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Confronting the water potential information gap

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Water potential directly controls the function of leaves, roots and microbes, and gradients in water potential drive water flows throughout the soil–plant–atmosphere continuum. Notwithstanding its clear relevance for many ecosystem processes, soil water potential is rarely measured in situ, and plant water potential observations are generally discrete, sparse, and not yet aggregated into accessible databases. These gaps limit our conceptual understanding of biophysical responses to moisture stress and inject large uncertainty into hydrologic and land-surface models. Here, we outline the conceptual and predictive gains that could be made with more continuous and discoverable observations of water potential in soils and plants. We discuss improvements to sensor technologies that facilitate in situ characterization of water potential, as well as strategies for building new networks that aggregate water potential data across sites. We end by highlighting novel opportunities for linking more representative site-level observations of water potential to remotely sensed proxies. Together, these considerations offer a road map for clearer links between ecohydrological processes and the water potential gradients that have the 'potential' to substantially reduce conceptual and modelling uncertainties.

Gradients in the water potential (Ψ) of soils and plants form the energetic basis for the transport of water, and elements contained therein, through a connected continuum linking the deepest soil layers to the top of plant canopies (Fig. 1). The Ψ can be a positive or negative pressure, although it is typically negative—a tension force—in unsaturated soils and within plant hydraulic systems. Ψ gradients have been recognized as the fundamental driver of water fluxes between soils, streams and groundwater for more than a century, and they appear in some of the most foundational equations in hydrology[1] (for example, Darcy's Law and Richards' Equation). Likewise, the critical role of Ψ gradients in driving water flows through the soil–plant–atmosphere continuum has been known for decades[2].

Beyond redistributing water through ecosystems, Ψ is also a direct control of many biophysical processes. Soil Ψ (Ψ_S) regulates the flow of water into and out of soil microbe cells and determines their metabolism[3]. In plants, leaf Ψ (Ψ_L) is a key driver of stomatal conductance and photosynthetic carbon uptake[4,5], and its close connection to branch and stem Ψ (Ψ_X) controls the risk of drought-driven xylem embolism and mortality[6,7]. Consequently, most ecosystem services, including water storage, food and fibre supply, and water and climate regulation, are fundamentally linked to Ψ.

While undeniably important for soil and plant function, for reasons that will be discussed in more detail, Ψ_S is rarely measured in situ[8,9], and observations of plant Ψ have historically been limited to destructive and disjunct manual measurements. The objective of this paper is to demonstrate key uncertainties linked to the dearth of soil and plant Ψ data and to discuss the theoretical and modelling progress that could be enabled with richer and more discoverable information about Ψ. We begin by discussing issues surrounding the measurement, modelling and synthesis of Ψ_S and then address additional considerations linked to the measurement and prediction of Ψ in plants. We then present a road map for creating accessible and open Ψ databases and discuss promising new approaches for detecting Ψ using remote sensing.

Concepts and uncertainties linked to Ψ_S

Water flows 'downhill' energetically, moving from areas of higher potential to areas of lower potential, such that Ψ_s gradients are the driving force of subsurface water flows[1]. In most unsaturated soils, Ψ_s is dominated by the matric potential, which becomes more negative when soils dry, and the effective radii of water-filled pore spaces in the soil become smaller. This process produces the general shape of the water-retention curve (also known as the 'moisture characteristic' or 'water release' curve), which relates Ψ_s to volumetric soil moisture content (θ). Critically, variation in soil physical properties can cause Ψ_S to differ by an order of magnitude across soil types, even if θ is the same[10,11] (Fig. 2a).

Field observations of θ are common[12], but with a few exceptions[9,13], Ψ_S is rarely measured systematically in field research settings[8,9]. The reasons why θ became the predominant metric for describing soil water status are not entirely clear[8], but may reflect the fact that no single instrument captures the entire range of Ψ_S (from saturation to the very dry end), and sensors for measuring Ψ_S in the field have historically been associated with unique limitations and uncertainty[8,14].

Even if Ψ_S data were plentiful, strategies for relating θ to Ψ_S would still be necessary in models to connect water-balance equations with

