University of Reading

Soil hydrology in the Earth system

Article

Accepted Version

Vereecken, H., Amelung, W., Bauke, S. L., Bogena, H., Brüggemann, N., Montzka, C., Vanderborght, J., Bechtold, M., Blöschl, G., Carminati, A., Javaux, M., Konings, A. G., Kusche, J., Neuweiler, I., Or, D., Steele-Dunne, S., Verhoef, A. ORCID: https://orcid.org/0000-0002-9498-6696, Young, M. and Zhang, Y. (2022) Soil hydrology in the Earth system. Nature Reviews Earth & Environment, 3. pp. 573-587. ISSN 2662-138X doi: 10.1038/s43017-022-00324-6 Available at https://centaur.reading.ac.uk/105378/

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.

To link to this article DOI: http://dx.doi.org/10.1038/s43017-022-00324-6

Publisher: Nature

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the End User Agreement.

www.reading.ac.uk/centaur

University of Reading

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Title: Soil hydrology in the Earth system

Author(s): Harry Vereecken[†], Agrosphere Institute, IBG-3, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, h.vereecken@fz-juelich.de, phone: +49 2461 61 6392, Fax+49 2461 61-1768

Wulf Amelung Wulf, Institute of Crop Science and Resource Conservation (INRES) - Soil Science and Soil Ecology, University of Bonn, Germany, wulf.amelung@uni-bonn.de, phone: +49 228 732780, fax: +49 228 732782

Sara L. Bauke, Institute of Crop Science and Resource Conservation (INRES) - Soil Science and Soil Ecology, University of Bonn, Germany, sarabauke@uni-bonn.de, phone: +49 228 732965, fax: +49 228 732782

Heye Bogena, Agrosphere Institute, IBG-3, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, h.bogena@fz-juelich.de, phone: +49 2461 61 6392, Fax: +49 2461 61-1768

Nicolas Brüggemann, Agrosphere Institute, IBG-3, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, n.brueggemann@fz-juelich.de, phone: +49 2461 61 8643, Fax: +49 2461 61-1970

Carsten Montzka, Agrosphere Institute, IBG-3, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, c.montzka@fz-juelich.de, phone: +49 2461 61 6392, Fax: +49 2461 61-1768

Jan Vanderborght, Agrosphere Institute, IBG-3, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, j.vanderborght@fz-juelich.de, phone: +49 2461 61 6392, Fax+49 2461 61-1768

Michel Bechtold, Department of Earth and Environmental Sciences, KU Leuven, Belgium, michel.bechtold@kuleuven.be, phone: +32 471 740655, fax: +32 163 21957

Günter Blöschl, Institute of Hydraulic and Water Resources Engineering, Technische Universitat Wien, Karlsplatz 13/222, 1040, Vienna, Austria, bloeschl@hydro.tuwien.ac.at, phone: +431 58801-22315

Andrea Carminati, Dep. of Environmental Systems Science, ETH, Zürich, Switzerland, andrea.carminati@usys.ethz.ch, phone: +41 44 633 61 60

Mathieu Javaux, Earth and Life Institute, Environmental Sciences, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, mathieu.javaux@uclouvain.be, phone +32 10 47 37 08

Alexandra G. Konings, Department of Earth System Science, Stanford, California, US, konings@stanford.edu, phone: +1 650 736-2083

Jürgen Kusche, Institute of Geodesy and Geoinformation, University of Bonn, Nussallee 17, 53115 Bonn, Germany, kusche@geod.uni-bonn.de, phone: +49-228-73-2629, fax: +49-228-73-3029

Insa Neuweiler, Hannover University, Institut für Strömungsmechanik und Umweltphysik im Bauwesen, Hannover University, Germany, neuweiler@hydromech.uni-hannover.de, phone: + 49 511 762 3567, fax: +49 511 762 3777

Dani Or, Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland, dani.or@env.ethz.ch and Division of Hydrologic Sciences, Desert Research Institute, Reno, NV, USA dani.or@dri.edu, phone: +1 775 409 2275

Susan Steele-Dunne, Department of Geoscience and Remote Sensing, TU Delft, The Netherlands, S.C.Steele-Dunne@tudelft.nl

Anne Verhoef, Department of Geography and Environmental Science, The University of Reading, Reading, UK, a.verhoef@reading.ac.uk, phone: +44 1183786074

Michael Young, Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, USA, michael.young@beg.utexas.edu, phone: +1 512 475 8830

Yonggen Zhang, School of Earth System Science, Tianjin University, China, ygzhang@tju.edu.cn, phone: +86 17695926877, fax: +86 22 27405051

†email: h.vereecken@fz-juelich.de

0. Abstract

Predicting the impact of land use and climate change on the Earth system hinges on credible representation of soil hydrological processes (SHP), adequate availability of parameters and hydrological states and inclusion of key soil properties. There is increasing evidence that extreme events such as droughts and high intensity precipitation, and land use changes, affect fundamental hydrological processes such as infiltration and runoff generation. In this review, we analyse the influence of soil structure on SHP, critically evaluate the parameterization of soil hydrologic properties and their importance in representing the terrestrial water cycle and highlight the key role of soil hydrology in the functioning of carbon-rich soils and in linking the water and carbon cycles. It emerges that linking soil hydrology and pedology will lead to better understanding critical zone processes, especially in tropical regions. Further, we discuss the role of local scale hydrological processes in understanding root water uptake, vegetation and groundwater dynamics and feedbacks. These processes control and modulate the impact of extreme events such as droughts, floods and heatwaves and they are essential to assess drought and flooding. Finally, new emerging technologies such as wireless and automated sensing approaches, soil moisture observation through novel synthetic aperture radars satellites, big data analysis and machine learning approaches offer unique opportunities to advance soil hydrology.

1. Introduction

The terrestrial water cycle is subject to rapid changes, resulting in an increase of extreme events such as frequent and intense droughts, floods and heat waves that promote wildfires, cause crop failure and threaten communities in arid regions[1-4] . SHP play an important role in modulating the rates by which the Earth system is pushed towards its boundaries within which mankind can operate safely[5]. These processes are confined to a thin layer of soil which stores only 0.05% of the total freshwater on Earth, yet supports 70% of the annual terrestrial evaporation and transpiration flux[6]. This thin skin plays a pivotal role in supporting life in natural and managed ecosystems. The partitioning of incident radiation and precipitation on the land surface and into fluxes of energy, water and matter from terrestrial surfaces is controlled by SHP[7,8]. The SHP comprise the storage of water in the subsurface down to the groundwater, also termed vadose zone, evapotranspiration, infiltration, redistribution, drainage, capillary rise and runoff (Fig.1).

The partitioning of precipitation at the land surface into water that infiltrates into the soil and surface runoff is strongly controlled both by soil structure and soil moisture content. Root water uptake processes that impact the transpiration of water are modulated by the soil water status and by the properties of soil. The groundwater level is determined by the fluxes in the water balance and impacts the partitioning of energy at the soil surface[7]. Through capillary rise, groundwater provides soil water that can be used by plants, while deep rooting plants can also access groundwater directly. Soil hydrology controls root water uptake and thus evapotranspiration[9] which constitutes the second largest flux in the soil water balance.

The global increase in droughts and floods in the last decade pointed out the need to improve our understanding and parameterization of SHP at catchment, river basin and continental scales[10,11]. Current approaches in hydrological and land surface modeling still have room to improve SHP description and parameterization including estimation of soil hydraulic properties using pedotransfer functions (PTF) and describing SHP in carbon rich soils[8,12,13] and tropical soils[14]. SHP also modulate the impact of climate change on terrestrial ecosystems and control feedback mechanisms between the water, energy and carbon and nitrogen cycles[7,15,16]. However, soils differ in properties such as texture, organic matter, and structure but also their spatial distribution and the vegetation cover affect SHP, resulting in differences in the provision of soil moisture supply to crops, infiltration and runoff[17]. Regional impacts of climate change on the land surface also challenges soil hydrology to expand beyond the soil profile or pedon scale (Fig. 1). The critical zone concept (CZC) addresses this challenge by framing soils in a landscape and regional context and analyzing SHP from the bottom of the groundwater through the vadose zone, and vegetation up into the atmosphere[18].

In this review, we highlight the role of soil hydrology in the Earth system. We discuss key soil properties that influence SHP, the estimation of soil hydraulic parameters and highlight the links between water and carbon cycles with a focus on carbon-rich soils. We demonstrate the importance of local scale SHP in understanding root water uptake, vegetation and groundwater dynamics and feedbacks. We explore the role of SHP in controlling and modulating the impact of extreme events such as droughts, floods and heatwaves and how soil hydrology contributes to assessing drought and floods. Finally, we explore the potential of new emerging technologies for advancing the field of soil hydrology.

1. Soil properties and hydrology

All water fluxes depicted in Fig. 1 are strongly controlled by physical, chemical and biological properties of soils. Primarily, physical properties such as soil texture and bulk density have widely been used to parametrize soil hydraulic properties in land surface models (LSM) by using PTF[8,19]. There is, however, increasing awareness that other pedological properties and processes also affect soil hydraulic properties and thus soil water dynamics (Text box 1).

Based on this awareness, hydropedology was introduced[20] two decades ago with the aim of integrating hydrological and pedological knowledge to better understand and predict SHP at the landscape scale. Later on, hydropedology[21] was embedded in the CZC, which allowed addressing SHP at and beyond the pedon scale and to frame local processes such as bypass flow, water accessibility and hydrophobicity in a landscape context. It also allows to consider effects of soil structure, spatially varying soil horizons and anisotropy on local and non-local water flow. Remarkably, soil structure and related hydraulic properties, which have evolved slowly over decades to millenia, are sensitive to changes in land management and global change and can therefore rapidly change[22] (Fig.2).

2.1 Soil structure

Soil structure is a key property that is lacking in current hydrological, land surface and Earth system models. Soil structure describes the spatial arrangement of particles in soil, which determines pore size distribution, connectivity and tortuosity. At the microscale, soil water flux is controlled by aggregation processes: organic gluing agents such as extracellular polymeric substances and microbial gums, and inorganic cementing agents like carbonate precipitates and oxy-hydroxides bind primary particles to form clay- and silt-sized organo-mineral complexes (< 20 µm diameter). With adherence to fungal hyphae and fine roots, soil further clusters into micro- and macroaggregates (20-250 µm and > 250 µm respectively) and finally peds[23,24]. The voids or pores existing within and in-between the aggregates are usually small (up to a few µm in diameter) and of high tortuosity[25]. These pores mainly contribute to capillary water flow in the soil matrix and thus to its hydraulic conductivity and water retention within the soil profile[24]. They generally indirectly affect infiltration, as it depends on the initial soil water content at the onset of infiltration processes[8], but they can dominate near-surface water flow processes in older, structured soils.

Soil structure formation differs among different soil groups (Text box 1). In Phaeozems, Chernozems or Luvisols with silty texture, the biological formation of macropores by plants is stabilized by, e.g., earthworms[26,27] and other burying animals. In Vertisols, elevated clay contents promote crack formation, especially in dry conditions, enabling rapid bypass flow of precipitation until these cracks close again during soil rewetting. Preferential flow can significantly change groundwater recharge[28]; but in Planosols, Stagnosols or Plinthosols root-restricting layers can induce anisotropies and impair vertical water flow. In Leptosols, high stone contents funnel infiltrating water into smaller volumes[29], and crusts build up following particle dispersion after heavy rain and/or due to high salt contents. Further, specific SHP prevail in organic soils, such as bogs and fens and folic Histosols, which have a high capacity to store plant-available water but have a different connection to groundwater (section 2.3).

Natural soil structure forming processes create larger scale pores in between macroaggregates and peds. These macropores include cracks formed by shrinkage in clayey soils due to soil drying, but in many terrestrial systems, vegetation and soil fauna are two of the main factors in macropore formation. Both root systems and burrowing activity of the soil fauna (Fig. 2) create such biopores, which in contrast to the above-described inter- and intra-aggregate pores, are wider in diameter (up to several mm or even cm), have low tortuosity and often connect the soil surface with the subsoil to a depth of several metres[30,31] (Fig. 1). In loamy and silty soils, in particular, the accumulation and persistence of macropores alters SHP and gas exchange significantly. Under most soil conditions, macropores are drained and contribute to enhanced gas exchange pathways in the soil. During intense precipitation events, however, water-filled macropores can contribute to rapid infiltration and transmission of water through the soil profile via preferential flow pathways[31-33].

Natural soil structure formation takes decades to centuries, yet it may be disrupted by a single tillage or erosion event with significant ramifications for soil functioning and carbon storage. Agronomic management of soil structure, for example, has been practiced since the dawn of civilization producing short lived and fragile seedbed for crops[34]. Tillage induces loss of macroporosity, interrupts pore continuity, and potentially forms compacted plough pans that impede root growth and vertical water fluxes. Tilled soil surfaces are prone to aggregate slaking during heavy rain, causing the clogging of fine pores and formation of surface crusts[35]. The degree to which these processes occur varies with tillage and land-use practices[36,37]. However, the largely unknown time scales of aggregates and macro-porosity turnover challenge assumptions of stable pore-size distributions used in SHP modelling.

