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PSInet: A new global water potential network

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Abstract:

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, 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: (1) 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. (2) Fostering an inclusive and diverse collaborative environment for all scientists studying water potential in various stages of their careers. (3) 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. (4) 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:

Water potential, plant hydraulics, database, plants, drought, network.

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). Moisture stress can cause detrimental 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 (Kannenberg et al., 2021; Flo et al. 2021; Li et al., 2020; McCulloh et al., 2019; Martínez-Vilalta et al., 2017), incorporating plant hydraulics into predictive models (Kennedy et al., 2019; Mirfenderesgi et al., 2019; 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 (United States and Canada) and Europe (Figure 1), which together comprise approximately 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, 1965). 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 (typically at least pre-dawn and midday) and at intervals spanning weeks or longer, to capture gradients in key environmental drivers. While pressure chamber data is 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, 2021; Shackel et al., 2021). Finally, it serves as a reliable reference dataset for the validation of remote sensing techniques used in monitoring vegetation water status (Momen 2017, Holtzman 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 presenting unique inherent challenges.

The PSInet water potential dataset and community

The PSInet Research Coordination Network (https://psinetrcn.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, Novick et al. 2018, Baldocchi 2008), the SAPFLUXNET database of continuous tree water use observations (Poyatos et al., 2012), and the Xylem Functional Traits (XFT) 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.

We anticipate that the wealth of information and the collaborative ethos of PSInet will prove instrumental in addressing a spectrum of crucial research questions at plant-to-ecosystem scales. These questions might encompass topics such as understanding how plants respond to increasing VPD induced by climate change, unraveling the mechanisms underlying tree mortality and hydraulic failure in drought-affected environments, enhancing strategies to incorporate plant hydraulics within Earth system models, and pioneering methods to map the dynamics of Ψ across both spatial and temporal dimensions.

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 ecophysiologists, 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 (Figure 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.

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 one 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 Figure 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 plan to initiate a separate campaign 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 (Figure 4). Several techniques offer promising, automated methods to monitor Ψ on the order of days to months. These techniques could be broadly classified as (1) direct sensing of water potential such as psychrometry, and most recently micro-tensiometers and hydrogel nano-reporters, and (2) indirect measurements such as remote sensing, or geophysical monitoring methods (e.g., Capacitance such as TDR (time domain reflectometry), FDR (frequency domain reflectometry), 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: (1) assessing method selection based on the specific plant tissue under investigation (e.g., Ψ_L vs Ψ_X vs root water potential - Ψ_R), (2) scaling challenges from individual plants to the ecosystem level, (3) 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), (4) the necessity of species-specific calibration parameters, and (5) 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 (Figure 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 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.

Stem psychrometry has been proven suitable for monitoring Ψ_X directly on individual plants at longer temporal resolutions (Dixon & 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 (Luo et at, 2022).

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 (Khare et al., 2022; Novick et al., 2022; Martínez-Vilalta et al., 2021). Current soil sensors often have limitations, typically providing accuracy only up to -2 MPa (with a few exceptions like the dielectric Decagon MPS-6, 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.

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.

