BAMS
Meeting Summary

Rethinking Soils in Land Surface Models

Anne Verhoef,[a] Yijian Zeng,[b] Nurit Agam,[c] Martin Best,[d] Sara Bonetti,[e]
Souhail Boussetta,[f] Nathaniel Chaney,[g] Matthias Cuntz,[h] John Edwards,[d] Surya Gupta,[i]
Josh Heitman,[j] Min Huang,[k] Nicholas Jarvis,[l] Shijie Jiang,[m] Rajsekhar Kandala,[a]
Filip Kiałka,[n] Taiqi Lian,[e] Mengyuan Mu,[o,p] Attila Nemes,[q] Sinikka J. Paulus,[m]
Nina Raoult,[f] Kangari Narender Reddy,[a] Nunzio Romano,[r] Manon Sabot,[m]
Jan Vanderborght,[s] Martine van der Ploeg,[t] Peter van Oevelen,[u] Yong Wang,[a]
Yunquan Wang,[v] Tobias Karl David Weber,[w] Toby Marthews,[x] and Lutz Weihermüller[s]

KEYWORDS:
Atmosphere-land interaction;
Soil moisture;
Soil temperature;
Land surface model;
Numerical weather prediction/forecasting;
Parameterization

The ISMC–GEWEX SoilWat 2025 Meeting

What: The International Soil Modeling Consortium (ISMC)–Global Energy and Water Exchanges project (GEWEX) Soil and GEWEX Water Initiative (SoilWat) 2025 meeting brought together a diverse group of ~40 experts from the subsurface modeling community (broadly represented by members of the ISMC) and the climate modeling community (represented by those active in GEWEX). The main objective of the meeting was to identify the next frontiers and challenges relating to the modeling of soil and subsurface processes in weather and climate models.

When: 14–16 July 2025

Where: University of Reading, Reading, United Kingdom, and online streaming (https://www.gewexevents.org/meetings/ismc-soilwat2025/)

DOI: 10.1175/BAMS-D-26-0003.1

Corresponding author: Anne Verhoef, a.verhoef@reading.ac.uk

Manuscript in final form 10 January 2026

AFFILIATIONS: [a] University of Reading, Reading, United Kingdom; [b] University of Twente, Enschede, Netherlands; [c] Ben-Gurion University of the Negev, Beersheba, Israel; [d] Met Office, Exeter, United Kingdom; [e] École Polytechnique Fédérale de Lausanne, Sion, Switzerland; [f] European Centre for Medium-Range Weather Forecasting, Reading, United Kingdom; [g] Duke University, Durham, North Carolina; [h] Université de Lorraine, AgrosParisTech, INRAE, UMR Silva, Nancy, France; [i] Department of Environmental Sciences, University of Basel, Basel, Switzerland; [j] Department of Crop and Soil Sciences, North Carolina State University, Raleigh, North Carolina; [k] University of Maryland, College Park, College Park, Maryland; [l] Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden; [m] Max Planck Institute for Biogeochemistry, Jena, Germany; [n] Laboratoire de Géologie, École Normale Supérieure, CNRS UMR 8538, Institut Pierre-Simon Laplace, PSL Research University, Paris, France; [o] Department of Environmental and Geosciences, Lund University, Lund, Sweden; [p] Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia; [q] NIBIO, Ås, Norway; [r] Department of Agricultural Sciences, University of Naples Federico II, Naples, Italy; [s] Forschungszentrum Jülich GmbH, Agrosphere Institute IBG-3, Jülich, Germany; [t] Wageningen University, Wageningen, Netherlands; [u] International GEWEX Project Office, George Mason University, George Mason, Virginia; [v] School of Environmental Studies, China University of Geosciences at Wuhan, Wuhan, China; [w] Soil Sciences and Agrohydrology, University of Kassel, Kassel, Germany; [x] UK Centre for Ecology and Hydrology, Wallingford, United Kingdom

1. Introduction

Land surface models (LSMs) are central to weather and climate prediction, flood and drought risk assessment, and climate adaptation planning through their representation of key processes that regulate energy, water, and carbon exchanges between land and atmosphere (Stephens et al. 2023).

Yet, in many LSMs, descriptions of soil processes rely on simplified parameterizations of static properties, with parameters typically derived from pedotransfer functions (PTFs) calibrated on legacy datasets and applied to global soil maps of variable quality. These approaches often struggle to capture real-world variability and change (Brêda et al. 2024). Unsurprisingly, soil parameterizations have been identified as a major cause of persistent biases in hydrological fluxes and land–atmosphere feedbacks predicted by LSMs (Dennis and Berbery 2021; Xu et al. 2023).

The hybrid Soil and GEWEX Water Initiative (SoilWat)_2025 meeting, held 14–16 July 2025 at the University of Reading (United Kingdom), aimed to confront this issue. The meeting brought together soil physicists, land surface modelers, micrometeorologists, hydrologists, ecologists, plant physiologists, and remote sensing experts, from 12 countries and 30 institutions, and spanning a wide range of career stages (Fig. 1). We examined how soils and root systems are represented in LSMs and how this representation must evolve to meet emerging Earth system modeling needs. The program combined invited keynotes, short talks, plenary discussions, and synthesis sessions to coordinate next steps.