2.2 Soil hydrological parameterization

A reliable parameterization of soil hydraulic properties is critical for SHP representation in soil water balance models, hydrological models, land surface models (LSM), and climate models and ESM[8,38]. In these models, the fluxes and states of soil water are mostly described by Richards Equation (Eq.1) which links Darcy-Buckingham flux law with conservation of mass:

$$\frac{\partial\theta}{\partial t} = -div.\vec{q} - S \quad (1)$$

where $\vec{q} = -\boldsymbol{K}(h,\theta)\nabla\,(h+z)$ with $\vec{q}$ the Darcy flux, *div* is the divergence operator describing the local sinks of $\vec{q}$, *h* is the soil matric potential, *z* the vertical coordinate and $\boldsymbol{K}(h,\theta)$ the soil hydraulic conductivity tensor which becomes a scalar quantity, $K(h,\theta \equiv K)$ for isotropic one-dimensional domains, and S describes a general external sink-source term such as root water uptake. Frequently used numerical model codes to solve Richards equation have been extensively reviewed[39]. The use of Richards' equation requires explicit knowledge of key soil hydraulic functions: the soil moisture retention $\theta(h)$ and K. These characteristic functions describe the volumetric water content or *K* as functions of soil water tension (matric potential). The choice of hydraulic functions and associated parameters have a significant impact on model performance in terms of water fluxes in the soil water balance, and model numerical stability[40]. Moreover, spatial variability of soil hydraulic parameters has to be accounted for to correctly describe SHP. The determination of these functions for larger scale approaches remains an ongoing challenge.

Direct measurements of soil hydraulic properties are often difficult and time-consuming[41,42], and impossible at larger spatial scales. PTF were therefore developed to estimate soil hydraulic parameters, as well as parameters in equations related to soil heat flow, and biogeochemical parameters from readily available soil properties such as soil texture, bulk density, and organic carbon content[19]. Text box 1 shows how PTF based on simple soil properties translate this information in soil hydraulic parameters that can be used to estimate SHP such as soil water storage, infiltration and evapotranspiration. In several cases, however, the use of PTF can lead to inaccurate or even false parametrizations of the functions used to describe the soil hydraulic properties. Several reasons account for such failure. The determination of basic and hydraulic soil properties is frequently conducted with different measurement methods[19,43], thus producing systematic biases, and inconsistent results[43,44]. Therefore, it is critical to standardize and unify measurement methods and protocols. Soil structure is not explicitly represented in soil hydraulic functions and related PTF development[45]. Such limitations have prompted efforts to revise the soil-centered framework by considering environmental covariates that modify soil structure and properties such as vegetation cover and type[33,46], and climatic soil forming processes that alter clay type[47,48]. These local variations not encapsulated in the standard texture-based PTF offer a means to improve soil hydraulic parameterization and potentially improve the representation of hydrologic processes in LSM. Further options to account for soil structure in PTF include the incorporation of geometrical properties of structured soils derived from non-invasive techniques such as Micro-Computed Tomography or Magnetic Resonance Imaging[49], and applying machine learning methods to adapt to soil-class-specific information within continuous PTF[50,51]. Also, a poor representation of specific soil properties such as the distribution of soil organic matter significantly affect modeling of hydraulic functions, in particular in peatlands and carbon-rich permafrost soils.

But further efforts are needed to improve the description of SHP processes in models using PTF. While dual-modal and multi-modal hydraulic functions have already been developed[52,53], they are currently not used in LSM and reliable PTF for these functions are not yet available. Moreover, it is important to take into account the effect of rock or gravel content on soil hydraulic properties[54] as this is generally overlooked in most PTF. In addition, there is a need for unifying theoretical soil physical approaches, which requires fully coupling soil hydraulic, thermal and gas flow properties [55,56]. This would allow for a more consistent description of interactions and feedbacks between the soil water balance, the thermal regime, and the carbon fluxes in LSM. Ideally, multi-scale PTF should be developed that can be used seamlessly from the soil profile to the global scale, building for example on the development[57,58] of multiscale Bayesian neural network based PTF, which allow upscaling and downscaling of soil hydraulic parameters.

Most models rely on a single set of PTF to estimate soil hydraulic properties[19,59]. This often results in statistical bias, underestimation PTF uncertainty, and overconfidence in the predictive ability of PTF. To alleviate such bias, ensemble PTFs that unify multiple sets of PTFs are recommended[59,60].

In addition, most of the measurements for PTF parameterization originate from arable land and have been developed for temperate regions. These PTF frequently fail in fine-textured soils of the tropics and subtropics[14,61]. Due to absence of glaciation, these soils are highly weathered, and in Ferralsols and Acrisols low-activity clays dominate the mineral composition (Text box 1). These clays react with oxides and form pseudo-silt and pseudo-sand, i.e., a micro-aggregated structure that the hydrology of silty or sandy sites. With some additional macroaggregates formed with inputs of soil organic matter as found in Cambisols, the parameters used to describe the soil hydraulic properties of tropical soils generally differ from those of respective soils in temperate climates[14,62]. Therefore, there is an urgent need for PTF development for soils that formed below natural vegetation and consider different regions[63,64].

Finally, PTF assume that estimated properties are constant in time. Yet we know that properties like saturated *K* and porosity vary not only in space but also in time, due to land management[43]. The next generation of PTFs should therefore account for this temporal dependence.

2.3 Carbon-rich soils

The SHP of carbon-rich soils feature specific properties, which are of fundamental importance for their carbon sink function but challenging to be represented in LSM. Across the globe, carbon-rich soils are unevenly distributed. Particularly, many permafrost soils are rich in organic carbon and store an estimated 1700 Pg of carbon, twice as much as carbon storage in the atmosphere[65,66]. Large areas on terrestrial Earth are covered by permafrost, accounting for 13.9 x 10^6 km^2 in the Northern hemisphere alone[67]. Part of the carbon-rich soils (mainly in permafrost regions but also elsewhere) are classified as peatlands. These cover 3 % of the global land surface only, but store approximately 644 Pg C[68], and a significant portion of near-surface freshwater with intimate atmospheric exchange.

A key controlling factor on soil moisture dynamics in carbon-rich soils is exerted by the shallow groundwater level in peat and permafrost soils. Because of their high content of organic matter, carbon-rich soils have frequently total pore volumes of 70 to > 90%, and pore sizes reaching 5 mm[69]. This high macroporosity dampens groundwater level fluctuations and thus importantly stabilizes the wet conditions that are critical to inhibit aerobic soil organic matter decomposition. The shallow groundwater conditions are further supported by the low *K* of deeper organic soil layers or the flow barrier of the permafrost layer that limit the drainage losses and causes trapping of rain, snow melt or run-on water[70].

The factors leading to shallow groundwater levels are currently significantly altered either directly or indirectly by humans. In dry conditions, the structure of the soil organic matter of carbon-rich soils substantially changes due to microbial decomposition and irreversible compaction[69]. The soils lose their high water storage capacity and thus groundwater level fluctuations are amplified which eventually further enhances decomposition. In its extremes, these alterations in structure of organic soils can be observed in peatlands that were directly drained by humans and in which the enhanced decomposition causes peatlands to be global hotspots of greenhouse gas emissions[68]. Another threat to the shallow groundwater levels of carbon-rich soils is exerted by ongoing permafrost thaw that may increase drainage losses and also initiate a negative feedback loop between soil moisture and decomposition[71].

Despite the critical role of SHP for the carbon cycle of carbon-rich soils, specific SHP for such soils are currently only beginning to be implemented in a sophisticated manner in LSM and climate models[13,72]. It has been noted that conventional hydrological concepts for groundwater that are based on the TOPMODEL[73] and that relate subgrid-scale topography to groundwater table (GW) and soil moisture variability, fail in the extensive flat terrains typical of most peat and carbon-rich permafrost soils and miss critical small-scale processes relevant to shallow GW conditions[70,74]. In response, modules to simulate the shallow GW and other specific features of peat and carbon-rich permafrost soils were added to a number of LSM[70,74,75]. To advance their reliability, the community currently faces two major challenges.

First, there is a lack of spatial input data for peatlands and carbon-rich permafrost soils that could be used to parameterize spatially variable soil hydraulic properties and lateral water fluxes. About half of the carbon-soils classified as peatlands are bogs and in contrast to fens, by definition are solely fed by rainwater and do not depend on water inputs from surface water or the aquifer underlying the peat layer. Given the lack of spatial input on the distribution of bogs and fens, current peat-specific global land model implementations either assume all peatlands to be either bogs[74] or fens[76].

Second, the hydraulic properties of peat and carbon-rich permafrost soils are dynamic at different timescales, which critically control their resilience to short- and long-term changes in boundary conditions[69,71]. In addition, the thermal soil properties affect freeze-thaw cycles with strong implications for soil water flow dynamics[77]. Soil moisture fluctuations can cause reversible changes in soil properties due to swelling and shrinking, but there are also irreversible changes to hydraulic properties caused by cryoturbation, permafrost thawing or enhanced peat degradation in response to climate change or direct anthropogenic disturbance. These changes are typically accompanied by a change in vegetation that is the main substrate provider for the future organic layers. The implementation of these key ecohydrological feedbacks will be critical in simulating trends over multiple decades[78,79].

We recommend that future research on the hydrology of carbon-rich soils should put specifically emphasize conducting detailed field studies in data scarce regions, such as large parts of tropical[80] and permafrost peatlands[71], to understand and quantify the variability of local feedback mechanisms. Besides there is the need to combine remote sensing data on hydrology[81] , vegetation and peatland type[82,83] with soil hydrological models to eventually constrain the spatial variability of parameters. Finally, this approach will contribute to adequately simulating the feedback loops between water, energy, and biogeochemical cycles on Earth.

3. Local scale hydrology

Soils play an important role in buffering the precipitation (P) signal and storing incoming water. How water is transferred to deeper soil layers or kept in the upper soil layers depends on soil hydraulic properties. At the scale of soil pedon, a field, or a forest stand, the moisture status of soils, the vegetation and the GW dynamics impact each other. In respect to vegetation growth, the uptake of water by plant roots, described by the sink term S in Eq.(1) controls transpiration (T) fluxes. The proportion of S with respect to P varies with climate, vegetation type, and the soil properties. Global averages of the ratio of evapotranspiration (ET) to P, ET/P, on land vary between 0.6 and 0.7[84,85]. The partitioning of ET into evaporation (E) and T are much more uncertain, and estimates of global terrestrial T/ET ratios range between 0.25 and 0.6, but local ratios vary almost across the entire range between 0 and 1[86]. Accurate estimation of T is, however, important to assess the impact of land use or land cover changes on the soil water and to determine how the soil water balance may change with changing climate. Since T is related to carbon assimilation, accurate predictions of T fluxes are also of relevance for the terrestrial carbon cycle and the water-use efficiency of terrestrial vegetation. In the following, we discuss how climate, soil, and vegetation properties, with a focus on root properties, influence each other and the soil water balance components. Fig. 3 illustrates the different processes and interactions between soil, vegetation and groundwater.

3.1 Root water uptake in soils

T is driven by the available energy that can be used for evaporating water, that is T demand, and is downregulated by stomatal closure that responds to the energy required to extract water from the soil, that is T supply. The simplest models of T supply from root water uptake (RWU) use a stress function that express how the ratio of T supply to T demand declines with decreasing fraction of total available water in the root zone, that is the water stored in the root zone at water potentials between -10 kPa for sandy soils or -30 kPa for silty soils (field capacity) and -1500 kPa (permanent wilting point). However, since they only consider soil water content, they lack a direct sensitivity to T demand which is overcompensated by oversensitivity to soil moisture, making predictions of the impact of globally increasing T demand on T and vegetation stress uncertain[87]. The inclusion of plant hydraulics in the soil-plant atmosphere systems allows estimating the leaf water potential needed to sustain a given transpiration rate for a given soil water distribution. Since stomatal regulation depends on leaf water status, soil-plant-hydraulic models mechanistically link stomatal regulation to soil drying[88].

Typically, soil moisture is non-uniformly in the root zone and the distribution of roots and water in the root zone affects the total RWU. The extent to which roots can shift water extraction to wetter zones (RWU compensation) and can redistribute water from wet to dry soil zones bypassing the soil (root water redistribution and hydraulic lift) is a hydraulic process that is driven by water potential gradients and depends on soil and root hydraulic properties[89,90]. Text box 2 gives more details about soil-root hydraulic properties and how they can be represented and simplified in soil-plant hydraulic models. Reported magnitudes of these water transfers[91] range from 0.04 to 3 mm d^{-1} and they can delay stomatal closure by several weeks and maintain T by vegetation that accesses deeper groundwater during drought spells. In addition, it plays an important role in soil biogeochemical cycles, as it prevents surface layers from drying out causing a strong reduction in microbial activity[92].