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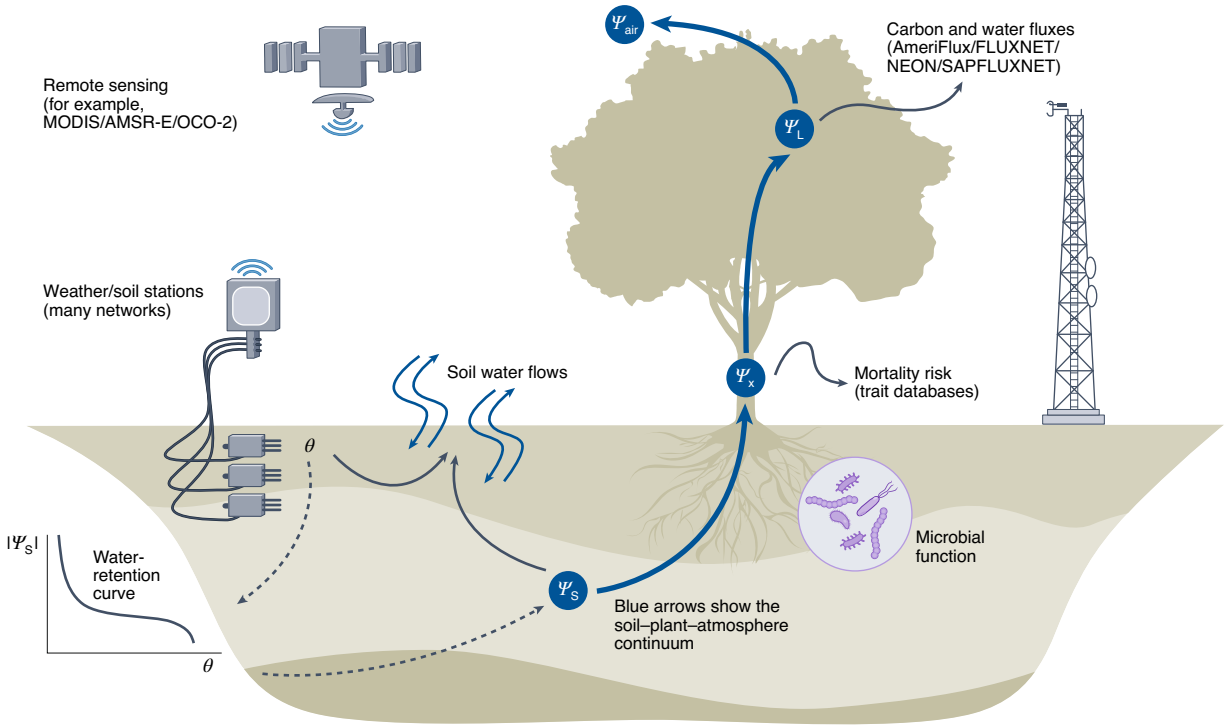

Fig. 1 | Ψ links environmental drivers to biophysical responses. Water flows downhill along gradients of Ψ in the soils (Ψ_S, where Ψ is relatively high, often >−1 MPa) through the stems (Ψ_x) to the leaves (Ψ_L, where potential is relatively low) and eventually to the air (Ψ_{air}, where it can be as low as −100 MPa). Ψ also directly controls key biological processes, including microbial function, mortality risk arising from damaged plant xylem, and plant–atmosphere gas exchange. While observations of environmental drivers, θ, and carbon and water fluxes are broadly accessible from environmental networks and remote sensing, Ψ time series are more discrete, sparse and generally not coordinated or discoverable.

potential-driven flows. Most hydrologic and land-surface models thus rely on water-retention-curve models[15], with those proposed by refs. [10,11] ranking high in popularity. Pedotransfer functions (PTFs) predict the parameters of water-retention-curve models using empirical equations driven by a limited set of soil characteristics (typically %sand, %clay and bulk density[16–18]).

While developing PTFs is an active field[15], PTF parameter distributions are poorly constrained and prevent confident transformation of θ to Ψ_S. For example, even relatively small variations in a single parameter of the van Genuchten model[11] cause Ψ_S to vary by an order of magnitude over a wide range of θ (Fig. 2b–d). Soil structure, which differs from soil texture and is governed by biophysical properties, may be a key omission in PTFs[19] explaining some of this uncertainty. For example, growth of roots and mycorrhizae into soil pores, and deposition of root exudates, increase overall water retention[20,21], and macropores can create preferred flow pathways that are challenging to incorporate into PTFs. Moreover, depth into the soil may also affect hydraulic properties by controlling connectivity with root systems and through slowly evolving changes in soil morphology. Finally, most PTFs assume that the water-retention curve is static, but many relevant processes occurring in natural landscapes (including drying–rewetting cycles, fire, and management shifts) may cause time-dependent hysteresis of the water-retention curve[22–24].

This uncertainly linked to PTFs propagates through water-cycle models in highly consequential ways.[25,26] Previous work performed in the Shale Hills Critical Zone Observatory confirms that van Genuchten model[11] parameters are the dominant source of model uncertainty in a coupled three-dimensional (3D) land-surface and hydrological model[27], and that water-retention-curve parameters must be measured locally and optimized through data assimilation[28] for watershed hydrologic variables to be predicted with any degree of certainty[29]. Here, using a popular 1D water-balance model, we further demonstrate that uncertainty in a single PTF parameter drives large uncertainty in modelled predictions of evapotranspiration, soil moisture and Ψ_S (Fig. 2e).