The SoilWat effort interfaces two communities (Zeng et al. 2021): the International Soil Modeling Consortium (ISMC) and the Global Energy and Water Exchanges project (GEWEX) via its Global Land–Atmosphere System Study (GLASS) panel. SoilWat_2025 continued from the first GEWEX SoilWat Initiative Planning Workshop held in Leipzig in 2016 (Or 2017), which catalyzed ISMC working groups and widely cited reviews on PTFs (Van Looy et al. 2017; Weber et al. 2024), hydrological processes (Vereecken et al. 2019, 2022),

Fig. 1. SoilWat_2025 group photo, Whiteknights Campus, Reading University, 14 Jul 2025.

soil structure (Fatichi et al. 2020; Bonetti et al. 2021), and soil biophysical feedbacks (Robinson et al. 2019), among others.

At SoilWat_2025, we took stock of recent progress in critical zone science and identified new frontiers in an era of machine learning, digital twins, and kilometer-scale Earth system modeling. Three topics surfaced repeatedly: (i) How can we represent soils and roots in a way that is physically grounded yet computationally tractable? (ii) Which below-ground processes matter most for surface fluxes, atmospheric boundary layer development, and extremes? And (iii) how can the soil and LSM communities move beyond incremental ad hoc updates and jointly address scaling from pedon to global scales?

2. Soil hydraulic–thermal properties and pedotransfer functions

A clear message from the meeting was that soil hydraulic parameterizations in LSMs require updating. Across models [e.g., Community Atmosphere–Biosphere Land Exchange (CABLE); CLM; ECMWF Land Surface Modeling System (ecLand); HydroBlocks; ISBA; JULES; Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO); Noah-MP; ORCHIDEE; and Simultaneous Transfer of Energy, Mass, and Momentum in Unsaturated Soils–Soil Canopy Observation of Photochemistry and Energy fluxes (STEMMUS-SCOPE)], hydraulic parameters are still commonly derived from soil texture (sometimes augmented with bulk density and organic carbon) using PTFs developed decades ago for limited regions and with sparse metadata on land management, vegetation, and soil mineralogy (Weber et al. 2024). Participants also noted that vertical variations in soil properties are rarely represented adequately in LSMs, despite the widespread use of multilayer soil columns.

Beyond updating "classic" PTFs, discussions emphasized the need for covariate geotransfer functions (CoGTFs) (Gupta et al. 2021, 2022) that include environmental covariates (vegetation, topography, climate, and lithology). A related discussion point was that most PTFs are calibrated at the soil profile support and should not be applied at gridcell scales without explicit change-of-support: robust upscaling frameworks (e.g., stochastic/geostatistical methods and effective parameter approaches) are needed to account for heterogeneity, lateral redistribution, and preferential flow.

Participants highlighted emerging “spectral PTFs” that use reflectance spectra as covariates for landscape-scale parameter inference (Romano et al. 2023; Zeng et al. 2025). Two priorities crystallized: (i) develop and test “scale-aware” parameterizations with specific support (point, plot, catchment, or grid cell) and (ii) quantify how parameter choices propagate into infiltration capacity, runoff partitioning, and soil moisture dry-downs, noting that legacy threshold concepts (e.g., field capacity and wilting point) contribute to model structural ambiguity (Romano et al. 2025).

Presentation of Soil Parameter Model Intercomparison Project (SP-MIP; Gudmundsson and Cuntz 2017) results reinforced that soil parameter uncertainty is a first-order issue: swapping soil maps and/or PTFs can substantially alter simulated soil moisture, ecosystem fluxes, and extreme event behavior (Weihermüller et al. 2021; Paschalis et al. 2022). The meeting also stressed that LSMs focus on capillary water, whereas in (semi)arid regions, adsorbed water can strongly affect surface fluxes (Verhoef et al. 2006; Bekin et al. 2025). Therefore, several talks proposed more explicit and consistent treatment of adsorbed and capillary water (e.g., Weber et al. 2019) when modeling soil hydraulic properties in LSMs.

A key outcome of the discussions was a commitment to evaluate emerging unified hydraulic–thermal parameterizations across multiple LSMs—formulations in which soil hydraulic and thermal properties share parameters representative of soil pore size distribution (e.g., Fu et al. 2025). Participants also noted opportunities to better constrain the adsorption branch by incorporating mineralogical covariates (e.g., clay-mineral-based specific surface area) within CoGTF frameworks.

3. Uncertainty and model evaluation

Another recurring theme in the meeting was the uncertainty of soil representation in LSMs. Participants highlighted three intertwined sources: (i) the PTFs and their applicability across regions and land management regimes, (ii) the underlying soil maps, and (iii) model structural assumptions such as the choice of functions that describe the hydraulic–thermal properties or the decision to keep soil parameters constant in time. While uncertainties stemming from (i) to (iii) can be masked in models by “ad hoc” tuning and bespoke calibration to improve model–data agreement, such practices limit the predictive power of models particularly under novel conditions and extremes.