3.2 Soil, climate and vegetation properties

In order to adapt to the dynamics of available soil water and T demand, vegetation properties are strongly interlinked with soil properties, climate, and management. Ecohydrological models that solve a stochastic root-zone soil water balance[93], use two dimensionless numbers to characterize its dependence on soil, vegetation, and climate properties. These are the number of average daily rainfall events required to fill the plant accessible soil water reservoir and either the Budyko[94] dryness index (long term potential ET to precipitation rate) or the ratio of the time to deplete the plant accessible water reservoir by potential ET to the characteristic time between rainfall events. Such models can predict the change in vegetation properties as a function of soil and climate and assess the development of vegetation in the course of climate change. When coupled to an optimization of the carbon cost for root development, stochastic eco-hydrological models[95,96], could reproduce the relation between root zone depth, climate and soil type, with deeper roots in seasonally dry, semiarid to humid tropical regions and less likely in medium textured soils[97].

Infiltration of surface runoff (run-on), and capillary rise from groundwater also contribute to root zone soil moisture. In addition to climate, soil type and depth, and topography, GW table depth is important to predict and produce global maps of root distributions[98]. Runoff-run-on processes as well as groundwater recharge and flow are scale-dependent lateral flow processes that both determine and are influenced by vegetation growth, composition, and patterning[99,100]. Soil E, infiltration, and runoff from non-vegetated surfaces play a crucial role in the ecohydrology, vegetation patterning and water balances of catchments in arid and semi-arid regions. These processes are controlled by soil surface hydraulic properties that depend on soil structure. Aggregate destruction and crust building by rain splash on barely vegetated soil surfaces reduces the infiltration capacity leading to increased surface runoff. In contrast infiltration capacity, run-on, and preferential flow reducing water losses through E from the soil surface, are larger in vegetated patches with macropores created by roots and soil fauna and water repellency due to increased organic matter input[22]. Manipulation of these processes by changing soil surface hydraulic properties is the basis of water harvesting and water saving methods in dryland agriculture that focus on the reduction of soil E from bare soil and increasing run-on and infiltration. However, near surface soil structure and soil hydraulic properties vary strongly with depth and time which complicates accurate prediction and simulation of soil E[101] and rapid infiltration.

Data on root distributions are scarce and models often underestimate the rooting depth. This is especially true in stony soils and (weathered) bedrocks, from which plants can also extract water[102,103]. In addition to root distributions, plants can also adapt root hydraulic traits such as xylem cavitation resistance to adapt to environmental conditions. To access strongly bound soil water, desert shrub species develop higher cavitation resistances in loamy than in sandy soils[104]. The differentiation of root systems of different species to access specific subsurface niches[105] and interactions from deep rooting species facilitating water uptake from wet deep soil layers to shallower, drier layers with subsequent water uptake by species with shallow root systems [91]are used to explain the higher resilience and productivity of mixed ecosystems[106]. But the mechanisms and conditions under which mixed species perform better than homogeneous systems are context-dependent and not fully understood[107,108]. Higher productivity can lead to an ‘overcrowding effect’ which reduces resilience to drought. Mechanistic modelling of RWU in these complex ecosystems is important for a better understanding of the belowground competition for and facilitating water uptake[109]. Yet, upscaled relations between soil moisture distribution and RWU of different species or individuals sharing the same land surface and soil volume and that are derived in a bottom-up approach based on canopy and root hydraulic traits are still lacking.

3.3 Vegetation and groundwater feedbacks

Changes in vegetation and land cover impact water, energy and carbon exchanges between the land surface and the atmosphere. Vegetation cover reduction leads to an increase of soil E. Since the travel distance of water to the surface where E takes place is much larger than to the absorbing root surfaces in the root zone, the water storage that can be depleted by soil E is much smaller than what can be extracted by plant roots. As a consequence, a decrease in vegetation cover generally leads to a decrease in ET losses, an increase in groundwater recharge and runoff, larger warming of the land surface, and higher air temperatures near the surface.

Soil surface and root zone drying are mitigated by upward capillary flow from the subsurface. It sustains ET during dry spells and decreases groundwater recharge on a longer time scale and it depends on the wetness of the subsurface and ultimately on the GW depth. The non-linear dependence of soil hydraulic properties on soil water content is propagated into a non-linear relation between GW depth, subsurface moisture content, and upward capillary flow. For GW depths above roughly 1 m, the root zone stays wet and ET is controlled by the available energy whereas GWs deeper than 10 m have no influence on root zone wetness and land surface-atmosphere interactions[110]. The depth range over which GW depth influences land surface atmosphere interactions depends on the soil hydraulic properties and the rooting depth. Steady upward capillary flow at typical potential ET rates can be maintained over a few cm in sandy and heavy clays soils up to roughly 1 m in loamy soils[111]. Rooting depth can adapt to the specific site conditions and to changes in GW depth that are not too fast or too strong and do not exceed adaption rate (root growth rate) and the cost-benefit ratio of this adaptation[112].

4. Large scale impact of soil hydrology

Soil hydrology plays a central role in shaping the impacts of climate change on terrestrial ecosystems, not only at the local scale but also at much larger scales due to the close interaction between the land surface and the atmosphere at all scales. In addition, SHP are central to the feedback effects of the land surface on the Earth's climate system[113]. In the following section, we will explore these feedback processes in more detail, as well as the effects of extreme climate events. Finally, we will address the importance of terrestrial water storage (TWS) in deeper soil layers and its more precise quantification for the response of the terrestrial system to climate change.

4.1 Climate system feedbacks

An important aspect of changes in SHP as well as whole ecosystem processes caused by land use, land-use change and climate change is their feedback to the climate system via direct and tele-connected processes, leading to large uncertainty in regional climate predictability[114]. For example, increased soil moisture can trigger precipitation events, especially under spatially heterogeneous soil moisture conditions, with precipitation preferentially falling on dry patches of land[115]. Following the same observed trend, increased deforestation has led to large changes in precipitation patterns in Rondônia, Brazil, in the range of ±25% between the upwind and downwind parts of the deforested area relative to the mean precipitation of the entire area [116]. Agricultural intensification, especially in combination with irrigation, may lead to cooling at the subcontinental scale due to increased ET and persistent changes in atmospheric circulation and moisture transport, as observed, for example, for the U.S. Midwest[117]. In contrast, drought at the regional, continental and global scale is exacerbated by the feedbacks of decreasing soil moisture on land surface temperature and relative humidity, leading to a decrease in P, which in turn exacerbates this feedback loop[118].

Long-term simulations with fully-coupled land–atmosphere–climate models revealed a strong positive relationship between heatwave intensity and drought severity for water-limited regions, such as the southwestern U.S.A.[119] and the Mediterranean[120]. However, a strong link and feedback loop between precipitation and soil moisture has also been identified for wetter regions such as the tropics[121]. It is important to note that major soil moisture perturbations can last much longer than the cause of the perturbations and therefore also represent a long-term feedback on the climate system[122]. Ultimately, these multiple interactions and feedbacks between soil, land surface, and atmosphere can be summarized as a negative soil feedback loop between soil moisture and temperature, that is, a decrease in soil moisture leads to an increase in temperature, and a positive feedback loop between soil moisture and precipitation, that is, an increase in soil moisture leads to an increase in precipitation[7].

Local SHP play an important role in controlling and modulating the impact of extreme events, such as high intensity rainfall as well as prolonged droughts and heat waves, on the land surface but also the consequences caused by sea level rise on soils in coastal areas, such as saltwater intrusion and inundation. Changes in infiltration capacity at the land surface, loss of soil porosity and a decrease in soil organic matter caused, for example, by changes in land use (such as deforestation due to agricultural intensification) and land cover (for example by surface sealing due to urbanization) may lead to an increased likelihood of large-scale flooding and soil erosion[123].

To project the behavior of floods, as well as extreme low flow conditions, into the future, it is essential to attribute such changes to their driving processes. The predominant mechanism of runoff generation is overland flow when rainfall intensity exceeds the infiltration capacity at the soil surface[124]. In this context, infiltration capacity is highly susceptible to land-use changes, such as those associated with more intensive agriculture[125]. On the other hand, flooding in larger watersheds is usually caused by storms of lower intensity and longer duration[126], which generate surface runoff through the mechanism of saturation excess when the water table reaches the soil surface. This mechanism is controlled more by soil depth and less by land-use change, which explains the decreasing importance of land-use change with increasing scale.

Extreme events may also alter intrinsic soil properties that control SHP. Prolonged droughts can promote macropore formation, primarily through the formation of cracks in clay-rich soils[127]. Changes in effective porosity due to climate change would result in changes in saturated soil K ranging from -55 to +34 percent in five different physiographic regions in the USA, depending on whether climate change results in an increase or decrease in precipitation at the regional scale[128]. High intensity rainfalls may lead to sealing of the soil surface, a reduction of soil porosity and thus a reduction in infiltration capacity of soils. This reduction in infiltration capacity may cause increased overland flow and soil erosion.

4.2 Terrestrial water storage

The dynamics of subsurface and groundwater storage are important not only for the impacts of climate change on terrestrial systems and their feedback to the climate system, but also for the conservation and sustainable use of the world's freshwater resources[129], and for the coupling of water and carbon cycles[130]. However, these dynamics are currently not well understood[131], and cannot be well constrained by observations except in the regions with shallow soils. To infer the terrestrial water budget, information is needed on water storage and residence time also at depths below the vadose zone. While surface soil moisture, temperature and Pion can be measured at the land surface with sensors or from satellite-based systems, the major obstacle to understanding water availability dynamics at depth has been the lack of observational capabilities. As a result, long-term changes in TWS were often simply assumed to be zero, for example in water balance models[132]. Since 2002, the gravity satellite missions GRACE and GRACE-FO have provided global observations of TWS anomalies. Because of the measurement principle, TWS refers to water storage in all compartments, including rivers, lakes and reservoirs, canopy water, and atmospheric moisture (the latter removed in data analysis). Only temporal anomalies are observed and referenced to a long-term average, and due to sensor limitations, the data products provide monthly averages and an effective resolution of about 300 km[133]. Water balance can be inferred with GRACE/GRACE-FO data[134] for catchments down to 100.000 km^2. Extreme events are recorded[130,135], but are difficult to interpret due to coarse data resolution.

In general, soil moisture dynamics exhibits an increasing phase shift and decreasing amplitudes with depth. Combining soil water and soil temperature measurements with GRACE data in the central U.S., over 40% of the variability in water storage of the unsaturated zone was found to occur below 75 cm, while groundwater storage calculated as the residual had a variability that was well correlated and comparable in magnitude to soil moisture variability in the uppermost 4 m[136]. Combining GRACE data with observed and gridded Fluxnet ET data improved the simulation of soil E in the Community Land model (CLM) by replacing an empirical parameterization of soil resistivity with a mechanistic formulation in which soil E is controlled by the diffusion rate of water vapor through a dry surface layer[137].

Significant improvements in simulating soil water availability in the root zone of grasslands and croplands were also reported by jointly assimilating satellite soil moisture products and GRACE data into an ecohydrological model[138]. This assimilation resulted in a better agreement between vegetation response and soil water availability in the root zone, suggesting the potential for model tuning and better prediction of vegetation conditions. Recently, it was demonstrated that merging GRACE and satellite soil moisture data with LSM can improve the estimation of moisture profiles in mountainous areas and can be successfully used as a predictor in global landslide models[139].

It is known from GRACE/GRACE-FO that TWS is not in equilibrium at decadal time scales for natural and anthropogenic reasons[129,140]. On the global scale, the variability of water stored on continents responds strongly to the El Niño Southern Oscillation (ENSO), resulting in pronounced sea-level declines. For example, the exceptional sea-level drop in 2011 was explained by Australia's endorheic hydrology responding to intense rainfall[141]. The GRACE data have shown that hydrology models underestimate decadal trends, while better representing seasonal dynamics, and they have helped identify the need for better representation of soil column depth and layers, snow storage, and groundwater storage changes in coupled climate models[142].

5. Emerging technologies

To adequately inform soil hydrological and land surface models and to better use existing observational capabilities, there is a need for improved data acquisition, data curation and analytical tools. Here we present an overview of the status of modern sensing technologies, citizen science approaches, cyber infrastructures and global data cubes to advance our understanding of SHP at all scales.