The parameters of the water-retention curve are also key sources of uncertainty explaining variability in carbon cycle fluxes from global-scale land-surface models. In this study, we used a global sensitivity experiment[30] to explore the variability of these parameters along with other key parameters of the ORCHIDEE land-surface model[31,32] (see Methods for details). The parameters of the water-retention curve explained between 10% and 32% of the modelled GPP variance across three diverse sites (Fig. 3). Moreover, when considering the wider set of soil hydrology parameters (including the hydraulic conductivity, field capacity and permanent wilting point of the soil), the percentage of explained GPP variance increased to 22–53% across sites.

The dearth of information about Ψ_S is not only a problem for models, but also confounds observation-driven work. Because θ is widely measured, and Ψ_S is not, it is extremely common to see key response variables such as carbon and water fluxes explained as a function of measured θ[33–35]. These relationships are usually nonlinear and threshold driven[36,37]. This is not surprising, as these responses embed site-to-site variability in the water-retention curve, which itself is nonlinear and threshold driven (Fig. 2a–d). The shape of these response functions thus depends very much on whether Ψ_S or θ is chosen as the driving variable[38]. Indeed, the relationship between gross primary productivity (GPP) and soil water status is more linear and less spatially heterogeneous when Ψ_S, as opposed to θ, appears on the x axis (Fig. 4). Likewise, substantial skill in predicting soil respiration can be gained when model functions are driven explicitly by Ψ_S (ref. [3]). Thus, more abundant and aggregated site-level Ψ_S information could reduce conceptual

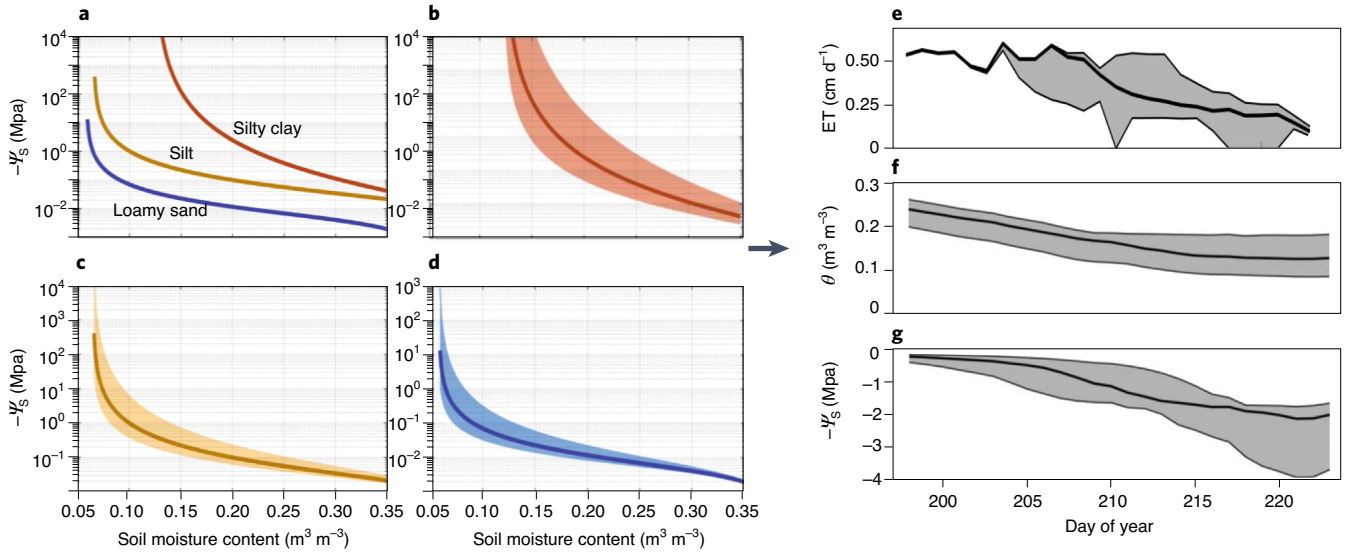

Fig. 2 | Water-retention curve and PTF uncertainty. a, Across three soil types, Ψ_s can differ by an order of magnitude for a given θ (with curves generated from the van Genuchten model[11]; see Methods). **b**–**d**, The uncertainty in the water-retention curve attributable to PTF parameter uncertainty. The shaded area shows the 90% confidence interval due solely to variation in a single parameter of the van Genuchten model (the *n* shape parameter, which is linked to pore size) within just one standard deviation of its reported distribution for each soil class from a popular PTF[18]: silty clay (**b**), silt (**c**) and loamy sand (**d**). Thick lines in **b**–**d** are the same as in **a**. The PTF-driven uncertainty in the water-retention curve propagates into large uncertainty for modelled fluxes and pools. **e**–**g**, Specifically, variation in the van Genuchten *n* parameter within again just one standard deviation of its reported range[18] causes the 90% confidence intervals on modelled evapotranspiration (ET) (**e**), θ (**f**) and Ψ_S (**g**) (shaded grey areas) to vary by a magnitude comparable to the mean value of each parameter (thick black line). Simulations were run using the HYDRUS 1D[79] model for a forest site in Indiana, USA[80], during a drought event (see Methods for details).