In response, the participants strongly endorsed evaluation strategies that look beyond surface fluxes alone. Rather than treating the land surface model as an “opaque” system that produces total latent and sensible heat fluxes, participants called for systematic benchmarking of internal variables and fluxes such as soil temperatures, root zone moisture, and soil evaporation fluxes. Modeling experiments were presented in which soil hydraulic parameters were constrained by matching simulated soil moisture dynamics to in situ– and satellite-derived observations using data assimilation and machine learning–assisted optimization (Cooper et al. 2021; Mu et al. 2021; Raoult et al. 2021). This illustrated both the potential and the pitfalls of parameter estimation and underlined the importance of retaining physical interpretability.

4. From static to dynamic soil properties

A third major theme was the recognition that key soil properties should not be treated as static model inputs. Participants emphasized that porosity, water retention curve and hydraulic conductivity, and thermal conductivity can vary over time due to wetting–drying and freeze–thaw cycles, biological activity, and land use and management (Jarvis et al. 2013, 2024; Jha et al. 2023; Robinson et al. 2022; Blanchy et al. 2023). Notwithstanding, in most operational LSMs, these soil properties remain fixed during a model run.

Discussions captured a shift in mindset: from prescribing soil properties as immutable texture-derived parameters to treating them as “state” variables that coevolve with climate, vegetation, and management. While total pore volume and pore size distribution are strongly linked to texture, they are continually reshaped by soil–plant interactions, microbial and faunal activity, physical processes, and human activities. These modulations will affect soil hydraulic, thermal, mechanical, and biochemical properties; transport processes; and biogeochemical reactions and transformations, which in turn will influence pore size distribution again (Fig. 2).

Human activities were frequently discussed, noting that tillage, grazing, traffic, irrigation, erosion, and vegetation leave persistent signatures in soil structure and function. The idea of "anthropo-environmental transfer functions" (beyond PTFs or CoGTFs) gained traction: semimechanistic relationships that translate management histories into model-relevant changes in soil parameters, embedded within dynamic soil property frameworks. Its feasibility will depend on "soil memory," which differs across disturbances and soil properties (Rahmati et al. 2023).

5. Heterogeneity and kilometer-scale Earth system modeling

Participants presented and discussed the benefits and drawbacks of existing approaches to represent multiscale heterogeneity in LSMs. This challenge is driven primarily by the scale mismatch between observed soil landscape heterogeneity (10–1000 m) and the resolved spatial heterogeneity in Earth system models (10–100 km). One approach that was discussed was "HydroBlocks" that clusters observed heterogeneity according to their hydrological similarity; this allows for subgrid heterogeneity in soil and land cover to be preserved as a set of representative tiles within each grid cell while maintaining computational efficiency (Chaney et al. 2018). Another approach presented is to explicitly resolve soil heterogeneity in fully distributed catchment-scale models (Lian et al. 2025).

With Earth system modeling moving to finer resolutions, it becomes more pressing to address deficiencies in soil and land surface parameterizations. The meeting highlighted that subgrid soil moisture heterogeneity can generate horizontal air temperature and humidity gradients that feed back to the atmospheric boundary layer, influencing convective rainfall, and land–atmosphere coupling (Simon et al. 2021). Various discussions underscored the continued need to test the influence of soil and root parameterizations not only for local