5.1 Sensing soil hydrology

Information on soil water content, temperature, matric potential and other states requires a variety of established and novel technologies that capture their high degree of variability in time and space[143] . Established in-situ point methods include electromagnetic approaches to measure in situ water content, for example time domain reflectometry (TDR)[144], time domain transmission (TDT)[145], and capacitance[146] and impedance sensors[147], while other point-based approaches use thermal soil properties (thermal pulse sensors)[148]. In-situ sensed soil moisture has been coupled with the remote sensing data to acquire large scale soil profile moisture variation using physically based methods[149], data assimilation methods[150], (semi-) empirical methods[151], data-driven methods[152], and statistical methods[153].

Field-scale soil moisture measurements can be obtained by non-invasive methods, such as cosmic-ray neutron sensing (CRNS), Global Navigation Satellite System Reflectometry (GNSS-R), gamma-ray monitoring, and ground penetrating radar (GPR)[154]. Regional to global coverage of near-surface soil moisture content is usually achieved with satellite-based sensors such as the Soil Moisture and Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP), Advanced Scatterometer (ASCAT)[155], Advanced Microwave Scanning Radiometer (AMSR-E/AMSR-2) with a resolution of tens of kilometers[156-158]. Through multi-sensor integration higher resolutions[159] or global long-term (1978-now) products[160] are generated. Native finer resolution data (tens of meters) involve synthetic aperture radars (SAR) such as ESA´s Sentinel-1[161] and JAXA´s ALOS-2[162]. The upcoming SAR missions NISAR (NASA ISRO Synthetic Aperture Radar)[163], and ROSE-L (Radar Observing System for Europe at L-band)[164] operate at longer wavelengths than previous SAR sensors which monitor soil moisture over a depth of about 5 cm. Soil moisture information down to a depth of about 25 cm will be provided by P-band sensors used by BIOMASS mission[165] and the SigNals Of Opportunity: P-band Investigation (SNOOPI). The latter exploits transmissions from telecommunications satellites reflected at the Earth's surface to retrieve soil moisture[166]. Similarly, the Global Navigation Satellite Systems-Reflectometry (GNSS-R) concepts use navigation signals of opportunity to perform scatterometry with ground-based[167] or space-borne receivers[168]. The relatively lower cost of sensors that take advantage of such existing 'signals of opportunity' theoretically enables more frequent observations by making it cost-effective to fly a large number of sensors.

5.2 Monitoring networks and citizen science

Understanding the impact of anthropogenic change on SHP and designing adaptation strategies requires long-term observations[169,170]. The concept of soil hydrologic in-situ monitoring networks is increasingly relevant for a range of environmental issues[171], leading to an increasingly multi-disciplinary focus of long-term observatories[170], often coordinated as networks[172,173]. Ongoing national and international observatory networks that include soil hydrological observations are Critical Zone Observatories (CZO)[172,174], NEON (National Ecological Observatory Network)[175], TERENO (Terrestrial Environmental Observatories)[176], TERN (Terrestrial Ecosystem Research Network)[177], and ISMN (International Soil Moisture Network)[178]providing in-situ soil moisture data from 2842 stations worldwide. These networks can be supported by public participation of non-scientists known as Citizen Science (CS)[179]. CS ranges from community-based data collection to Internet-based execution of various scientific tasks, with the help of large numbers of volunteers and crowd-sourcing[180,181]. Recent sensor development, data processing and visualization have opened new opportunities for engaging the public in scientific research[182]. For example, low-cost, low-maintenance soil moisture sensors have enabled the development of large-scale public sensor networks[183]. Another recent CS project used human perception to evaluate similarity and dissimilarity between spatial patterns in the simulation results of a hydrologic model[184]. It was shown that human perception in distinguishing between similarity and dissimilarity provides additional information that is valuable for model diagnosis. CS is typically staff intensive and requires proper training and education of those involved[181] as well as openness to data sharing[185]. Techniques are being developed to assess and increase the accuracy of crowdsourced environmental data[186].

5.3 Cyber infrastructure and big data

Cyber-physical infrastructures provide solutions for the integrated management of heterogeneous data resources such as live sensors, sensor models, simulation systems; collaborative observation systems based on multiple platforms such as wireless sensing networks, remote sensing, and methods for scalable processing and fusion of multi-sourced environmental data (Fig. 4). Cyber-physical infrastructures improve environmental research by combining different types of data such as real-time wireless sensor network data with global remote sensing data. They also become important in the framework of the Internet of Things (IoT)[187], which provides real-time environmental data, enabling large-scale networks and possibly continental coverage in the near future[188]. Global internet access is being pursued via high altitude balloons, solar planes, and hundreds of planned satellite launches, providing a means to exploit the IoT[189]. Such global access will enable real-time collection of data from billions of smartphones or from remote research platforms and adequate cyber-physical infrastructures are essential to manage the petabytes of data that could be produced in the future by such systems. This presents a unique opportunity to gain new insights that advance fundamental aspects of soil science. However, given the discrete and irregular nature of the associated data, this will require a radical rethinking of how we deploy and use these new observing systems[189], and the cyber tools needed to harmonize and synthesize these unstructured data into a comprehensive picture of Earth system processes and properties.

For decades, a huge amount of data related to soil hydrology has been recorded by satellites, monitoring networks, and governments. However, these data is often underutilized due a lack of availability, discoverability, accessibility, storage capacities, processing methods, visualization and dissemination tools, or high performance computing facilities with low usability levels. Here, public Analysis Ready Data (ARD) repositories with the possibility to apply new processing and analysis methods ideally with affordable processing power are needed[190]. Both public and private entities invest in this field of big data accessibility and cloud computing, for example DIAS (Data and Information Access Service) the European Commission, Theia in France, BDAP (Big Data Analytics Platform) of the Joint Research Center, (Copernicus Data and Exploitation Platform – DE) of the German Aerospace Center, Google Earth Engine, and Open Data on Amazon Web Services, just to name a few. Furthermore, there is a growing recognition that data storage principles are needed to enable reuse and repurposing of data; for example, the FAIR principles (findability, accessibility, interoperability, reusability) are now being adopted in many venues.

Basic land surface data is typically available on cloud platforms, and sometimes also soil moisture information, but more detailed soil hydrology data need to be processed with new approaches. Here, portable and efficient software container solutions like Docker and kubernetes[191] can be implemented, as well as interactions with scripts of common languages such as python and R via application programing interfaces (API) performed. These solutions open also the potential to apply deep learning methods, to perform advanced analytics approaches similar to those used for the SoilGrids250m soil information data such as random forest, gradient boosting or multinomial logistic regression techniques[192]. For example, training environmental monitoring data to point-scale in situ soil measurements could provide spatial maps at sufficient accuracy for further implementation in regional or global soil hydrological simulations. Moreover, methods for generating new soil hydrological understanding may benefit from a combination of both process and empirical modelling[193]. The wealth of data being generated provides news opportunities to explore novel data analysis methods. Machine learning approaches (MLA) such as artificial neural networks and support vector machines have been widely used in the past decades to simulate various hydrological processes, including soil water dynamics[194,195]. In addition, MLA have been successfully applied to the prediction of soil moisture using remote sensing data[196,197]. It is important that such models are first trained on a training data set, which should contain as much data and conditions as possible, so that they can also take unusual events into account and achieve good prediction accuracy. Given suitable input data, machine learning approaches can also be used for irrigation planning and agricultural water resource management[198].

6. Outlook

In the last two decades, the field of soil hydrology has evolved to a research field that not only studies local scale SHP but also embraces the challenge of quantifying and understanding the influence of SHP at catchment, regional and continental scale. This increase in scale requires a better understanding of a broad variety of processes and phenomena ranging from biogeochemical and hydrological processes to extreme events such as drought, heat waves and floods amplified by climate change. These advances have been made possible by an unprecedented increase in measuring capabilities empowered by novel remote sensing technologies and new ground-based technologies to measure key soil hydrological properties such as soil moisture. Daily, and even sub-daily, global observations such as soil moisture and ET (evapotranspiration), are now a reality. Research activities in the near future should comprise a better use of observational capabilities to inform soil hydrological and LSM predicting SHP. A combination of CS approaches, cyberinfrastructures and global data cubes will advance our understanding of SHP at all scales, if leveraged appropriately. To this end, big SHP data need to be integrated to continuously improve the accuracy of the derived information, which is of key importance to reduce the significant uncertainties that are still present in soil hydrology models used to predict effects of global environmental change on terrestrial systems. Machine learning tools are expected to be pivotal in this integration

In the future, soil hydrologists will increasingly need to address challenges related to adapting land management in the frame of the ongoing climate and land use change. The warming of our planet also strongly affects large permafrost regions in the Northern Hemisphere. More than ever a better understanding and description of key SHP such as infiltration, evapotranspiration and its separation in E and T as well as the accurate estimation and forecasting of soil moisture dynamics is needed to assess the future release potential of CO_2 and other greenhouse gases and the complex feedbacks this invokes between the various biochemical cycles and the water- and energy cycles. The predictions of hydrological and biogeochemical processes using LSM as part of global climate models strongly depends on how soils and SHP are being characterized and parameterized. Despite its importance, the role of soil structure and its dynamic impact on SHP and soil biogeochemical processes have been almost completely neglected, and a closer cooperation between soil scientists and global land surface and climate modelers is urgently needed.

References

1 Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nature Climate Change* **2**, 491-496, doi:10.1038/nclimate1452 (2012).

2 Hallegatte, S., Green, C., Nicholls, R. J. & Corfee-Morlot, J. Future flood losses in major coastal cities. *Nature Climate Change* **3**, 802-806, doi:10.1038/nclimate1979 (2013).

3 Lehner, F. *et al.* Projected drought risk in 1.5 degrees C and 2 degrees C warmer climates. *Geophys Res Lett* **44**, 7419-7428, doi:10.1002/2017gl074117 (2017).

4 Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G. & Lobel, D. B. Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change* **11**, 306-U328, doi:10.1038/s41558-021-01000-1 (2021).

5 Rockstrom, J. *et al.* Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* **14** (2009).

6 Programme, U. W. W. A. *The United Nations world water development report 2018: nature-based solutions for water*. (2018).

7 Seneviratne, S. I. *et al.* Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews* **99**, 125-161, doi:10.1016/j.earscirev.2010.02.004 (2010).

8 Vereecken, H. *et al.* Infiltration from the Pedon to Global Grid Scales: An Overview and Outlook for Land Surface Modeling. *Vadose Zone J* **18**, doi:10.2136/vzj2018.10.0191 (2019).

9 Jung, M. *et al.* Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* **467**, 951-954, doi:10.1038/nature09396 (2010).

10 Saini, R., Wang, G. L. & Pal, J. S. Role of Soil Moisture Feedback in the Development of Extreme Summer Drought and Flood in the United States. *Journal of Hydrometeorology* **17**, 2191-2207, doi:10.1175/jhm-d-15-0168.1 (2016).

11 Bloschl, G. *et al.* Changing climate shifts timing of European floods. *Science* **357**, 588-590, doi:10.1126/science.aan2506 (2017).

12 Vereecken, H. *et al.* Soil hydrology: Recent methodological advances, challenges, and perspectives. *Water Resources Research* **51**, 2616-2633, doi:10.1002/2014wr016852 (2015).

13 Sapriza-Azuri, G., Gamazo, P., Razavi, S. & Wheater, H. S. On the appropriate definition of soil profile configuration and initial conditions for land surface-hydrology models in cold regions. *Hydrology and Earth System Sciences* **22**, 3295-3309, doi:10.5194/hess-22-3295-2018 (2018).

14 Hodnett, M. G. & Tomasella, J. Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: a new water-retention pedo-transfer functions developed for tropical soils. *Geoderma* **108**, 155-180, doi:10.1016/s0016-7061(02)00105-2 (2002).

15 Lohse, K. A., Brooks, P. D., McIntosh, J. C., Meixner, T. & Huxman, T. E. Interactions Between Biogeochemistry and Hydrologic Systems. *Annual Review of Environment and Resources* **34**, 65-96, doi:10.1146/annurev.environ.33.031207.111141 (2009).

16 Green, J. K. *et al.* Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature* **565**, 476-+, doi:10.1038/s41586-018-0848-x (2019).

17 Lin, H. *et al.* Hydropedology: Synergistic integration of pedology and hydrology. *Water Resources Research* **42**, doi:10.1029/2005wr004085 (2006).

18 Brooks, P. D. *et al.* Hydrological partitioning in the critical zone: Recent advances and opportunities for developing transferable understanding of water cycle dynamics. *Water Resources Research* **51**, 6973-6987, doi:10.1002/2015wr017039 (2015).

19 Van Looy, K. *et al.* Pedotransfer Functions in Earth System Science: Challenges and Perspectives. *Reviews of Geophysics* **55**, 1199-1256, doi:10.1002/2017rg000581 (2017).

20 Bouma, J. Hydropedology as a powerful tool for environmental policy research. *Geoderma* **131**, 275-286, doi:10.1016/j.geoderma.2005.03.009 (2006).