uncertainty about how ecosystem fluxes respond to soil water deficits and permit other sources of spatio-temporal variability to be more discernable.

Plant Ψ: key concepts and controversies

The effective radii of evaporating water surfaces within plant cell walls are extremely small, resulting in tension forces strong enough to pull water upwards from soils, where it is already tightly bound, to the leaves. Thus, the difference between Ψ_L and Ψ_S is the driving force for transpiration, which is closely coupled with photosynthetic carbon uptake. Moreover, Ψ_X, which is coupled with Ψ_L, interacts with anatomical features of the plant's water transport system to determine the risk of xylem embolism that can lead to mortality[6,7,39–41]. Stomatal regulation of gas exchange is also critical for buffering plants from the very low Ψ of the atmosphere (see Fig. 1), which is extremely sensitive to relative humidity[42].

Historically, observations of plant Ψ have been limited to manually collected 'snapshots' (for example, with a pressure chamber[43]). These data have proved indispensable for shaping our theoretical understanding of how plants respond to soil water stress[6,7,40,44]. However, because pressure-chamber measurements are destructive and labour intensive, they are typically limited to weekly or seasonal temporal resolutions. While the weekly timescale is well matched to soil drying, it is too coarse to capture faster-acting hydrodynamic processes, including stomatal response to vapour pressure deficit (VPD[45]) and the depletion and refilling of plant water pools over the course of a day[46]. Moreover, with some exceptions[47], Ψ_L and Ψ_X are not often monitored over long periods (for example, years to decades), and centralized databases and networks for time series of Ψ do not yet exist.

The discrete and undiscoverable nature of plant Ψ observations limits our ability to characterize the distributions of the minimum plant Ψ that are so critical for determining plant mortality risk[41]. The gap also limits understanding of how plant Ψ and Ψ_S are coordinated and coupled. For example, a fundamental assumption in plant eco-physiology is that Ψ_L and Ψ_X are equilibrated with Ψ_S across the root zone in pre-dawn hours[48]. This assumption has allowed eco-physiologists to circumvent the Ψ_S data scarcity problem by relying on pre-dawn Ψ_L observations as a proxy for root-zone Ψ_S—an approach that treats the plants as an instrument for recording the soil water environment. Yet experiments have shown that night-time transpiration—while small—can still occur[49,50], lowering pre-dawn Ψ_L and decoupling it from Ψ_S (ref. [51]). Synthetic assessments of pre-dawn equilibrium are hindered by the absence of nocturnal Ψ_L observations collected together with data on Ψ_S and/or stem water flows (for example, from sap flux), or collected frequently enough to determine whether stationarity in pre-dawn Ψ_L, which should be a hallmark of equilibrium, has been achieved.

Likewise, the Ψ information gap limits understanding of how Ψ_S and plant Ψ are coupled at mid-day. The relationship between mid-day Ψ_L and the root-zone Ψ_S is frequently used to classify plant water-use strategies[44,52,53]. For example, plants with conservative water-use strategies ('isohydric' species) close stomata quickly as Ψ_S declines, whereas 'anisohydric' plants keep stomata open longer, sustaining gas exchange but with more rapid declines in Ψ_L that may increase the risk of xylem embolism. The (an)isohydry framework is popular but controversial, with several studies highlighting critical interactions with other environmental drivers beyond Ψ_S (refs. [54–56]), including VPD[57]. Moreover, coordinated observations of sap flow, enhanced with data on Ψ_S and Ψ_X, hold great promise for understanding how the dynamics of hydraulic conductance of different plant organs influence whole-plant hydraulic physiology[58]. Plant hydraulics schemes relying on concepts such as isohydry are rapidly being incorporated in hydrologic and Earth system models[59–61]. Benchmarking and testing these schemes would benefit from open and spatially representative databases of plant Ψ and Ψ_S time series, measured together at a temporal frequency (for example, hourly) over which key drivers such as VPD vary.