Data and Materials Availability

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

Conflict of Interest

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

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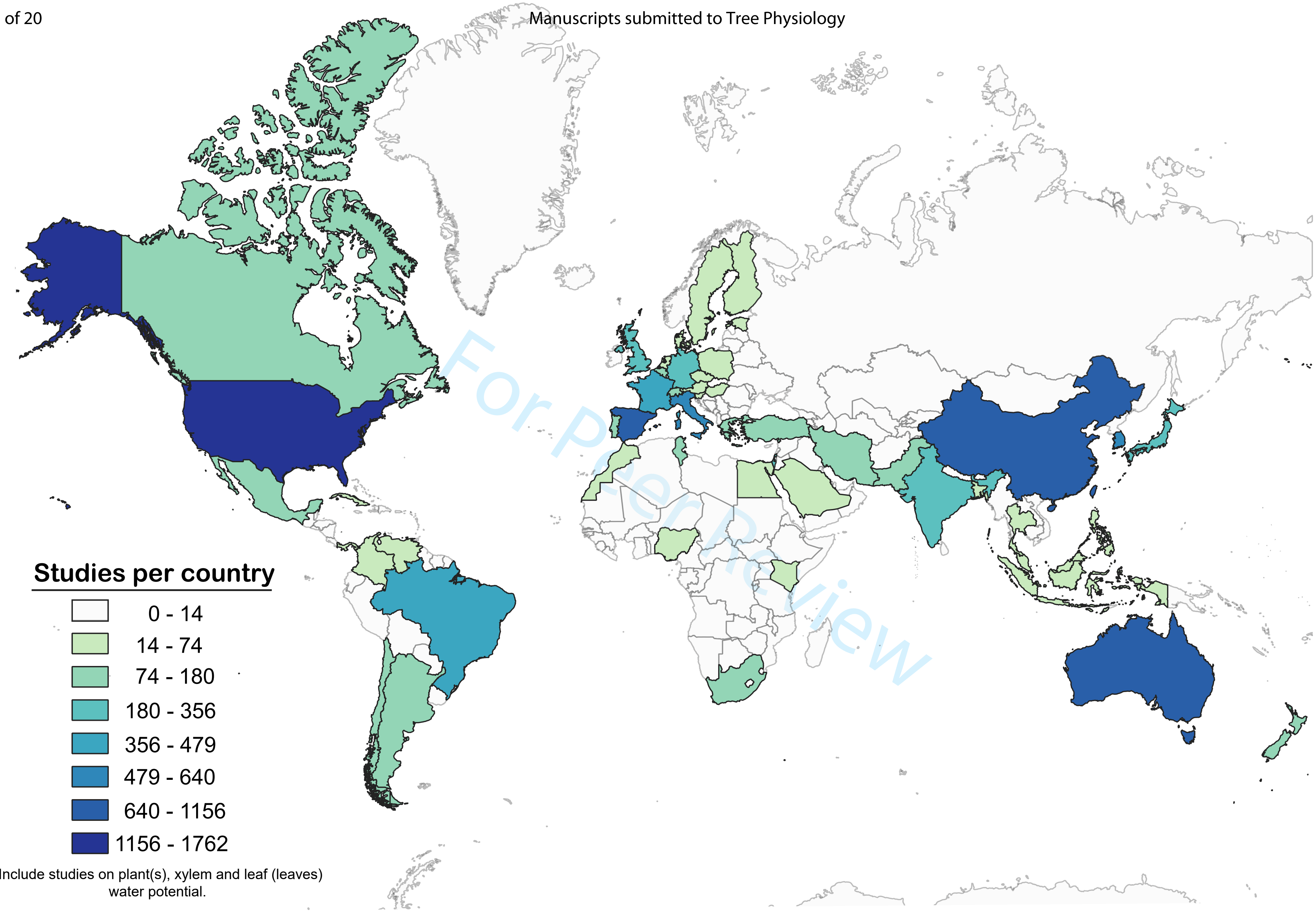
Figure Legends

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, supplementary table 1) is visualized by color-coding the number of studies in each country. Notably, the United States stands out with the highest number of studies (1,257), followed by China (794) studies 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 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 becomes accessible initially to the contributors and after to the public.

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 about 79%, followed by remote sensing (~15%), geophysical techniques such as Resistivity, TDR, FDR (~2.7%), and psychrometry (2.6%).



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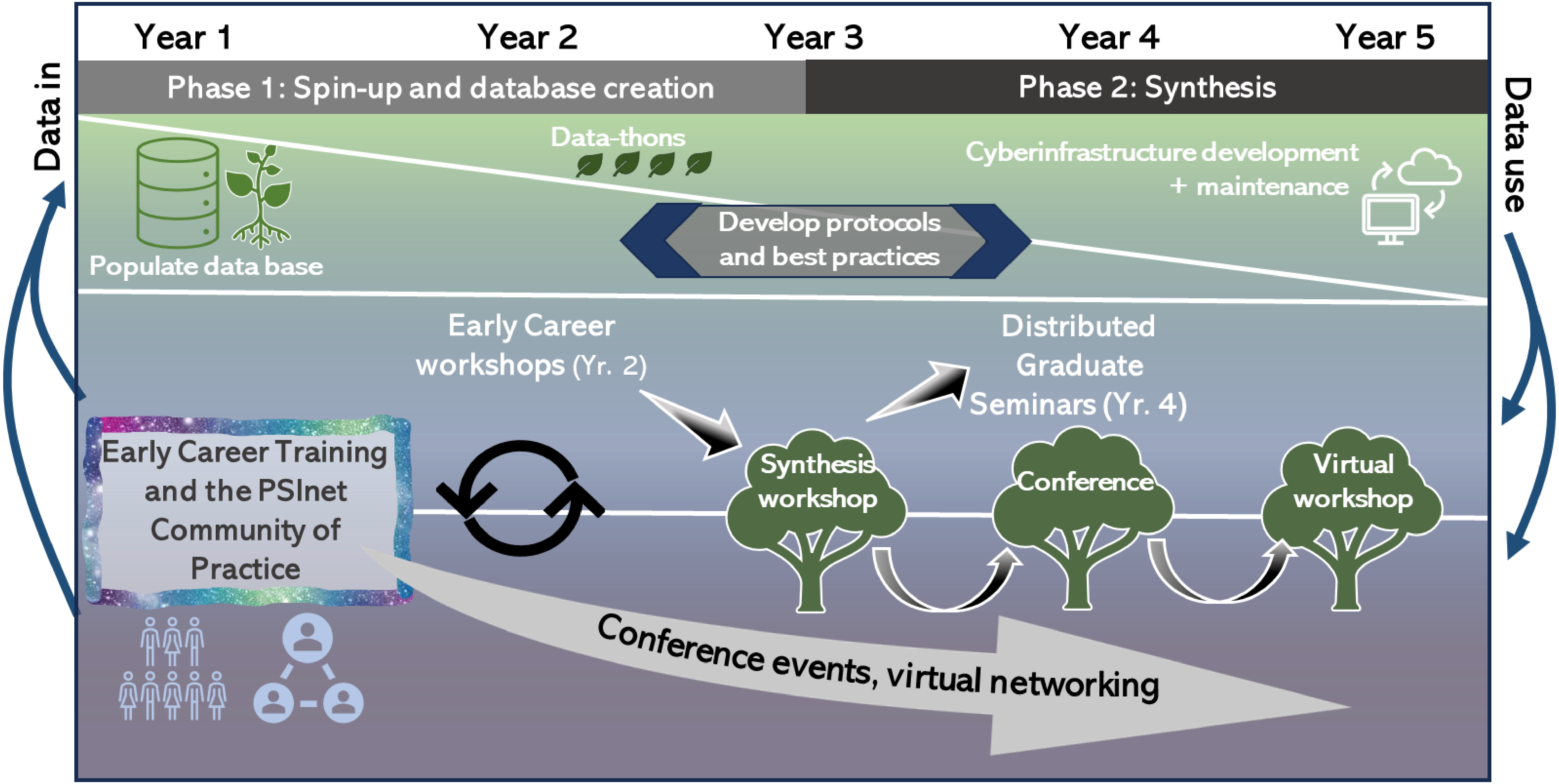