21 Lin, H. Earth's Critical Zone and hydropedology: concepts, characteristics, and advances. *Hydrology and Earth System Sciences* **14**, 25-45, doi:10.5194/hess-14-25-2010 (2010).

22 Robinson, D. A. *et al.* Global environmental changes impact soil hydraulic functions through biophysical feedbacks. *Global Change Biology* **25**, 1895-1904, doi:10.1111/gcb.14626 (2019).

23 Young, I. M. & Crawford, J. W. Interactions and self-organization in the soil-microbe complex. *Science* **304**, 1634-1637, doi:10.1126/science.1097394 (2004).

24 Totsche, K. U. *et al.* Microaggregates in soils. *Journal of Plant Nutrition and Soil Science* **181**, 104-136, doi:10.1002/jpln.201600451 (2018).

25 Peth, S. *et al.* Three-dimensional quantification of intra-aggregate pore-space features using synchrotron-radiation-based microtomography. *Soil Science Society of America Journal* **72**, 897-907, doi:10.2136/sssaj2007.0130 (2008).

26 Athmann, M. *et al.* Six months of L-terrestris L. activity in root-formed biopores increases nutrient availability, microbial biomass and enzyme activity. *Applied Soil Ecology* **120**, 135-142, doi:10.1016/j.apsoil.2017.08.015 (2017).

27 Wendel, A. S., Bauke, S. L., Amelung, W. & Knief, C. Root-rhizosphere-soil interactions in biopores. *Plant and Soil*, doi:10.1007/s11104-022-05406-4.

28 Fatichi, S. *et al.* Soil structure is an important omission in Earth System Models. *Nature Communications* **11**, doi:10.1038/s41467-020-14411-z (2020).

29 Bornemann, L., Herbst, M., Welp, G., Vereecken, H. & Amelung, W. Rock Fragments Control Size and Saturation of Organic Carbon Pools in Agricultural Topsoil. *Soil Science Society of America Journal* **75**, 1898-1907, doi:10.2136/sssaj2010.0454 (2011).

30 Kautz, T. *et al.* Contribution of anecic earthworms to biopore formation during cultivation of perennial ley crops. *Pedobiologia* **57**, 47-52, doi:10.1016/j.pedobi.2013.09.008 (2014).

31 Katuwal, S. *et al.* Linking air and water transport in intact soils to macropore characteristics inferred from X-ray computed tomography. *Geoderma* **237**, 9-20, doi:10.1016/j.geoderma.2014.08.006 (2015).

32 Jarvis, N. J. A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. *European Journal of Soil Science* **58**, 523-546, doi:10.1111/j.1365-2389.2007.00915.x (2007).

33 Bonetti, S., Wei, Z. W. & Or, D. A framework for quantifying hydrologic effects of soil structure across scales. *Communications Earth & Environment* **2**, doi:10.1038/s43247-021-00180-0 (2021).

34 Or, D., Keller, T. & Schlesinger, W. H. Natural and managed soil structure: On the fragile scaffolding for soil functioning. *Soil & Tillage Research* **208**, doi:10.1016/j.still.2020.104912 (2021).

35 Awadhwal, N. K. & Thierstein, G. E. SOIL CRUST AND ITS IMPACT ON CROP ESTABLISHMENT - A REVIEW. *Soil & Tillage Research* **5**, 289-302, doi:10.1016/0167-1987(85)90021-2 (1985).

36 Bronick, C. J. & Lal, R. Soil structure and management: a review. *Geoderma* **124**, 3-22, doi:10.1016/j.geoderma.2004.03.005 (2005).

37 Lobe, I., Sandhage-Hofmann, A., Brodowski, S., du Preez, C. C. & Amelung, W. Aggregate dynamics and associated soil organic matter contents as influenced by prolonged arable cropping in the South African Highveld. *Geoderma* **162**, 251-259, doi:10.1016/j.geoderma.2011.02.001 (2011).

38 Vereecken, H. *et al.* Modeling Soil Processes: Review, Key Challenges, and New Perspectives. *Vadose Zone J* **15**, doi:10.2136/vzj2015.09.0131 (2016).

39 Zha, Y. Y. *et al.* Review of numerical solution of Richardson-Richards equation for variably saturated flow in soils. *Wiley Interdisciplinary Reviews-Water* **6**, doi:10.1002/wat2.1364 (2019).

40 Weihermuller, L. *et al.* Choice of Pedotransfer Functions Matters when Simulating Soil Water Balance Fluxes. *Journal of Advances in Modeling Earth Systems* **13**, doi:10.1029/2020ms002404 (2021).

41 Toth, B. *et al.* New generation of hydraulic pedotransfer functions for Europe. *European Journal of Soil Science* **66**, 226-238, doi:10.1111/ejss.12192 (2015).

42 Zhang, Y. G. & Schaap, M. G. Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3). *J. Hydrol.* **547**, 39-53, doi:10.1016/j.jhydrol.2017.01.004 (2017).

43 Vereecken, H. *et al.* Using Pedotransfer Functions to Estimate the van Genuchten-Mualem Soil Hydraulic Properties: A Review. *Vadose Zone J* **9**, 795-820, doi:10.2136/vzj2010.0045 (2010).

44 Zhang, Y. G. & Schaap, M. G. Estimation of saturated hydraulic conductivity with pedotransfer functions: A review. *J. Hydrol.* **575**, 1011-1030, doi:10.1016/j.jhydrol.2019.05.058 (2019).

45 Romero-Ruiz, A., Linde, N., Keller, T. & Or, D. A Review of Geophysical Methods for Soil Structure Characterization. *Reviews of Geophysics* **56**, 672-697, doi:10.1029/2018rg000611 (2018).

46 Gupta, S., Lehmann, P., Bonetti, S., Papritz, A. & Or, D. Global Prediction of Soil Saturated Hydraulic Conductivity Using Random Forest in a Covariate-Based GeoTransfer Function (CoGTF) Framework. *Journal of Advances in Modeling Earth Systems* **13**, doi:10.1029/2020ms002242 (2021).

47 Lehmann, P. *et al.* Clays are not created equal: how clay mineral type affects soil parameterization. *Geophys. Res. Let.* **48**, e2021GL095311, doi:10.1029/2021GL095311 (2021).

48 Gupta, S. *et al.* Global Mapping of Soil Water Characteristics Parameters - Fusing Curated Data with Machine Learning and Environmental Covariates. *Remote Sensing* **14**, doi:10.3390/rs14081947 (2022).

49 Rabot, E., Wiesmeier, M., Schluter, S. & Vogel, H. J. Soil structure as an indicator of soil functions: A review. *Geoderma* **314**, 122-137, doi:10.1016/j.geoderma.2017.11.009 (2018).

50 Schaap, M. G., Leij, F. J. & van Genuchten, M. T. Neural network analysis for hierarchical prediction of soil hydraulic properties. *Soil Science Society of America Journal* **62**, 847-855, doi:10.2136/sssaj1998.03615995006200040001x (1998).

51 Elshorbagy, A. & Parasuraman, K. On the relevance of using artificial neural networks for estimating soil moisture content. *J. Hydrol.* **362**, 1-18, doi:10.1016/j.jhydrol.2008.08.012 (2008).

52 Durner, W. HYDRAULIC CONDUCTIVITY ESTIMATION FOR SOILS WITH HETEROGENEOUS PORE STRUCTURE. *Water Resources Research* **30**, 211-223, doi:10.1029/93wr02676 (1994).

53 Li, Y. & Vanapalli, S. K. A novel modeling method for the bimodal soil-water characteristic curve. *Computers and Geotechnics* **138**, doi:10.1016/j.compgeo.2021.104318 (2021).

54 Dai, Y. J. *et al.* A Global High-Resolution Data Set of Soil Hydraulic and Thermal Properties for Land Surface Modeling. *Journal of Advances in Modeling Earth Systems* **11**, 2996-3023, doi:10.1029/2019ms001784 (2019).

55 Lu, N. & Dong, Y. Closed-Form Equation for Thermal Conductivity of Unsaturated Soils at Room Temperature. *Journal of Geotechnical and Geoenvironmental Engineering* **141**, doi:10.1061/(asce)gt.1943-5606.0001295 (2015).

56 He, H. L., Dyck, M. & Lv, J. L. A new model for predicting soil thermal conductivity from matric potential. *J. Hydrol.* **589**, doi:10.1016/j.jhydrol.2020.125167 (2020).

57 Jana, R. B. & Mohanty, B. P. Enhancing PTFs with remotely sensed data for multi-scale soil water retention estimation. *J. Hydrol.* **399**, 201-211, doi:10.1016/j.jhydrol.2010.12.043 (2011).

58 Jana, R. B., Mohanty, B. P. & Springer, E. P. Multiscale Bayesian neural networks for soil water content estimation. *Water Resources Research* **44**, doi:10.1029/2008wr006879 (2008).

59 Guber, A. K. *et al.* Multimodel Simulation of Water Flow in a Field Soil Using Pedotransfer Functions. *Vadose Zone J* **8**, 1-10, doi:10.2136/vzj2007.0144 (2009).

60 Zhang, Y. G., Schaap, M. G. & Wei, Z. W. Development of Hierarchical Ensemble Model and Estimates of Soil Water Retention With Global Coverage. *Geophys Res Lett* **47**, doi:10.1029/2020gl088819 (2020).

61 Ottoni, M. V., Ottoni, T. B., Schaap, M. G., Lopes-Assad, M. & Rotunno, O. C. Hydrophysical Database for Brazilian Soils (HYBRAS) and Pedotransfer Functions for Water Retention. *Vadose Zone J* **17**, doi:10.2136/vzj2017.05.0095 (2018).

62 Lehmann, P. *et al.* Clays Are Not Created Equal: How Clay Mineral Type Affects Soil Parameterization. *Geophys Res Lett* **48**, doi:10.1029/2021gl095311 (2021).

63 Jarvis, N., Koestel, J., Messing, I., Moeys, J. & Lindahl, A. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrology and Earth System Sciences* **17**, 5185-5195, doi:10.5194/hess-17-5185-2013 (2013).

64 Minasny, B. & Hartemink, A. E. Predicting soil properties in the tropics. *Earth-Science Reviews* **106**, 52-62, doi:10.1016/j.earscirev.2011.01.005 (2011).

65 Friedlingstein, P. *et al.* Global Carbon Budget 2020. *Earth System Science Data* **12**, 3269-3340, doi:10.5194/essd-12-3269-2020 (2020).

66 Hugelius, G. *et al.* A new data set for estimating organic carbon storage to 3m depth in soils of the northern circumpolar permafrost region. *Earth System Science Data* **5**, 393-402, doi:10.5194/essd-5-393-2013 (2013).

67 Obu, J. *et al.* Northern Hemisphere permafrost map based on TTOP modelling for 2000-2016 at 1 km(2) scale. *Earth-Science Reviews* **193**, 299-316, doi:10.1016/j.earscirev.2019.04.023 (2019).

68 Leifeld, J. & Menichetti, L. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications* **9**, doi:10.1038/s41467-018-03406-6 (2018).

69 Rezanezhad, F. *et al.* Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. *Chemical Geology* **429**, 75-84, doi:10.1016/j.chemgeo.2016.03.010 (2016).

70 Andresen, C. G. *et al.* Soil moisture and hydrology projections of the permafrost region a model intercomparison. *Cryosphere* **14**, 445-459, doi:10.5194/tc-14-445-2020 (2020).

71 Hugelius, G. *et al.* Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 20438-20446, doi:10.1073/pnas.1916387117 (2020).

72 Slater, A. G. & Lawrence, D. M. Diagnosing Present and Future Permafrost from Climate Models. *Journal of Climate* **26**, 5608-5623, doi:10.1175/jcli-d-12-00341.1 (2013).

73 Beven, K. J. & Kirkby, M. J. Towards a simple, physically based, variable contributing area model of catchment hydrology. *Bulletin of the International Association of Scientific Hydrology* **24**, 43-69 (1979).

74 Bechtold, M. *et al.* PEAT-CLSM: A Specific Treatment of Peatland Hydrology in the NASA Catchment Land Surface Model. *Journal of Advances in Modeling Earth Systems* **11**, 2130-2162, doi:10.1029/2018ms001574 (2019).

75 Wania, R., Ross, I. & Prentice, I. C. Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes. *Global Biogeochemical Cycles* **23**, doi:10.1029/2008gb003412 (2009).

76 Qiu, C. J. *et al.* ORCHIDEE-PEAT (revision 4596), a model for northern peatland CO2, water, and energy fluxes on daily to annual scales. *Geoscientific Model Development* **11**, 497-519, doi:10.5194/gmd-11-497-2018 (2018).

77 Dai, Y. J. *et al.* Evaluation of Soil Thermal Conductivity Schemes for Use in Land Surface Modeling. *Journal of Advances in Modeling Earth Systems* **11**, 3454-3473, doi:10.1029/2019ms001723 (2019).