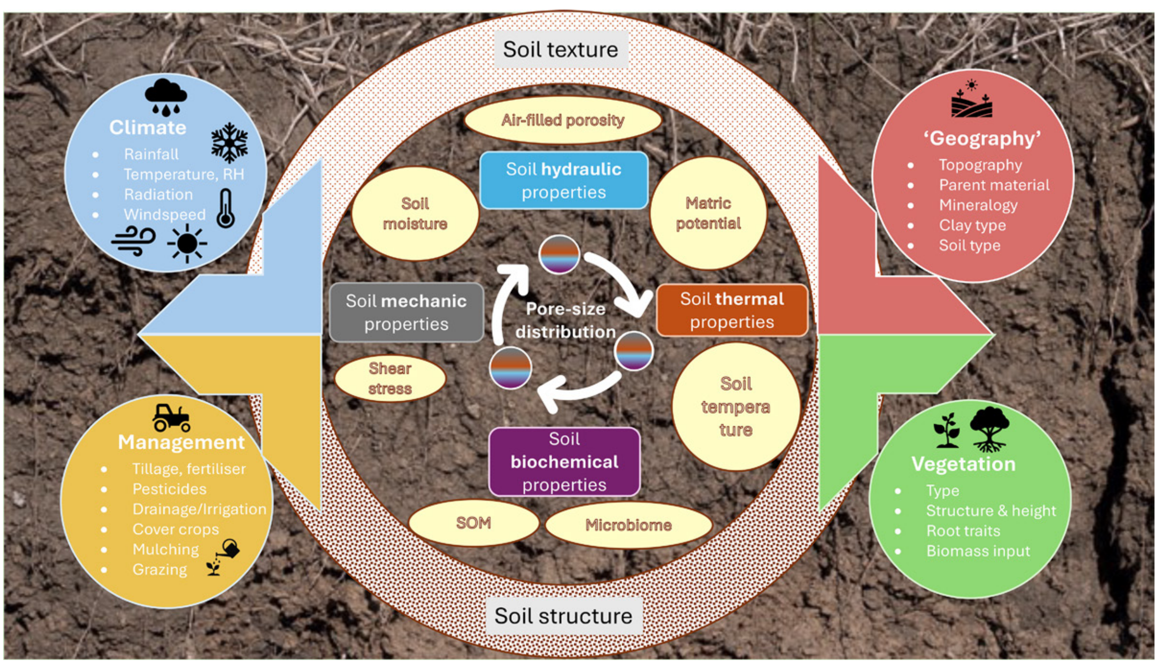

Fig. 2. Interactive effects of soil texture, soil structure, and external drivers on soil properties and state variables (light yellow), highlighting the central role of pore size distribution.

effects but also in terms of their impact on boundary layer development and extreme events via coupled simulations.

6. Soil–root–plant interactions

Although soils were the nominal focus of SoilWat_2025, plant hydraulics and root dynamics featured prominently. Participants noted that, in most LSMs, rooting depth and root profiles still depend on plant functional type, and the link between root distribution, soil structure, and plant hydraulics is either absent or largely implicit. This limits the ability of models to capture vegetation responses to droughts, heat waves, and changing carbon dioxide (CO_2) and nutrients. Moreover, not only soil depth but also groundwater table depth and soil hydrology are affecting root depth (Fan et al. 2017). Roots can also extract water stored in the bedrock below the soil (Bert et al. 2025).

Several talks showed how dynamic models of root growth, architecture, and hydraulic traits can be coupled to evolving soil pore structure, allowing simulation of root access to water and the feedbacks of root growth, exudation, and decay on soil structure. Others highlighted advances in trait-based and "hydraulic functional type" approaches, in which plant hydraulic parameters are inferred from measurable plant traits. Progress will depend on better global coverage and standardization (including reliable metadata) of plant hydraulic and root trait data, including information from rhizotrons, lysimeters, and root trait databases (Baca Cabrera et al. 2024).

New theoretical developments such as the implementation of Münch theory (pressure flow; Giraud et al. 2023) in crop models, eco-evolutionary optimality theories for vegetation function (Harrison et al. 2021; Sabot et al. 2022), and mechanistic frameworks that couple soil and plant hydraulics to explain critical plant water potentials were presented as promising avenues (Su and Zeng 2025). Participants explored the idea of contrasting "plant hydraulic strategies" with "soil hydraulic strategies," asking how vegetation adjusts its hydraulic traits in response to soil hydraulic limitations and how this coadaptation should be reflected in parameterizations (Carminati and Javaux 2020).

7. Hybrid modeling, machine learning, and computational tools

Machine learning (ML) approaches were discussed throughout the meeting as both an opportunity and a risk, with the latter related to unconstrained, purely data-driven ML. Several speakers warned that unconstrained machine learning models can easily overfit or violate basic soil water, energy, and matter conservation laws. Instead, participants showcased applications in which machine learning components are coupled to physical models to estimate soil parameters (Bandai et al. 2024; Raoult et al. 2025) or infer difficult to observe system states, e.g., active root zone storage (Blougouras et al. 2025). Surrogate LSMs such as aiLand (Raoult and Pinnington 2025) were presented as examples of how emulators can accelerate sensitivity studies and LSM structural testing.

We saw that the GEWEX Machine Learning for Land Modeling (https://www.gewex.org/project/ml4lm/) activity and related efforts provide a focal point for such work, linking machine learning experts and land surface modelers. Participants also highlighted the role of data assimilation frameworks for soil state updating and parameter estimation. Idealized large-eddy simulations [e.g., used in the GEWEX Atmospheric Boundary Layer Study (GABLS) project] were noted as valuable tools to test land–atmosphere coupling schemes and the impact of soil parameter choices on boundary layer development.

8. Observational networks, multidisciplinary observatories, and data products

Participants discussed how to evaluate and constrain increasingly complex soil and root representations. Observational priorities included profiles of soil and plant water potential and soil temperature; joint hydraulic and thermal properties, across the full wetness range (and including frozen conditions); root distribution and trait data; time-variable information on soil structure and pore size distribution; and measurements of soil–atmosphere water fluxes in (semi)arid regions, including deserts: e.g., signatures of soil vapor adsorption are detectable in dry-condition land–atmosphere exchange obtained by eddy covariance systems (Paulus et al. 2025).

Multidisciplinary observatories were highlighted as essential. Emerging GEWEX Land–Atmosphere Feedback Observatories (GLAFOs) provide coordinated below- and above-ground measurements, including vertical atmospheric temperature and humidity profiles, enabling development and testing of parameterizations that capture soil–land–atmosphere feedbacks and nonlocal turbulence (Späth et al. 2023).