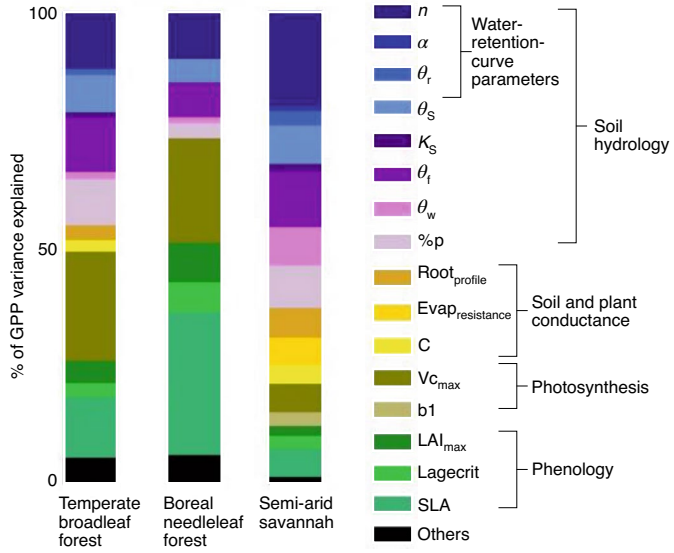

Fig. 3 | Water-retention-curve parameters are a key source of land-surface model uncertainty. A sensitivity analysis of key model parameters of the ORCHIDEE land-surface model[31,32] was performed to demonstrate the relative importance of each parameter in simulating daily GPP at three contrasting FLUXNET sites. **a**, A temperate broadleaf forest (Harvard Forest, FLUXNET code US-Ha1[81]). **b**, A boreal needleleaf forest (Sodankyla, FI-Sod,[82]). **c**, A semi-arid savannah (Demokeya, SD-Dem[83]). The Sobol method[30] was used to perform the sensitivity analysis; this method is based on variance decomposition and is able to capture interactions between parameters. More details can be found in Methods.

Coordinated observation of plant Ψ and Ψ_S could also offer new perspectives on the critical role of root hydraulic function. Pre-dawn observations of Ψ_L and Ψ_L from multiple depths could reveal interspecific patterns in functional rooting depth—a trait that is difficult to measure by other means and partially responsible for model difficulty in capturing plant drought responses[62]. When complemented with data on Ψ_x and/or root sap flow, profile observations of Ψ_S would also illuminate the important but poorly understood consequences of hydraulic redistribution of water from wetter to drier soil layers through plant roots[63,64]. While root Ψ_x is difficult to measure with pressure chambers, it could be monitored more easily with psychrometers or other techniques for continuous observation of plant Ψ_x. Data on root Ψ_x, especially when paired with laboratory-derived root xylem vulnerability curves, would also be useful for understanding the dynamics of root hydraulic conductance, noting that roots may be among the most vulnerable components of the plant hydraulic system[65,66]. Finally, differences in Ψ_S and root Ψ_x could also improve our understanding of gradients in Ψ occurring at the root–soil interface[67].

Strategies to address the Ψ information gap

Recent advances in measurement technology have substantially improved the ease and reliability of Ψ_S observations. In the lab, sensor improvement has reduced the time necessary to generate the 'wet end' of the water-retention curve[68]. A second instrument, typically a dew-point potentiometer, is required to capture the dry end of the curve, but this step proceeds relatively quickly. While the instrumentation and expertise necessary to characterize water-retention curves may be siloed within soil science disciplines, this barrier could be easily overcome through cooperative arrangements and/or knowledge transfer. At the same time, technology is improving for more confident observation of Ψ_S in situ[8]. Tensiometers, which are accurate when soil is relatively wet (for example, $\Psi_S > -0.1$ MPa), are widely used in agricultural settings for the purposes of irrigation scheduling. In the drier range, soil matric potential can be measured using psychrometry or from dielectric measurements, with several commercial sensors available at a relatively low cost (for example, the Teros 21 product, Meter Group). While the accuracy of sensors such as these is greatest when Ψ_S is above −2 MPa, this is still lower than the wilting point of many plant species[8].

With respect to plants, psychrometers permitting continuous and long-term observation of both Ψ_L and Ψ_X are becoming more widely and commercially available (for example, the PSY1 products, ICT International), drawing from a long history of psychrometric approaches for measuring plant Ψ (ref. [69]). Stem psychrometers can now be deployed on branches and boles of some species for weeks to months at a time[55], and evidence is mounting that high-frequency Ψ_L and Ψ_x data can indeed improve our understanding of plant water-use strategies and dynamics[55,70]. Psychrometers are still relatively expensive, best suited for broadleaf and non-resinous species and sensitive to biases linked to temperature fluctuations and wounding effects. Thus, for now, psychrometer data are best viewed as complementary to pressure-chamber measurements. Nonetheless, for many plants, these instruments allow for the collection of Ψ_L and/or Ψ_x data at the hourly timescales necessary to be harmonized with observed carbon and water fluxes (for example, from sap flux and flux towers) and to more rigorously test model frameworks.