78 Chadburn, S. E. *et al.* Impact of model developments on present and future simulations of permafrost in a global land-surface model. *Cryosphere* **9**, 1505-1521, doi:10.5194/tc-9-1505-2015 (2015).

79 Waddington, J. M. *et al.* Hydrological feedbacks in northern peatlands. *Ecohydrology* **8**, 113-127, doi:10.1002/eco.1493 (2015).

80 Apers, S. *et al.* Tropical peatland hydrology simulated with a global land surface model. *Earth and Space Science Open Archive*, doi:10.1002/essoar.10507826.1 (2021).

81 Bechtold, M. *et al.* Improved groundwater table and L-band brightness temperature estimates for Northern Hemisphere peatlands using new model physics and SMOS observations in a global data assimilation framework. *Remote Sensing of Environment* **246**, doi:10.1016/j.rse.2020.111805 (2020).

82 Mahdianpari, M. *et al.* The Third Generation of Pan-Canadian Wetland Map at 10 m Resolution Using Multisource Earth Observation Data on Cloud Computing Platform. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **14**, 8789-8803, doi:10.1109/jstars.2021.3105645 (2021).

83 Rasanen, A. *et al.* Detecting northern peatland vegetation patterns at ultra-high spatial resolution. *Remote Sensing in Ecology and Conservation* **6**, 457-471, doi:10.1002/rse2.140 (2020).

84 Oki, T. & Kanae, S. Global Hydrological Cycles and World Water Resources. *Science* **313**, 1068-1072, doi:10.1126/science.1128845 (2006).

85 Trenberth, K. E., Smith, L., Qian, T., Dai, A. & Fasullo, J. Estimates of the Global Water Budget and Its Annual Cycle Using Observational and Model Data. *Journal of Hydrometeorology* **8**, 758-769, doi:10.1175/jhm600.1 (2007).

86 Rothfuss, Y. *et al.* Reviews and syntheses: Gaining insights into evapotranspiration partitioning with novel isotopic monitoring methods. *Biogeosciences* **18**, 3701-3732, doi:10.5194/bg-18-3701-2021 (2021).

87 Liu, Y., Kumar, M., Katul, G. G., Feng, X. & Konings, A. G. Plant hydraulics accentuates the effect of atmospheric moisture stress on transpiration. *Nature Climate Change* **10**, 691-695, doi:10.1038/s41558-020-0781-5 (2020).

88 Anderegg, W. R. L. *et al.* Plant water potential improves prediction of empirical stomatal models. *PLOS ONE* **12**, e0185481, doi:10.1371/journal.pone.0185481 (2017).

89 Katul, G. G. & Siqueira, M. B. Biotic and abiotic factors act in coordination to amplify hydraulic redistribution and lift. *New Phytologist* **187**, 4-6 (2010).

90 Quijano, J. C. & Kumar, P. Numerical simulations of hydraulic redistribution across climates: The role of the root hydraulic conductivities. *Water Resources Research* **51**, 8529-8550, doi:10.1002/2014wr016509 (2015).

91 Neumann, R. B. & Cardon, Z. G. The magnitude of hydraulic redistribution by plant roots: a review and synthesis of empirical and modeling studies. *New Phytologist* **194**, 337-352, doi:10.1111/j.1469-8137.2012.04088.x (2012).

92 Quijano, J. C., Kumar, P. & Drewry, D. T. Passive regulation of soil biogeochemical cycling by root water transport. *Water Resources Research* **49**, 3729-3746, doi:10.1002/wrcr.20310 (2013).

93 Porporato, A., Daly, E. & Rodriguez-Iturbe, I. Soil water balance and ecosystem response to climate change. *Am Nat* **164**, 625-632, doi:10.1086/424970 (2004).

94 Budyko, M. I. *Climate and Life*. (Academic Press, 1974).

95 Laio, F., D'Odorico, P. & Ridolfi, L. An analytical model to relate the vertical root distribution to climate and soil properties. *Geophys Res Lett* **33**, doi:https://doi.org/10.1029/2006GL027331 (2006).

96 Schenk, H. J. The shallowest possible water extraction profile: A null model for global root distributions. *Vadose Zone J* **7**, 1119-1124, doi:10.2136/vzj2007.0119 (2008).

97 Schenk, H. J. & Jackson, R. B. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma* **126**, 129-140, doi:10.1016/j.geoderma.2004.11.018 (2005).

98 Fan, Y., Miguez-Macho, G., Jobbagy, E. G., Jackson, R. B. & Otero-Casal, C. Hydrologic regulation of plant rooting depth. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 10572-10577, doi:10.1073/pnas.1712381114 (2017).

99 Rodriguez-Iturbe, I., D'Odorico, P., Porporato, A. & Ridolfi, L. On the spatial and temporal links between vegetation, climate, and soil moisture. *Water Resources Research* **35**, 3709-3722, doi:https://doi.org/10.1029/1999WR900255 (1999).

100 Rietkerk, M., Dekker, S. C., Ruiter, P. C. d. & Koppel, J. v. d. Self-Organized Patchiness and Catastrophic Shifts in Ecosystems. *Science* **305**, 1926-1929, doi:doi:10.1126/science.1101867 (2004).

101 Assouline, S., Narkis, K., Gherabli, R., Lefort, P. & Prat, M. Analysis of the impact of surface layer properties on evaporation from porous systems using column experiments and modified definition of characteristic length. *Water Resources Research* **50**, 3933-3955, doi:10.1002/2013wr014489 (2014).

102 Brunet, P., Clement, R. & Bouvier, C. Monitoring soil water content and deficit using Electrical Resistivity Tomography (ERT) - A case study in the Cevennes area, France. *J. Hydrol.* **380**, 146-153, doi:10.1016/j.jhydrol.2009.10.032 (2010).

103 Estrada-Medina, H., Graham, R. C., Allen, M. F., Jiménez-Osornio, J. J. & Robles-Casolco, S. The importance of limestone bedrock and dissolution karst features on

tree root distribution in northern Yucatán, México. *Plant and Soil* **362**, 37-50, doi:10.1007/s11104-012-1175-x (2013).

104 Sperry, J. S. & Hacke, U. G. Desert shrub water relations with respect to soil characteristics and plant functional type. *Functional Ecology* **16**, 367-378, doi:https://doi.org/10.1046/j.1365-2435.2002.00628.x (2002).

105 Brum, M. *et al.* Hydrological niche segregation defines forest structure and drought tolerance strategies in a seasonal Amazon forest. *Journal of Ecology* **107**, 318-333, doi:https://doi.org/10.1111/1365-2745.13022 (2019).

106 Hildebrandt, A. in *Forest-Water Interactions* (eds Delphis F. Levia *et al.*) 319-348 (Springer International Publishing, 2020).

107 Ammer, C. Diversity and forest productivity in a changing climate. *New Phytologist* **221**, 50-66, doi:https://doi.org/10.1111/nph.15263 (2019).

108 Grossiord, C. Having the right neighbors: how tree species diversity modulates drought impacts on forests. *New Phytologist* **228**, 42-49, doi:https://doi.org/10.1111/nph.15667 (2020).

109 Fisher, R. A. *et al.* Vegetation demographics in Earth System Models: A review of progress and priorities. *Global Change Biology* **24**, 35-54, doi:https://doi.org/10.1111/gcb.13910 (2018).

110 Maxwell, R. M. & Kollet, S. J. Interdependence of groundwater dynamics and land-energy feedbacks under climate change. *Nat. Geosci.* **1**, 665-669, doi:doi:10.1038/ngeo315 (2008).

111 Lehmann, P., Assouline, S. & Or, D. Characteristic lengths affecting evaporative drying of porous media. *Phys. Rev. E* **77**, doi:056309 10.1103/PhysRevE.77.056309 (2008).

112 Naumburg, E., Mata-gonzalez, R., Hunter, R. G., McLendon, T. & Martin, D. W. Phreatophytic Vegetation and Groundwater Fluctuations: A Review of Current Research and Application of Ecosystem Response Modeling with an Emphasis on Great Basin Vegetation. *Environmental Management* **35**, 726-740, doi:10.1007/s00267-004-0194-7 (2005).

113 Stephens, C. M., Lall, U., Johnson, F. M. & Marshall, L. A. Landscape changes and their hydrologic effects: Interactions and feedbacks across scales. *Earth-Science Reviews* **212**, doi:10.1016/j.earscirev.2020.103466 (2021).

114 Roe, G. H., Feldl, N., Armour, K. C., Hwang, Y. T. & Frierson, D. M. W. The remote impacts of climate feedbacks on regional climate predictability. *Nat. Geosci.* **8**, 135-139, doi:10.1038/ngeo2346 (2015).

115 Guillod, B. P., Orlowsky, B., Miralles, D. G., Teuling, A. J. & Seneviratne, S. I. Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nature Communications* **6**, doi:10.1038/ncomms7443 (2015).

116 Khanna, J., Medvigy, D., Fueglistaler, S. & Walko, R. Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nature Climate Change* **7**, 200-+, doi:10.1038/nclimate3226 (2017).

117 Mueller, N. D. *et al.* Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change* **6**, 317-+, doi:10.1038/nclimate2825 (2016).

118 Berg, A. *et al.* Land-atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change* **6**, 869-+, doi:10.1038/nclimate3029 (2016).

119 Cheng, L. Y., Hoerling, M., Liu, Z. Y. & Eischeid, J. Physical Understanding of Human-Induced Changes in US Hot Droughts Using Equilibrium Climate Simulations. *Journal of Climate* **32**, 4431-4443, doi:10.1175/jcli-d-18-0611.1 (2019).

120 Zittis, G., Hadjinicolaou, P. & Lelieveld, J. Role of soil moisture in the amplification of climate warming in the eastern Mediterranean and the Middle East. *Climate Research* **59**, 27-37, doi:10.3354/cr01205 (2014).

121 May, W. *et al.* Contributions of soil moisture interactions to climate change in the tropics in the GLACE-CMIP5 experiment. *Climate Dynamics* **45**, 3275-3297, doi:10.1007/s00382-015-2538-9 (2015).

122 Stacke, T. & Hagemann, S. Lifetime of soil moisture perturbations in a coupled land-atmosphere simulation. *Earth System Dynamics* **7**, 1-19, doi:10.5194/esd-7-1-2016 (2016).

123 Bloschl, G. *et al.* Increasing river floods: fiction or reality? *Wiley Interdisciplinary Reviews-Water* **2**, 329-344, doi:10.1002/wat2.1079 (2015).

124 Bloschl, G. *et al.* The Hydrological Open Air Laboratory (HOAL) in Petzenkirchen: a hypothesis-driven observatory. *Hydrology and Earth System Sciences* **20**, 227-255, doi:10.5194/hess-20-227-2016 (2016).

125 Rogger, M. *et al.* Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research* **53**, 5209-5219, doi:10.1002/2017wr020723 (2017).

126 Viglione, A. *et al.* Attribution of regional flood changes based on scaling fingerprints. *Water Resources Research* **52**, 5322-5340, doi:10.1002/2016wr019036 (2016).

127 Zeng, H. *et al.* Drought-Induced Soil Desiccation Cracking Behavior With Consideration of Basal Friction and Layer Thickness. *Water Resources Research* **56**, doi:10.1029/2019wr026948 (2020).

128 Hirmas, D. R. *et al.* Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. *Nature* **561**, 100-+, doi:10.1038/s41586-018-0463-x (2018).

129 Rodell, M. *et al.* Emerging trends in global freshwater availability. *Nature* **557**, 650-+, doi:10.1038/s41586-018-0123-1 (2018).

130 Humphrey, V., Gudmundsson, L. & Seneviratne, S. I. Assessing Global Water Storage Variability from GRACE: Trends, Seasonal Cycle, Subseasonal Anomalies and Extremes. *Surveys in Geophysics* **37**, 357-395, doi:10.1007/s10712-016-9367-1 (2016).

131 Papa, F. & Frappart, F. Surface Water Storage in Rivers and Wetlands Derived from Satellite Observations: A Review of Current Advances and Future Opportunities for Hydrological Sciences. *Remote Sensing* **13**, doi:10.3390/rs13204162 (2021).

132 Chen, X., Alimohammadi, N. & Wang, D. B. Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework. *Water Resources Research* **49**, 6067-6078, doi:10.1002/wrcr.20493 (2013).

133 Tapley, B. D. *et al.* Contributions of GRACE to understanding climate change. *Nature Climate Change* **9**, 358-369, doi:10.1038/s41558-019-0456-2 (2019).

134 Springer, A., Eicker, A., Bettge, A., Kusche, J. & Hense, A. Evaluation of the Water Cycle in the European COSMO-REA6 Reanalysis Using GRACE. *Water* **9**, doi:10.3390/w9040289 (2017).