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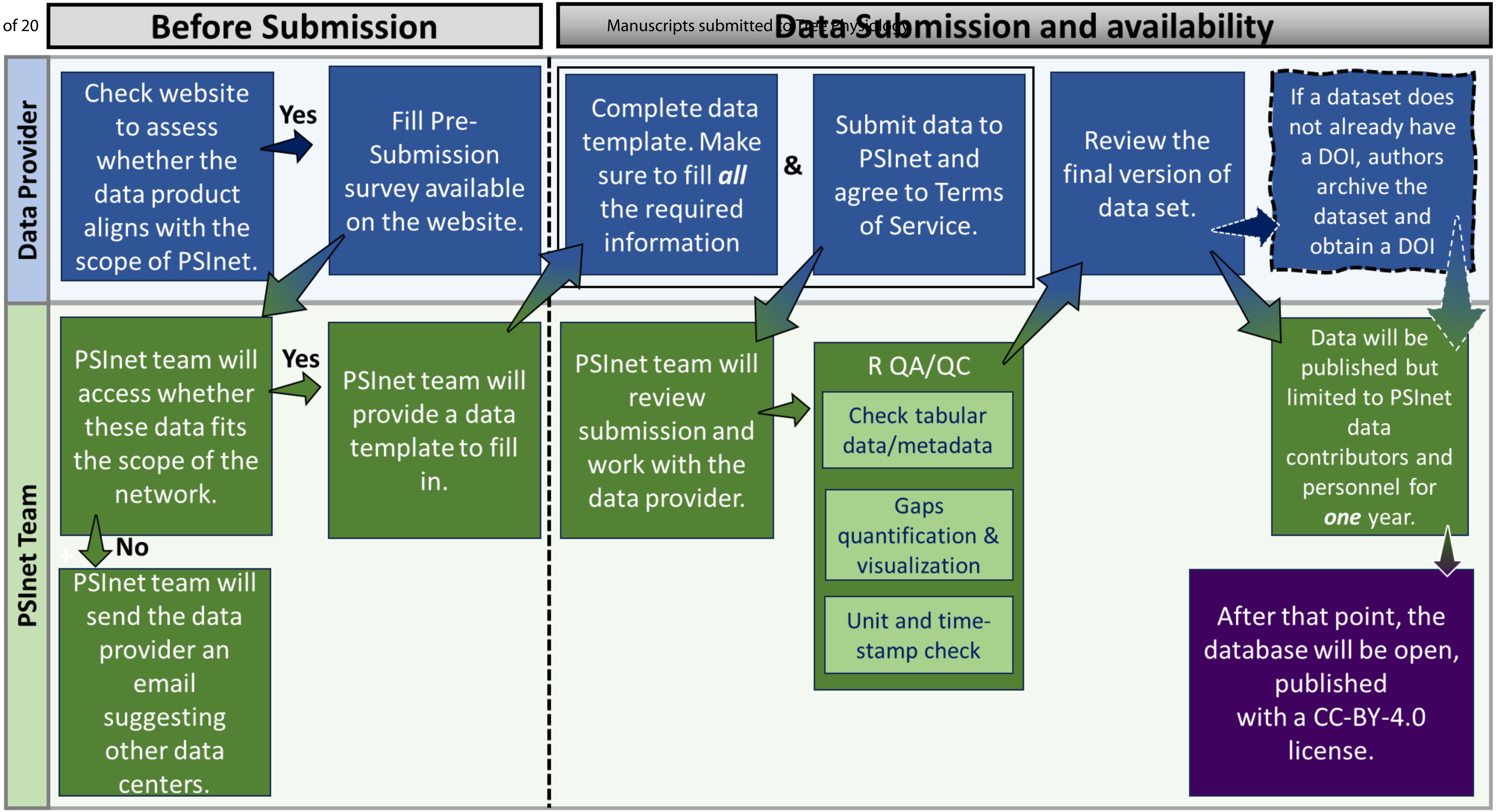