Ultimately, addressing environmental questions at policy- and management-relevant scales requires the collection and standardization of observations across many sites. This need has motivated the recent development of many environmental observation networks, including highly centralized initiatives such as the National Science Foundation's National Ecological Observatory Network[71], as well as more bottom-up networks such as AmeriFlux[72] and FLUXNET[73] and the new international SAPFLUXNET network[74]. Other approaches include 'network-of-networks' cyberinfrastructure such as the International Soil Moisture Network,[13] which aggregates soil moisture observations from dozens of individual networks.

Both bottom-up and top-down approaches could be useful for building new Ψ networks. On the one hand, centralized and standardized deployment of new Ψ sensors, ideally in locations that are already nodes of other networks, would have the advantage of uniformity in instrumentation and data quality control that facilitates cross-site synthesis. On the other hand, a community-driven effort to aggregate and redistribute both existing and new Ψ data could follow the highly successful 'coalition' model employed by networks such as AmeriFlux[72], increasing the discoverability of data while allowing room for innovation at the site level. Even a concerted effort to generate and/or collect laboratory-based water-retention curves from existing network sites could substantially constrain how much of the nonlinearity in the response of fluxes to observed soil water content can be explained by soil physics (for example, see Fig. 4). The success of a Ψ network would be maximized with (1) a focus on collecting data from sites that also support continuous plant- and/or stand-scale carbon and water fluxes, (2) cyberinfrastructure to support the discoverability and distribution of these databases, (3) a focus in at least some locations on within-site spatial heterogeneity in Ψ dynamics to better understand how many observation points (and at what depths) are necessary to substantially improve model skill, and (4) training programmes, such as summer short courses or distributed graduate seminars, to transfer knowledge about how to interpret network observations and to share best practices for sensor deployment.

Even with well-developed observation networks, it is not possible to measure key physiological variables such as Ψ everywhere and all the time. Thus, strategies for linking these variables to proxies observable from space are required for regional- and