135 Kusche, J., Eicker, A., Forootan, E., Springer, A. & Longuevergne, L. Mapping probabilities of extreme continental water storage changes from space gravimetry. *Geophys Res Lett* **43**, 8026-8034, doi:10.1002/2016gl069538 (2016).

136 Swenson, S., Famiglietti, J., Basara, J. & Wahr, J. Estimating profile soil moisture and groundwater variations using GRACE and Oklahoma Mesonet soil moisture data. *Water Resources Research* **44**, doi:10.1029/2007wr006057 (2008).

137 Swenson, S. C. & Lawrence, D. M. Assessing a dry surface layer-based soil resistance parameterization for the Community Land Model using GRACE and FLUXNET-

MTE data. *Journal of Geophysical Research-Atmospheres* **119**, doi:10.1002/2014jd022314 (2014).

138 Tian, S. Y., Renzullo, L. J., van Dijk, A., Tregoning, P. & Walker, J. P. Global joint assimilation of GRACE and SMOS for improved estimation of root-zone soil moisture and vegetation response. *Hydrology and Earth System Sciences* **23**, 1067-1081, doi:10.5194/hess-23-1067-2019 (2019).

139 Felsberg, A. *et al.* Global Soil Water Estimates as Landslide Predictor: The Effectiveness of SMOS, SMAP, and GRACE Observations, Land Surface Simulations, and Data Assimilation. *Journal of Hydrometeorology* **22**, 1065-1084, doi:10.1175/jhm-d-20-0228.1 (2021).

140 Eicker, A., Forootan, E., Springer, A., Longuevergne, L. & Kusche, J. Does GRACE see the terrestrial water cycle "intensifying"? *Journal of Geophysical Research-Atmospheres* **121**, 733-745, doi:10.1002/2015jd023808 (2016).

141 Fasullo, J. T., Boening, C., Landerer, F. W. & Nerem, R. S. Australia's unique influence on global sea level in 2010-2011. *Geophys Res Lett* **40**, 4368-4373, doi:10.1002/grl.50834 (2013).

142 Jensen, L., Eicker, A., Dobslaw, H., Stacke, T. & Humphrey, V. Long-Term Wetting and Drying Trends in Land Water Storage Derived From GRACE and CMIP5 Models. *Journal of Geophysical Research-Atmospheres* **124**, 9808-9823, doi:10.1029/2018jd029989 (2019).

143 Vereecken, H. *et al.* On the value of soil moisture measurements in vadose zone hydrology: A review. *Water Resources Research* **44**, doi:10.1029/2008wr006829 (2008).

144 Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D. & Friedman, S. P. A Review of Advances in Dielectric and Electrical Conductivity Measurement in Soils Using Time Domain Reflectometry. *Vadose Zone J* **2**, 444-475, doi:10.2136/vzj2003.0444 (2003).

145 Blonquist, J. M., Jones, S. B. & Robinson, D. A. A time domain transmission sensor with TDR performance characteristics. *J. Hydrol.* **314**, 235-245, doi:10.1016/j.jhydrol.2005.04.005 (2005).

146 Kojima, Y. *et al.* Low-Cost Soil Moisture Profile Probe Using Thin-Film Capacitors and a Capacitive Touch Sensor. *Sensors* **16**, doi:10.3390/s16081292 (2016).

147 Ojo, E. R. *et al.* Calibration and Evaluation of a Frequency Domain Reflectometry Sensor for Real-Time Soil Moisture Monitoring. *Vadose Zone J* **14**, doi:10.2136/vzj2014.08.0114 (2015).

148 Campbell, G. S., Calissendorff, C. & Williams, J. H. PROBE FOR MEASURING SOIL SPECIFIC-HEAT USING A HEAT-PULSE METHOD. *Soil Science Society of America Journal* **55**, 291-293, doi:10.2136/sssaj1991.03615995005500010052x (1991).

149 Manfreda, S., Brocca, L., Moramarco, T., Melone, F. & Sheffield, J. A physically based approach for the estimation of root-zone soil moisture from surface measurements. *Hydrology and Earth System Sciences* **18**, 1199-1212, doi:10.5194/hess-18-1199-2014 (2014).

150 Han, X. J. *et al.* Joint Assimilation of Surface Temperature and L-Band Microwave Brightness Temperature in Land Data Assimilation. *Vadose Zone J* **12**, doi:10.2136/vzj2012.0072 (2013).

151 Albergel, C. *et al.* From near-surface to root-zone soil moisture using an exponential filter: an assessment of the method based on in-situ observations and model simulations. *Hydrology and Earth System Sciences* **12**, 1323-1337, doi:10.5194/hess-12-1323-2008 (2008).

152 Zhang, N., Quiring, S., Ochsner, T. & Ford, T. Comparison of Three Methods for Vertical Extrapolation of Soil Moisture in Oklahoma. *Vadose Zone J* **16**, doi:10.2136/vzj2017.04.0085 (2017).

153 Tian, J. *et al.* Estimation of subsurface soil moisture from surface soil moisture in cold mountainous areas. *Hydrology and Earth System Sciences* **24**, 4659-4674, doi:10.5194/hess-24-4659-2020 (2020).

154 Bogena, H. R. *et al.* Emerging methods for non-invasive sensing of soil moisture dynamics from field to catchment scale: A review. *WIREs Water* **2**, 635–647, doi:10.1002/wat2.1097 (2015).

155 Wagner, W. *et al.* The ASCAT Soil Moisture Product: A Review of its Specifications, Validation Results, and Emerging Applications. *Meteorologische Zeitschrift* **22**, 5-33, doi:10.1127/0941-2948/2013/0399 (2013).

156 Bartalis, Z. *et al.* Initial soil moisture retrievals from the METOP-A Advanced Scatterometer (ASCAT). *Geophys Res Lett* **34**, doi:10.1029/2007gl031088 (2007).

157 Parinussa, R. M., Holmes, T. R. H., Wanders, N., Dorigo, W. A. & de Jeu, R. A. M. A Preliminary Study toward Consistent Soil Moisture from AMSR2. *Journal of Hydrometeorology* **16**, 932-947, doi:10.1175/jhm-d-13-0200.1 (2015).

158 Babaeian, E. *et al.* Ground, Proximal, and Satellite Remote Sensing of Soil Moisture. *Reviews of Geophysics* **57**, 530-616, doi:10.1029/2018rg000618 (2019).

159 Fang, B., Lakshmi, V., Bindlish, R. & Jackson, T. J. Downscaling of SMAP Soil Moisture Using Land Surface Temperature and Vegetation Data. *Vadose Zone J* **17**, doi:10.2136/vzj2017.11.0198 (2018).

160 Dorigo, W. *et al.* ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment* **203**, 185-215, doi:10.1016/j.rse.2017.07.001 (2017).

161 Bauer-Marschallingere, B. *et al.* Toward Global Soil Moisture Monitoring With Sentinel-1: Harnessing Assets and Overcoming Obstacles. *Ieee Transactions on Geoscience and Remote Sensing* **57**, 520-539, doi:10.1109/tgrs.2018.2858004 (2019).

162 Izumi, Y. *et al.* Potential of soil moisture retrieval for tropical peatlands in Indonesia using ALOS-2 L-band full-polarimetric SAR data. *International Journal of Remote Sensing* **40**, 5938-5956, doi:10.1080/01431161.2019.1584927 (2019).

163 Kim, S. B. & Liao, T. H. Robust retrieval of soil moisture at field scale across wide-ranging SAR incidence angles for soybean, wheat, forage, oat and grass. *Remote Sensing of Environment* **266**, doi:10.1016/j.rse.2021.112712 (2021).

164 Davidson, M., Gebert, N. & Giulicchi, L. in *EUSAR 2021; 13th European Conference on Synthetic Aperture Radar*. 1-2.

165 Tabatabaeenejad, A. *et al.* Assessment and Validation of AirMOSS P-Band Root-Zone Soil Moisture Products. *Ieee Transactions on Geoscience and Remote Sensing* **58**, 6181-6196, doi:10.1109/tgrs.2020.2974976 (2020).

166 Garrison, J. L. *et al.* in *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*. 164-167.

167 Vey, S., Guntner, A., Wickert, J., Blume, T. & Ramatschi, M. Long-term soil moisture dynamics derived from GNSS interferometric reflectometry: a case study for Sutherland, South Africa. *Gps Solutions* **20**, 641-654, doi:10.1007/s10291-015-0474-0 (2016).

168 Camps, A. *et al.* Sensitivity of GNSS-R Spaceborne Observations to Soil Moisture and Vegetation. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **9**, 4730-4742, doi:10.1109/jstars.2016.2588467 (2016).

169 Peters, D. P. C., Loescher, H. W., SanClements, M. D. & Havstad, K. M. Taking the pulse of a continent: expanding site-based research infrastructure for regional- to

continental-scale ecology. *Ecosphere* **5**, art29, doi:https://doi.org/10.1890/ES13-00295.1 (2014).

170 Bogena, H. R. *et al.* The TERENO-Rur Hydrological Observatory: A Multiscale Multi-Compartment Research Platform for the Advancement of Hydrological Science. *Vadose Zone J* **17**, doi:UNSP 180055, 10.2136/vzj2018.03.0055 (2018).

171 Tetzlaff, D., Carey, S. K., McNamara, J. P., Laudon, H. & Soulsby, C. The essential value of long-term experimental data for hydrology and water management. *Water Resources Research* **53**, 2598-2604, doi:10.1002/2017wr020838 (2017).

172 Brantley, S. L. *et al.* Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. *Earth Surface Dynamics* **5**, 841-860, doi:10.5194/esurf-5-841-2017 (2017).

173 Cosh, M. H. *et al.* Developing a strategy for the national coordinated soil moisture monitoring network. *Vadose Zone J* **20**, doi:10.1002/vzj2.20139 (2021).

174 White, T. *et al.* in *Developments in Earth Surface Processes* Vol. 19 (eds John R. Giardino & Chris Houser) 15-78 (Elsevier, 2015).

175 Loescher, H. W., Kelly, E. F. & Russ, L. in *Terrestrial Ecosystem Research Infrastructures: Challenges and Opportunities* (eds A. Chabbi & Henry W. Loescher) Ch. 2, (CRC Press, Taylor & Francis Group, 2017).

176 Zacharias, S. *et al.* A Network of Terrestrial Environmental Observatories in Germany. *Vadose Zone J* **10**, 955-973, doi:10.2136/vzj2010.0139 (2011).

177 Thurgate, N., A.J. Lowe and T.F. Clancy. in *Terrestrial Ecosystem Research Infrastructures: Challenges, New developments and Perspectives* (ed A. Chabbi and Loescher H.) 427-448 (CRS Press, 2017).

178 Dorigo, W. *et al.* The International Soil Moisture Network: serving Earth system science for over a decade. *Hydrology and Earth System Sciences* **25**, 5749-5804, doi:10.5194/hess-25-5749-2021 (2021).

179 Silvertown, J. A new dawn for citizen science. *Trends in Ecology & Evolution* **24**, 467-471, doi:10.1016/j.tree.2009.03.017 (2009).

180 Dickinson, J. L. *et al.* The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* **10**, 291-297, doi:10.1890/110236 (2012).

181 Gura, T. Citizen science: Amateur experts. *Nature* **496**, 259-261, doi:10.1038/nj7444-259a (2013).

182 Buytaert, W. *et al.* Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science* **2**, doi:10.3389/feart.2014.00026 (2014).

183 Kovács, K. Z. *et al.* Citizen observatory based soil moisture monitoring – the GROW example. *Hungarian Geographical Bulletin* **68**, 119-139, doi:10.15201/hungeobull.68.2.2 (2019).

184 Koch, J. & Stisen, S. Citizen science: A new perspective to advance spatial pattern evaluation in hydrology. *Plos One* **12**, doi:10.1371/journal.pone.0178165 (2017).

185 Li, X. *et al.* Boosting geoscience data sharing in China. *Nat. Geosci.* **14**, 541-542, doi:10.1038/s41561-021-00808-y (2021).

186 Cheng, K., Quan, S. & Yan, J. in *2021 IEEE 24th International Conference on Computer Supported Cooperative Work in Design (CSCWD).* 855-860.

187 Atzori, L., Iera, A. & Morabito, G. Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm. *Ad Hoc Networks* **56**, 122-140, doi:10.1016/j.adhoc.2016.12.004 (2017).

188 Wang, J. Y., Wang, X. Z. & Wu, Q. Core network service model and networking scheme oriented NB-IoT. *Telecommunications Science* 149-151 (2017).

189 McCabe, M. F. *et al.* The future of Earth observation in hydrology. *Hydrology and Earth System Sciences* **21**, 3879-3914, doi:10.5194/hess-21-3879-2017 (2017).

190 Gomes, V. C. F., Queiroz, G. R. & Ferreira, K. R. An Overview of Platforms for Big Earth Observation Data Management and Analysis. *Remote Sensing* **12**, doi:10.3390/rs12081253 (2020).