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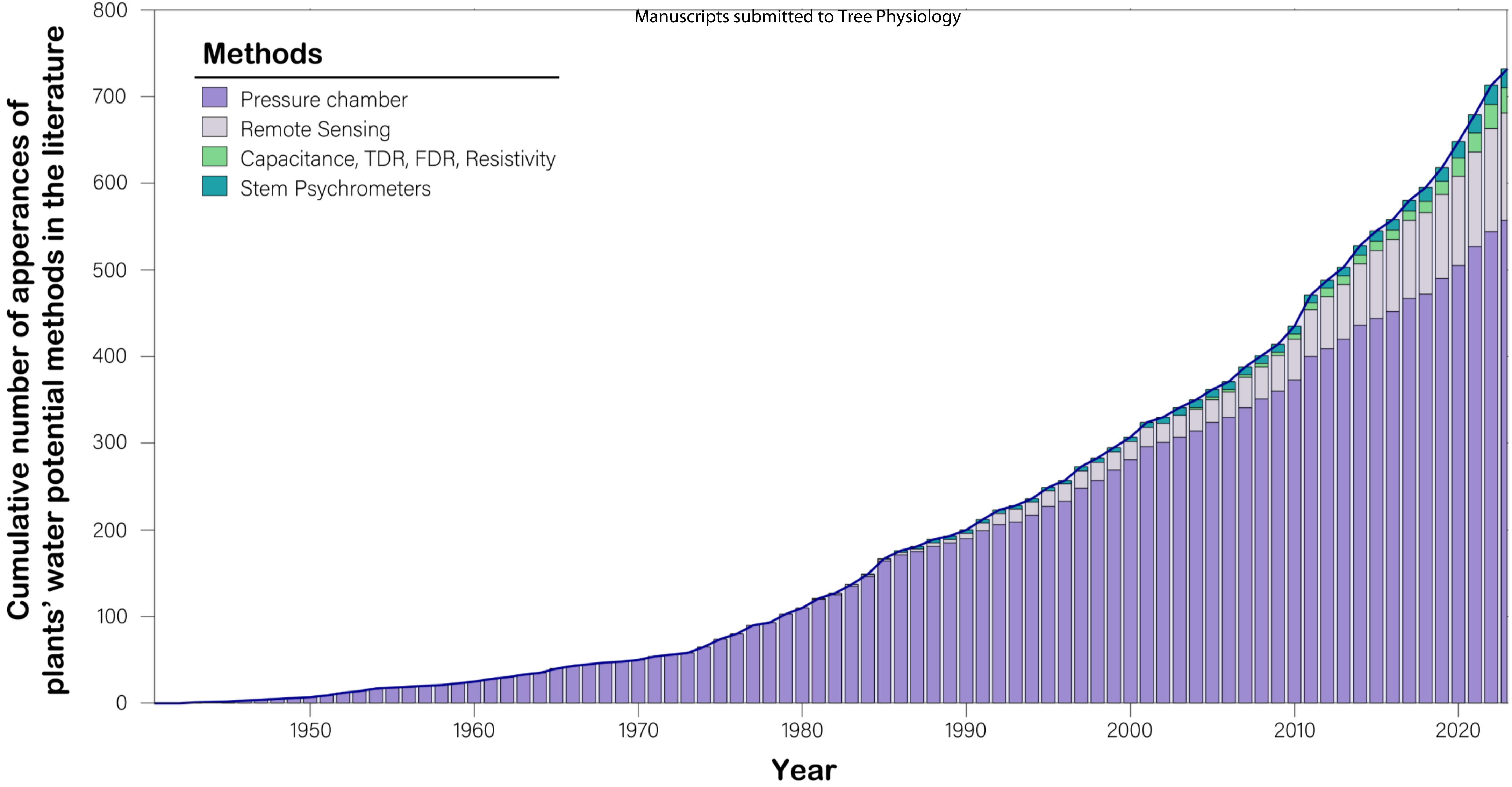

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