The SoilWat community is also advancing "blended observations." The Vegetation as a Soil Sensor (VaaSS) concept (Zeng et al. 2025) combines soil–plant hydraulic modeling with satellite observables (e.g., vegetation optical depth, solar-induced fluorescence, leaf area index, soil moisture, land surface temperature) to infer root zone soil properties and dynamics. In parallel, runoff and river discharge were noted as basin-scale "integrators" for LSM evaluation (Boussetta et al. 2021).

Data products formed another focal point. Participants discussed new global and regional soil property maps derived using CoGTFs, spectral PTFs, and satellite–model fusion products. These datasets, together with community platforms supported by the ISMC (e.g., the Soil Water Infiltration Global database; Rahmati et al. 2018) and GLASS [e.g., Protocol for the Analysis of Land Surface Models (PALS) Land Surface Model Benchmarking Evaluation Project number 2 (PLUMBER2); Abramowitz et al. 2024], are critical for benchmarking, parameter estimation, and model training.

9. Remaining challenges and communication opportunities

Despite clear progress, balancing realism, transferability, and computational cost remains difficult. Speakers cautioned against adding complexity tailored to "typical" soils while neglecting fire-affected soils, permafrost, hyperarid, and tropical environments, which require improved representation of hydrophobicity, freeze–thaw processes, vapor/absorption effects, and strong weathering.

With growing use of data assimilation and artificial intelligence (AI), maintaining physical realism and internal consistency of hydraulic–thermal parameters is an added challenge. Participants also noted that soil information below ~2 m is still poorly constrained in many regions, yet deeper profiles can improve simulations, especially of soil heat transfer; better three-dimensional soil property information and improved representation of deep soil–groundwater interactions are needed.

Progress also depends on broader collaboration beyond traditional communities. Participants emphasizing integrating insights from the hydrological community with LSM development, noting the relevance of the GEWEX Groundwater Network, and reiterated that open data and model sharing are prerequisites for robust benchmarking and hybrid modeling.

10. Working groups and a community roadmap

A key outcome of SoilWat_2025 was the formation of several working groups structured around cross-cutting themes:

- Unified hydraulic–thermal parameterizations: to evaluate, refine, and implement formulations that jointly describe soil hydraulic and thermal properties, across a range of land surface models and climates.

- Dynamic soil properties and pore size distributions: to develop model frameworks in which soil properties evolve as state variables, linked to climate, vegetation, and management, and to test these frameworks against long-term data of soil structure observatories.
- Soil–surface–atmosphere interface processes: to improve the representation of infiltration, evaporation, vapor transport, and surface soil heat fluxes, including numerical aspects of flux calculation and consistency between energy and water budgets.
- Root dynamics, plant hydraulics, and soil–plant interactions: to couple dynamic root models and plant hydraulic schemes with evolving soil structure and to assess implications for drought response, mortality risk, and vegetation resilience.
- "Blended" soil property estimation, including "Vegetation as a Soil Sensor" approach: to combine bottom-up information (texture, laboratory measurements) with top-down constraints from flux towers, remote sensing, and soil moisture networks using data assimilation, hybrid modeling, and physics-informed machine learning.

For each theme, participants drafted initial objectives, candidate activities, and expected outcomes, along with lists of potential contributors spanning universities, research institutes, and operational forecast centers. The overarching intent is to design coordinated experiments across multiple land surface models using common driving and evaluation data and evaluation metrics. These experiments are meant to complement ongoing benchmarking efforts, including PLUMBER2, and to dovetail with broader World Climate Research Programme and GEWEX priorities on land–atmosphere coupling and extremes.

11. Looking ahead

A clear narrative emerged from the SoilWat_2025 discussions: soils and roots are not just boundary conditions for the atmosphere; they are dynamic, evolving parts of the Earth system whose behaviors shape weather, climate, water resources, and ecosystem resilience. Representing this dynamism in models will require moving beyond static soil properties and fixed plant functional types, toward frameworks that integrate evolving soil structure, plant hydraulics, land management, and richer observational constraints.

Participants left SoilWat_2025 with a shared sense not only of urgency but also of opportunity. The tools now exist, some more developed than others—unified hydraulic–thermal parameterizations, dynamic soil and root models, hybrid modeling approaches and ML, and expanding observational networks—to tackle long-standing deficiencies in soil representation in LSMs. The challenge is to connect them, test them rigorously across models and scales, and embed them in the operational systems that underpin weather and climate services.

The working groups launched at SoilWat_2025 are intended as concrete steps in this direction. Their success will depend on sustained collaboration across disciplinary, institutional, and national boundaries. As extreme events continue to expose the limits of current models, the community's commitment at SoilWat_2025 to "rethink soils" offers a hopeful path toward more reliable predictions and better-informed decisions for long-term management of ecosystems and water resources in a changing climate.

Acknowledgments. We are grateful to Dr. Eleanor Blyth from the Centre of Ecology and Hydrology (Wallingford, United Kingdom) who participated in the meeting and verified the accuracy of the contents of this summary. We also thank the GEWEX office for providing administrative and financial support.

