <https://doi.org/10.1093/jpe/rtv059>.
- Sperry JS. 2000. Hydraulic constraints on plant gas exchange. *Agric For Meteorol.* 104(1):13–23. [https://doi.org/10.1016/S0168-1923\(00\)00144-1](https://doi.org/10.1016/S0168-1923(00)00144-1).
- Sperry JS, Wang Y, Wolfe BT, Mackay DS, Anderegg WRL, McDowell NG, Pockman WT. 2016. Pragmatic hydraulic theory predicts stomatal responses to climatic water deficits. *New Phytol.* 212(3): 577–589. <https://doi.org/10.1111/nph.14059>.
- Sperry JS, Venturas MD, Anderegg WRL, Mencuccini M, Mackay DS, Wang Y, Love DM. 2017. Predicting stomatal responses to the environment from the optimization of photosynthetic gain and hydraulic cost. *Plant Cell Environ.* 40(6):816–830. <https://doi.org/10.1111/pce.12852>.
- Stocker BD, Zscheischler J, Keenan TF, Prentice IC, Peñuelas J, Seneviratne SI. 2018. Quantifying soil moisture impacts on light use efficiency across biomes. *New Phytol.* 218(4):1430–1449. <https://doi.org/10.1111/nph.15123>.
- van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci Soc Am J.* 44(5):892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>.
- Van Looy K, Bouma J, Herbst M, Koestel J, Minasny B, Mishra U, Montzka C, Nemes A, Pachepsky YA, Padarian J et al. 2017. Pedotransfer functions in Earth system science: Challenges and perspectives. *Reviews of Geophysics.* 55(4), 1199–1256. <https://doi.org/10.1002/2017RG000581>.

- Venturas MD, Todd HN, Trugman AT, Anderegg WRL. 2020. Understanding and predicting forest mortality in the western United States using long-term forest inventory data and modeled hydraulic damage. *New Phytol.* 230(5):1896–1910. <https://doi.org/10.1111/nph.17043>.
- Weihermüller L, Lehmann P, Herbst M, Rahmati M, Verhoef A, Or D, Jacques D, Vereecken H. 2021. Choice of pedotransfer functions matters when simulating soil water balance fluxes. *J Adv Model Earth Syst.* 13(3):e2020MS002404. <https://doi.org/10.1029/2020MS002404>.
- Xu X, Trugman AT. 2021. Trait-based Modeling of terrestrial ecosystems: advances and challenges under global change. *Curr Clim Change Rep.* 7(1):1–13. <https://doi.org/10.1007/s40641-020-00168-6>.
- Yao Y, Humphrey V, Konings AG, Wang Y, Yin Y, Holtzman N, Wood JD, Bar-On Y, Frankenberg C. 2024. Investigating diurnal and seasonal cycles of vegetation optical depth retrieved from GNSS signals in a broadleaf forest. *Geophys Res Lett.* 51(6):e2023GL107121. <https://doi.org/10.1029/2023GL107121>.