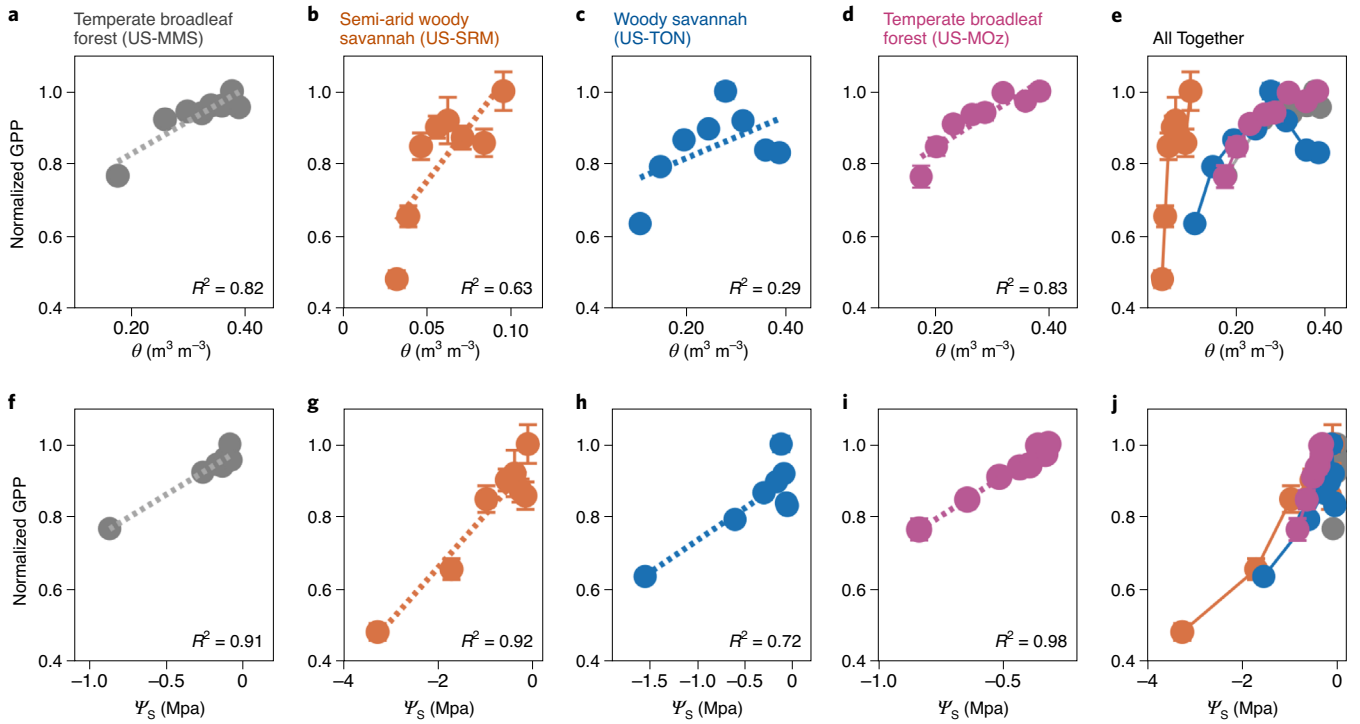

Fig. 4 | Ψ_S better explains variability in GPP when compared with θ. a–j, The relationship between GPP (normalized by its well-watered rate) and ΨS (**f**–**j**) is more linear than the relationship between GPP and θ (**a**–**e**) across four AmeriFlux sites for which site-specific water-retention curves were measured[38,84–86]: a temperate broadleaf forest (US-MMS) (**a**,**f**), a semi-arid woody savannah (US-SRM) (**b**,**g**), a woody savannah (US-TON) (**c**,**h**), another temperate broadleaf forest (US-MOz) (**d**,**i**), and all together (**e**,**j**). Moreover, cross-site heterogeneity in the response functions is reduced when it is Ψ_S, as opposed to θ, on the *x* axis (compare **e** with **j**). GPP estimates were obtained from AmeriFlux, with site codes given in parentheses. Error bars indicate one standard error of the mean, which is quite small for some of the binned averages. See Methods for more details.

continental-scale work, with microwave remote sensing representing a particularly promising approach. Microwave observations can be used to determine vegetation optical depth (VOD), which is sensitive to plant water content[75] and should be monotonically related to Ψ_L[76,77]. Comparison of observed Ψ_L with either space-borne[78] or tower-based[70] radiometry confirms that VOD and Ψ_L follow similar dynamics, especially after accounting for the effect of changing biomass and leaf area. However, the exact relationship between VOD and Ψ_L is influenced by vegetation type[76], and further study of this relationship is currently hindered by the sparsity of Ψ_L data.

Importantly, microwave remote-sensing observations can be made at night, which raises the question of whether nocturnal microwave remote sensing of Ψ_L can be used to infer dynamics of root-zone Ψ_S. Answering this question requires a critical understanding of when and where pre-dawn Ψ_L is equilibrated with root-zone Ψ_S. This knowledge gap can be addressed with network observations of Ψ_L from psychrometry or observations of plant Ψ and Ψ_S collected in the same site, which could then guide the design and interpretation of both tower- and satellite-mounted microwave remote-sensing systems. The approach will also require further refinement of retrieval algorithms for separating the contribution of plant and soil water content, for example, by leveraging emerging approaches for the remote sensing of vegetation structure[77].

In conclusion, we have highlighted how more numerous, discoverable and continuous observations of Ψ_S and plant Ψ can not only improve our conceptual understanding of biophysical processes throughout the soil–plant–atmosphere continuum, but also serve as a much-needed new tool for benchmarking and calibrating hydrologic and land-surface models and remote-sensing products. While in situ and site-specific observations of Ψ_S, Ψ_L and Ψ_x may not yet be easy, recent advancements in sensor technology have certainly made them easier than in decades past. The time is right for a new focus on the collection of these data in the field and the development of new networks to aggregate observations across sites complemented by new approaches for integrating these observations into Earth system models.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at [https://doi.org/10.1038/s41561-022-00909-2].

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Methods

Water-retention-curve uncertainty. The water-retention curves in Fig. 2 were created using the van Genuchten water-retention curve model[11] relating Ψ_S to θ. As described in more detail in the Supplementary Information, most parameters of the model were held constant within each soil type, specified as the mean values reported in the updated ROSETTA PTF[18] (Supplementary Table 1). The 'n' parameter—a key shape parameter of the van Genuchten model—was allowed to vary by randomly selecting a value from a uniform distribution bounded by ±1 standard deviation as reported for the ROSETTA PTF[18]. Overall, this was a conservative approach; drawing the values of n from the full distribution reported for each soil type expands the range of predicted Ψ_S by orders of magnitude.

The HYDRUS 1D simulations. Uncertainty in the water-retention curve linked to pedotransfer uncertainty (for example, as Fig. 2a–d) was propagated through predictions of Ψ_S and θ (at depths of 15 cm) and surface evapotranspiration (cm d^{-1}) using the HYDRUS 1D soil water-dynamics model[79]. Fifty simulations were performed for the Bradford Woods deciduous forest site in south-central Indiana, where the HYDRUS 1D model had been previously calibrated[80]. In general, model settings were left unchanged, with a few exceptions as discussed in more detail in the Supplementary Information. The soil at Bradford Woods is characterized by a 40-cm-depth AP (plowed A) horizon dominated by sandy loam and a BW (weathered B) horizon dominated by silt loam from a depth of 40 cm to 208 cm. The very bottom of the soil layer (depths 208–230 cm) was prescribed to be clay loam. The parameters of the van Genuchten model used in the HYDRUS simulations are shown in Supplementary Table 2, where again most were held constant, but n varied for the sandy and silt loam layers by drawing it from within one standard deviation of its distribution reported in the updated ROSETTA PTF[18]. The shaded areas in Fig. 2e,f thus illustrate the resulting variations in evapotranspiration, Ψ_S and θ due solely to variability in n.