References

Abramowitz, G., and Coauthors, 2024: On the predictability of turbulent fluxes from land: PLUMBER2 MIP experimental description and preliminary results. *Biogeosciences*, **21**, 5517–5538, https://doi.org/10.5194/bg-21-5517-2024.

Baca Cabrera, J. C., J. Vanderborght, V. Couvreur, D. Behrend, T. Gaiser, T. H. Nguyen, and G. Lobet, 2024: Root hydraulic properties: An exploration of their variability across scales. *Plant Direct*, **8**, e582, https://doi.org/10.1002/pld3.582.

Bandai, T., T. A. Ghezzehei, P. Jiang, P. Kidger, X. Chen, and C. I. Steefel, 2024: Learning constitutive relations from soil moisture data via physically constrained neural networks. *Water Resour. Res.*, **60**, e2024WR037318, https://doi.org/10.1029/2024WR037318.

Bekin, N., D. S. Ashilenje, A. Chehbouni, L. Bouchaou, D. Kool, and N. Agam, 2025: Pioneering evidence of the dynamics of water vapor and CO_2 fluxes in Sahara Desert soils. *J. Geophys. Res. Biogeosci.*, **130**, e2025JG009193, https://doi.org/10.1029/2025JG009193.

Bert, S. D., and Coauthors, 2025: Hydraulic properties of a rock-soil-root system: Insights from *Fraxinus ornus* L. saplings growing on different carbonate rocks. *Plant Cell Environ.*, **48**, 3448–3458, https://doi.org/10.1111/pce.15369.

Blanchy, G., L. Albrecht, G. Bragato, S. Garré, N. Jarvis, and J. Koestel, 2023: Impacts of soil management and climate on saturated and near-saturated hydraulic conductivity: Analyses of the Open Tension-disk Infiltrometer Meta-database (OTIM). *Hydrol. Earth Syst. Sci.*, **27**, 2703–2724, https://doi.org/10.5194/hess-27-2703-2023.

Blougouras, G., and Coauthors, 2025: Spatiotemporal dynamics of active root zone storage revealed from hybrid machine learning. ESS Open Archive, https://doi.org/10.22541/essoar.176280049.93675424/v1.

Bonetti, S., Z. Wei, and D. Or, 2021: A framework for quantifying hydrologic effects of soil structure across scales. *Commun. Earth Environ.*, **2**, 107, https://doi.org/10.1038/s43247-021-00180-0.

Boussetta, S., and Coauthors, 2021: ECLand: The ECMWF land surface modelling system. *Atmosphere*, **12**, 723, https://doi.org/10.3390/atmos12060723.

Brêda, J. P. L., L. A. Melsen, I. Athanasiadis, A. Van Dijk, V. A. Siqueira, A. Verhoef, Y. Zeng, and M. van der Ploeg, 2024: Predictor importance for hydrological fluxes of global hydrological and land surface models. *Water Resour. Res.*, **60**, e2023WR036418, https://doi.org/10.1029/2023WR036418.

Carminati, A., and M. Javaux, 2020: Soil rather than xylem vulnerability controls stomatal response to drought. *Trends Plant Sci.*, **25**, 868–880, https://doi.org/10.1016/j.tplants.2020.04.003.

Chaney, N. W., M. H. J. Van Huijgevoort, E. Shevliakova, S. Malyshev, P. C. D. Milly, P. P. G. Gauthier, and B. N. Sulman, 2018: Harnessing big data to rethink land heterogeneity in Earth system models. *Hydrol. Earth Syst. Sci.*, **22**, 3311–3330, https://doi.org/10.5194/hess-22-3311-2018.

Cooper, E., E. Blyth, H. Cooper, R. Ellis, E. Pinnington, and S. J. Dadson, 2021: Using data assimilation to optimize pedotransfer functions using field-scale in situ soil moisture observations. *Hydrol. Earth Syst. Sci.*, **25**, 2445–2458, https://doi.org/10.5194/hess-25-2445-2021.

Dennis, E. J., and E. H. Berbery, 2021: The role of soil texture in local land surface–atmosphere coupling and regional climate. *J. Hydrometeor.*, **22**, 313–330, https://doi.org/10.1175/JHM-D-20-0047.1.

Fan, Y., G. Miguez-Macho, E. G. Jobbagy, R. B. Jackson, and C. Otero-Casal, 2017: Hydrologic regulation of plant rooting depth. *Proc. Natl. Acad. Sci. USA*, **114**, 10 572–10 577, https://doi.org/10.1073/pnas.1712381114.

Fatichi, S., and Coauthors, 2020: Soil structure is an important omission in Earth system models. *Nat. Commun.*, **11**, 522, https://doi.org/10.1038/s41467-020-14411-z.

Fu, Y., R. Horton, and J. Heitman, 2025: Neural network estimation of thermal conductivity across full saturation for various soil types. *Comput. Electron. Agric.*, **235**, 110321, https://doi.org/10.1016/j.compag.2025.110321.

Giraud, M., and Coauthors, 2023: CPlantBox: A fully coupled modelling platform for the water and carbon fluxes in the soil–plant–atmosphere continuum. *In Silico Plants*, **5**, diad009, https://doi.org/10.1093/insilicoplants/diad009.