The ORCHIDEE GPP sensitivity analysis. The ORCHIDEE land surface model (CMIP6 version)[31,32], which is the terrestrial part of the IPSL (Institute Pierre-Simon Laplace) Earth system model, was used to explore the sensitivity of modelled GPP to uncertainty in a wide range of parameters. ORCHIDEE relies on the van Genuchten model to calculate Ψ_S, as well as the hydraulic conductivity and diffusivity required to solve the Richard's diffusion equation. ORCHIDEE discretizes the first 2 m of the soil column over 11 layers. For this experiment, we ran ORCHIDEE over three single-mesh locations using local half-hourly forcing data to drive the model at each site (Supplementary Table 3) and considered modelled GPP at a daily time step. The sensitivity analysis results shown in Fig. 3 were generated using Sobol's method[30], using the SALib python package[87] to sample the parameter space and execute the algorithms. Briefly, the model was run using different parameter ensembles, with parameters varied within their reported ranges of uncertainty. Then, each modelled GPP time series was compared with GPP derived from flux-tower observations. The variance of simulated GPP was then decomposed into fractions that can be attributed to each parameter tested. These results, shown in Fig. 3, capture both independent and interactive contributions of each parameter to the total variance. When interactions are removed, the independent contribution of water-retention-curve parameters is still significant, and actually increases for the semi-arid site (see details in Supplementary Information section 3).

The AmeriFlux GPP analysis. Half-hourly or hourly data from the four flux towers referenced in Fig. 4 were acquired from the AmeriFlux network (ameriflux.lbl.gov) and subjected to standardized quality-control, gap-filling, and partitioning approaches. The sites and quality-control procedures are described in more detail in Supplementary Table 5. The methods used to determine the relationship between GPP and soil moisture are similar to those previously used to explore the relationship between surface conductance and soil moisture[35]. Briefly, analysis was constrained to the peak of the growing season to limit bias linked to phenological variation in leaf area index. Estimates of Ψ_S for each site were determined from site-specific water-retention curves[38,81–83]. The data were then sorted into eight bins representing the 15th, 30th, 45th, 60th, 70th, 80th, 90th and 100th quantiles of the observed values of soil moisture content in each site. Within each bin, data were constrained to relatively high light (net radiation >300 W m^{-2}) conditions with VPD limited to $1 \leq \mathrm{VPD} \leq 1.5$ kPa in US-MMS, US-TON and US-MOz and $1.5 \leq \mathrm{VPD} \leq 2$ kPa in the more arid US-SRM site. The mean GPP, Ψ_S and θ were then calculated for each bin using the filtered data and normalized by the maximum bin-averaged value observed at each site.

Data availability

The FLUXNET tower data appearing in Fig. 3 are from the FLUXNET 2015 dataset (https://doi.org/10.18140/FLX/1440186 for SD-Dem, https://doi.org/10.18140/FLX/1440071 for US-HA1 and https://doi.org/10.18140/FLX/1440160 for FI-SOD). The AmeriFlux tower data appearing in Fig. 4 are available from the AmeriFlux network (https://doi.org/10.17190/AMF/1246080 for US-MMS, https://doi.org/10.17190/AMF/1246081 for US-MOz, https://doi.org/10.17190/AMF/1246104 for US-SRM and https://doi.org/10.17190/AMF/1245971 for US-TON).

Code availability

The HYDRUS 1D programme used to create the results of Fig. 2e–g is available for public download from https://www.pc-progress.com/en/Default.aspx?hydrus-1d. A reference version of the ORCHIDEE land-surface model, used for Fig. 3, is available at https://orchidee.ipsl.fr/. Details on the parameterizations of these models are presented in the Supplementary Information.

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Author contributions

K.A.N. conceived of the study with substantial input from D.L.F., A.G.K., K.J.D., T.A.G., R.L.S., B.N.S., Y.S. and N.M. Data analyses were performed by K.A.N., T.A.G., D.L.F. and N.R., who also created the resulting figures. D.B., R.L.S., K.A.N. and J.D.W. contributed AmeriFlux data used in Fig. 4. All authors wrote the text and provided substantial conceptual input to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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