Gudmundsson, G., and M. Cuntz, 2017: Soil Parameter Model Intercomparison Project (SP-MIP): Assessing the influence of soil parameters on the variability of land surface models. 8 pp., https://www.gewexevents.org/wp-content/uploads/GLASS2017_SP-MIP_Protocol.pdf.

Gupta, S., P. Lehmann, S. Bonetti, A. Papritz, and D. Or, 2021: Global prediction of soil saturated hydraulic conductivity using random Forest in a Covariate-based GeoTransfer Function (CoGTF) framework. *J. Adv. Model. Earth Syst.*, **13**, e2020MS002242, https://doi.org/10.1029/2020ms002242.

——, A. Papritz, P. Lehmann, T. Hengl, S. Bonetti, and D. Or, 2022: Global mapping of soil water characteristics parameters—Fusing curated data with machine learning and environmental covariates. *Remote Sens.*, **14**, 1947, https://doi.org/10.3390/rs14081947.

Harrison, S. P., and Coauthors, 2021: Eco-evolutionary optimality as a means to improve vegetation and land-surface models. *New Phytol.*, **231**, 2125–2141, https://doi.org/10.1111/nph.17558.

Jarvis, N., J. Koestel, I. Messing, J. Moeys, and A. Lindahl, 2013: Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrol. Earth Syst. Sci.*, **17**, 5185–5195, https://doi.org/10.5194/hess-17-5185-2013.

——, E. Coucheney, E. Lewan, T. Klöffel, K. H. E. Meurer, T. Keller, and M. Larsbo, 2024: Interactions between soil structure dynamics, hydrological processes, and organic matter cycling: A new soil-crop model. *Eur. J. Soil Sci.*, **75**, e13455, https://doi.org/10.1111/ejss.13455.

Jha, A., S. Bonetti, A. P. Smith, R. Souza, and S. Calabrese, 2023: Linking soil structure, hydraulic properties, and organic carbon dynamics: A holistic framework to study the impact of climate change and land management. *J. Geophys. Res. Biogeosci.*, **128**, e2023JG007389, https://doi.org/10.1029/2023JG007389.

Lian, T., S. Fatichi, M. Stähli, and S. Bonetti, 2025: Assessing spatial patterns of carbon and nutrient dynamics in catchments of complex topography. *Water Resour. Res.*, **61**, e2025WR040260, https://doi.org/10.1029/2025WR040260.

Mu, M., and Coauthors, 2021: Evaluating a land surface model at a water-limited site: Implications for land surface contributions to droughts and heatwaves. *Hydrol. Earth Syst. Sci.*, **25**, 447–471, https://doi.org/10.5194/hess-25-447-2021.

Or, D., 2017: 1st GEWEX SoilWat initiative planning workshop: Advancing Integration of Soil and Subsurface Processes in Climate Models, 28–30 June 2016 Leipzig, Germany. *GEWEX News*, No. 27, International GEWEX Project Office, Silver Spring, MD, 7–9, https://www.gewex.org/gewex-content/uploads/2024/02/1489715816Feb2017.pdf.

Paschalis, A., S. Bonetti, Y. Guo, and S. Fatichi, 2022: On the uncertainty induced by pedotransfer functions in terrestrial biosphere modeling. *Water Resour. Res.*, **58**, e2021WR031871, https://doi.org/10.1029/2021WR031871.

Paulus, S. J., M. Migliavacca, M. Reichstein, R. Orth, S.-C. Lee, A. Carrara, A. Hildebrandt, and J. A. Nelson, 2025: Insights into water vapor uptake by dry soils using a global eddy covariance observation network. *Global Change Biol.*, **31**, e70547, https://doi.org/10.1111/gcb.70547.

Rahmati, M., and Coauthors, 2018: Development and analysis of the soil water infiltration global database. *Earth Syst. Sci. Data*, **10**, 1237–1263, https://doi.org/10.5194/essd-10-1237-2018.

——, and Coauthors, 2023: Soil is a living archive of the Earth system. *Nat. Rev. Earth Environ.*, **4**, 421–423, https://doi.org/10.1038/s43017-023-00454-5.

Raoult, N., and E. Pinnington, 2025: DestinE Blog—Towards an ML-based Earth system model: land. Destination Earth, accessed 27 November 2025, https://destine.ecmwf.int/news/destine-blog-towards-an-ml-based-earth-system-model-land/.

——, C. Ottlé, P. Peylin, V. Bastrikov, and P. Maugis, 2021: Evaluating and optimizing surface soil moisture drydowns in the ORCHIDEE land surface model at in situ locations. *J. Hydrometeor.*, **22**, 1025–1043, https://doi.org/10.1175/JHM-D-20-0115.1.

——, and Coauthors, 2025: Parameter estimation in land surface models: Challenges and opportunities with data assimilation and machine learning. *J. Adv. Model. Earth Syst.*, **17**, e2024MS004733, https://doi.org/10.1029/2024MS004733.

Robinson, D. A., and Coauthors, 2019: Global environmental changes impact soil hydraulic functions through biophysical feedbacks. *Global Change Biol.*, **25**, 1895–1904, https://doi.org/10.1111/gcb.14626.

——, A. Nemes, S. Reinsch, A. Radbourne, L. Bentley, and A. M. Keith, 2022: Global meta-analysis of soil hydraulic properties on the same soils with differing land use. *Sci. Total Environ.*, **852**, 158506, https://doi.org/10.1016/j.scitotenv.2022.158506.

Romano, N., B. Szabó, A. Belmonte, A. Castrignanò, E. B. Dor, N. Francos, and P. Nasta, 2023: Mapping soil properties for unmanned aerial system–based environmental monitoring. *Earth Observation, Unmanned Aerial Systems for Monitoring Soil, Vegetation, and Riverine Environments*, S. Manfreda and E. B. Dor, Eds., Elsevier, 155–178.

——, C. Mazzitelli, and P. Nasta, 2025: Root-zone water-storage capacity and uncertainty: An intrinsic factor affecting agroecosystem resilience to drought. *Water Resour. Res.*, **61**, e2024WR037719, https://doi.org/10.1029/2024WR037719.

Sabot, M. E. B., and Coauthors, 2022: Predicting resilience through the lens of competing adjustments to vegetation function. *Plant Cell Environ.*, **45**, 2744–2761, https://doi.org/10.1111/pce.14376.

Simon, J. S., A. D. Bragg, P. A. Dirmeyer, and N. W. Chaney, 2021: Semi-coupling of a field-scale resolving land-surface model and WRF-LES to investigate the influence of land-surface heterogeneity on cloud development. *J. Adv. Model. Earth Syst.*, **13**, e2021MS002602, https://doi.org/10.1029/2021MS002602.

Späth, F., and Coauthors, 2023: The land–atmosphere feedback observatory: A new observational approach for characterizing land–atmosphere feedback. *Geosci. Instrum. Method Data Syst.*, **12**, 25–44, https://doi.org/10.5194/gi-12-25-2023.

Stephens, G., and Coauthors, 2023: The first 30 years of GEWEX. *Bull. Amer. Meteor. Soc.*, **104**, E126–E157, https://doi.org/10.1175/BAMS-D-22-0061.1.

Su, Z., and Y. Zeng, 2025: Photosynthesis and water potential: A new perspective for coupling water, energy, and carbon cycles. *Innovation Geosci.*, **3**, 100156–100152, https://doi.org/10.59717/j.xinn-geo.2025.100156.

Van Looy, K., and Coauthors, 2017: Pedotransfer functions in Earth system science: Challenges and perspectives. *Rev. Geophys.*, **55**, 1199–1256, https://doi.org/10.1002/2017RG000581.

Vereecken, H., and Coauthors, 2019: Infiltration from the pedon to global grid scales: An overview and outlook for land surface modeling. *Vadose Zone J.*, **18** (1), 1–53, https://doi.org/10.2136/vzj2018.10.0191.

——, and Coauthors, 2022: Soil hydrology in the Earth system. *Nat. Rev. Earth Environ.*, **3**, 573–587, https://doi.org/10.1038/s43017-022-00324-6.

Verhoef, A., A. Diaz-Espejo, J. R. Knight, L. Villagarcía, and J. E. Fernández, 2006: Adsorption of water vapor by bare soil in an olive grove in southern Spain. *J. Hydrometeor.*, **7**, 1011–1027, https://doi.org/10.1175/JHM556.1.

Weber, T. K. D., W. Durner, T. Streck, and E. Diamantopoulos, 2019: A modular framework for modeling unsaturated soil hydraulic properties over the full moisture range. *Water Resour. Res.*, **55**, 4994–5011, https://doi.org/10.1029/2018WR024584.

——, and Coauthors, 2024: Hydro-pedotransfer functions: A roadmap for future development. *Hydrol. Earth Syst. Sci.*, **28**, 3391–3433, https://doi.org/10.5194/hess-28-3391-2024.

Weihermüller, L., P. Lehmann, M. Herbst, M. Rahmati, A. Verhoef, D. Or, D. Jacques, and H. Vereecken, 2021: Choice of pedotransfer functions matters when simulating soil water balance fluxes. *J. Adv. Model. Earth Syst.*, **13**, e2020MS002404, https://doi.org/10.1029/2020MS002404.

Xu, C., L. Torres-Rojas, N. Vergopolan, and N. W. Chaney, 2023: The benefits of using state-of-the-art digital soil properties maps to improve the modeling of soil moisture in land surface models. *Water Resour. Res.*, **59**, e2022WR032336, https://doi.org/10.1029/2022WR032336.

Zeng, Y., and Coauthors, 2021: GEWEX-ISMC SoilWat project: Taking stock and looking ahead. *GEWEX Quart.*, **31**, 4–8.

——, and Coauthors, 2025: Monitoring and modeling the soil-plant system toward understanding soil health. *Rev. Geophys.*, **63**, e2024RG000836, https://doi.org/10.1029/2024RG000836.