191 Shah, J. & Dubaria, D. in *9th IEEE Annual Computing and Communication Workshop and Conference (CCWC).* 184-189 (2019).

192 Hengl, T. *et al.* SoilGrids250m: Global gridded soil information based on machine learning. *Plos One* **12**, doi:10.1371/journal.pone.0169748 (2017).

193 Searle, R. *et al.* Digital soil mapping and assessment for Australia and beyond: A propitious future. *Geoderma Regional* **24**, doi:10.1016/j.geodrs.2021.e00359 (2021).

194 Jiang, H. L. & Cotton, W. R. Soil moisture estimation using an artificial neural network: a feasibility study. *Canadian Journal of Remote Sensing* **30**, 827-839, doi:10.5589/m04-041 (2004).

195 Yu, Z. B. *et al.* A multi-layer soil moisture data assimilation using support vector machines and ensemble particle filter. *J. Hydrol.* **475**, 53-64, doi:10.1016/j.jhydrol.2012.08.034 (2012).

196 Ahmad, S., Kalra, A. & Stephen, H. Estimating soil moisture using remote sensing data: A machine learning approach. *Advances in Water Resources* **33**, 69-80, doi:10.1016/j.advwatres.2009.10.008 (2010).

197 Schonbrodt-Stitt, S. *et al.* Statistical Exploration of SENTINEL-1 Data, Terrain Parameters, and in-situ Data for Estimating the Near-Surface Soil Moisture in a Mediterranean Agroecosystem. *Frontiers in Water* **3**, doi:10.3389/frwa.2021.655837 (2021).

198 Karandish, F. & Simunek, J. A comparison of numerical and machine-learning modeling of soil water content with limited input data. *J. Hydrol.* **543**, 892-909, doi:10.1016/j.jhydrol.2016.11.007 (2016).

199 Zhang, X. *et al.* Geospatial sensor web: A cyber-physical infrastructure for geoscience research and application. *Earth-Science Reviews* **185**, 684-703, doi:10.1016/j.earscirev.2018.07.006 (2018).

200 Amelung, W. *et al.* Towards a global-scale soil climate mitigation strategy. *Nature Communications* **11**, doi:10.1038/s41467-020-18887-7 (2020).

201 Landsberg, J. J. & Fowkes, N. D. WATER-MOVEMENT THROUGH PLANT ROOTS. *Annals of Botany* **42**, 493-508, doi:10.1093/oxfordjournals.aob.a085488 (1978).

202 Meunier, F., Draye, X., Vanderborght, J., Javaux, M. & Couvreur, V. A hybrid analytical-numerical method for solving water flow equations in root hydraulic architectures. *Appl. Math. Model.* **52**, 648-663, doi:10.1016/j.apm.2017.08.011 (2017).

203 Doussan, C., Pagès, L. & Vercambre, G. Modelling of the Hydraulic Architecture of Root Systems: An Integrated Approach to Water Absorption—Model Description. *Annals of Botany* **81**, 213-223, doi:10.1006/anbo.1997.0540 (1998).

204 Couvreur, V., Vanderborght, J., Beff, L. & Javaux, M. Horizontal soil water potential heterogeneity: simplifying approaches for crop water dynamics models. *Hydrol. Earth Syst. Sci.* **18**, 1723-1743, doi:10.5194/hess-18-1723-2014 (2014).

205 Vanderborght, J. *et al.* From hydraulic root architecture models to macroscopic representations of root hydraulics in soil water flow and land surface models. *Hydrology and Earth System Sciences* **25**, 4835-4860, doi:10.5194/hess-25-4835-2021 (2021).

206 de Jong van Lier, Q., van Dam, J. C., Durigon, A., dos Santos, M. A. & Metselaar, K. Modeling Water Potentials and Flows in the Soil–Plant System Comparing Hydraulic Resistances and Transpiration Reduction Functions. *Vadose Zone J* **12**, doi:10.2136/vzj2013.02.0039 (2013).

207 Carminati, A., Zarebanadkouki, M., Kroener, E., Ahmed, M. A. & Holz, M. Biophysical rhizosphere processes affecting root water uptake. *Annals of Botany* **118**, 561-571, doi:10.1093/aob/mcw113 (2016).

208 Landl, M. *et al.* Modeling the Impact of Rhizosphere Bulk Density and Mucilage Gradients on Root Water Uptake. *Frontiers in Agronomy* **3**, doi:10.3389/fagro.2021.622367 (2021).

209 Carminati, A. *et al.* Do roots mind the gap? *Plant and Soil* **367**, 651-661, doi:10.1007/s11104-012-1496-9 (2013).

210 Salmon, Y. *et al.* Drought impacts on tree phloem: from cell-level responses to ecological significance. *Tree Physiology* **39**, 173-191, doi:10.1093/treephys/tpy153 (2019).

211 Pandey, R., Vengavasi, K. & Hawkesford, M. J. Plant adaptation to nutrient stress. *Plant Physiology Reports* **26**, 583-586, doi:10.1007/s40502-021-00636-7 (2021).

212 Baatz, R. *et al.* Reanalysis in Earth System Science: Toward Terrestrial Ecosystem Reanalysis. *Reviews of Geophysics* **59**, e2020RG000715, doi:https://doi.org/10.1029/2020RG000715 (2021).

213 Mahdavi-Amiri, A., Harrison, E. & Samavati, F. Hexagonal connectivity maps for Digital Earth. *International Journal of Digital Earth* **8**, 750-769, doi:10.1080/17538947.2014.927597 (2015).

214 Bowater, D. & Stefanakis, E. An open-source web service for creating quadrilateral grids based on the rHEALPix Discrete Global Grid System. *International Journal of Digital Earth* **13**, 1055-1071, doi:10.1080/17538947.2019.1645893 (2020).

215 Arrouays, D. *et al.* in *Advances in Agronomy, Vol 125* Vol. 125 *Advances in Agronomy* (ed D. L. Sparks) 93-+ (2014).

216 Enescu, II *et al.* Hypercube-Based Visualization Architecture for Web-Based Environmental Geospatial Information Systems. *Cartographic Journal* **52**, 137-148, doi:10.1080/00087041.2015.1119469 (2015).

217 Yao, X. C. *et al.* Enabling the Big Earth Observation Data via Cloud Computing and DGGS: Opportunities and Challenges. *Remote Sensing* **12**, doi:10.3390/rs12010062 (2020).

Highlighted references: None

Acknowledgements: Wulf Amelung, Nicolas Brüggemann, Carsten Montzka, Jan Vanderborght, and Harry Vereecken acknowledge support from the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy, EXC- 2070–390732324–PhenoRob. Wulf Amelung, Heye Bogena, Nicolas Brüggemann, Carsten Montzka, Jan Vanderborght, and Harry Vereecken acknowledge support from the Terrestrial Environmental Observatories, TERENO, funded by the Helmholtz–Gemeinschaft, Germany. This research was also funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1502/1–2022 - Projektnummer: 450058266

Authors contributions: H.V., W.A., S.B., H.B., N.B., C.M., and J.V. led the conceptualization, writing and figure drafting.

D.O., M.B., G.B., A.C., A.K., J.K., I.N., S.S., A.V., M.Y. and Y.Z. supported in equal parts the conceptualization, writing and figure drafting

Competing interest: None

Key points:

- Local scale soil hydrological processes regulate climatic effects on the global terrestrial water cycle
- Regional scale soil hydrology is modulated by land-use and climate change effects on soil structure
- Global scale soil hydrology benefits from emerging technologies and big data analysis but still faces parametrization challenges from specific soil processes
- Specific soil hydrological processes prevail in distinct soil groups like permafrost and peat soils

Figures legends and boxes:

Fig. 1: **The soil hydrological system from the pore to global scale.** At the pore scale, capillary and molecular forces act on the pore soil water. At the soil profile or pedon scale, hydrological processes include drainage, evapotranspiration, soil water storage, capillary rise, and runoff generation. Typically, water flows either through the matrix or through preferential flow paths such as macropores and cracks. At the regional scale, similar processes occur but in addition water is now routed through the landscape. At the global scale, SHP can influence larger scale atmospheric processes such as droughts and convective rainfall events caused by feedbacks and teleconnections but they also modulate the impact of extreme events.

Fig. 2: **Time scales and soil structure forming processes**. (a) soil genesis that can be different in different climates and soil forming processes; (b) natural soil structure at hydrologic time scales; (c) managed soil structure at agronomic time scales.

Fig. 3: **Effect of soil properties and moisture status on water fluxes in the soil-plant system**. Fig. 3a sketches the water fluxes during a dry period and Fig. 4b for a precipitation event in sandy soils (left) and loamy soils (right) with and without vegetation. During dry periods (fig. 3a), more water is lost by transpiration from vegetated areas than by evaporation from the soil surface in non-vegetated areas since vegetation can extract water from deeper soil layers. This leads to larger groundwater recharge in non-vegetated areas. In sandy soils, evaporation losses are lower than in loamy soils due to smaller capillary forces in sandy soils. Capillarity sustains larger upward flows from the groundwater to the root zone in loamy than in sandy soils and deep root systems act as hydraulic lifts that take up water from deeper and wetter soil layers and release it into shallower and drier layers. Loss of soil structure in non-vegetated areas leads to less infiltration and more run-off from non-vegetated surfaces during precipitation events. Biopores and soil structure that is stabilized by organic matter input in vegetated areas increase the infiltration capacity of vegetated areas where water can be transferred rapidly by preferential flow to deeper soil layers. After a precipitation event (Fig. 3b), water is redistributed faster and to deeper soil layers by matrix flow in sandy than in loamy soils. To access this redistributed water, vegetation develops deeper roots in sand than in loamy soils.

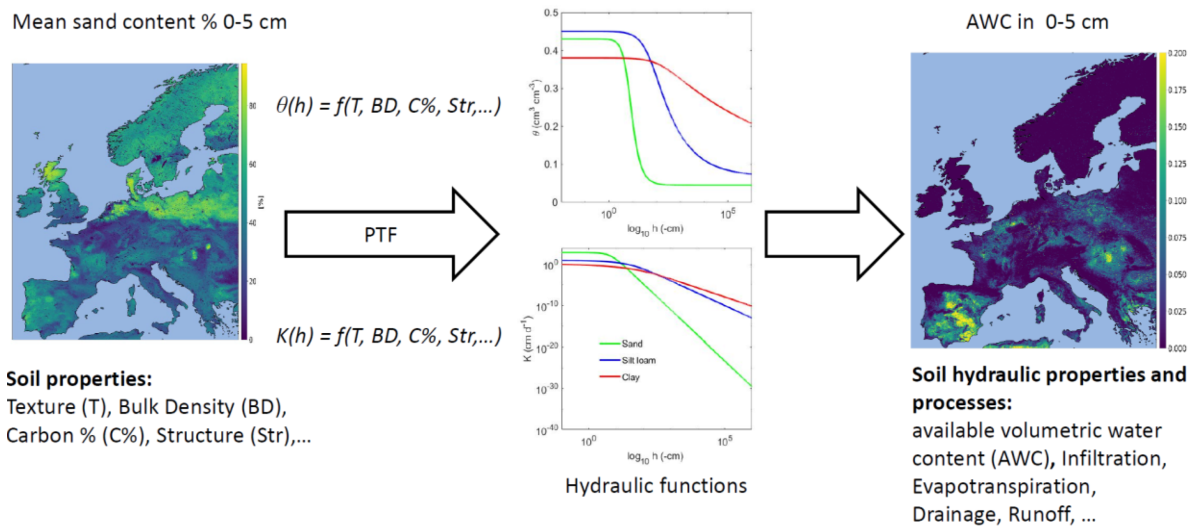
Fig. 4: **The four key elements for cyber-physical infrastructures**. It shows the role of wireless sensor networks (adapted from[199]) in providing soil hydrological information that can be injected into models using data assimilation methods or data-driven approaches.

Text box 1: The diversity of soils and PTF

Soils strongly differ in their formation factors, land cover and composition that greatly affect their hydraulic properties. Currently, we employ easy-to-measure soil physical properties such as texture, bulk density and organic matter in PTF used to estimate soil hydraulic properties (fig. 3). This approach tacitly assumes dominance of these attributes in determining soil hydraulic properties and applies auxiliary simplifying assumptions of homogeneity, unimodality of pore size distribution, while ignoring differences in rock fragments, mineralogy, chemical and biological properties. We thus expect improvements in PTF-based soil hydraulic properties with future inclusion on nuanced differences in soils and their specific properties[47]. Examples for soil groups[200] with pronounced properties not yet accounted for in PTF are:

- Formation and persistence of preferential flow paths due to animal burrows common in silty soils such as Phaeozems, Chermozems, or Luvisols; persistent unless disturbed by management;
- Temporal formation of preferential flow paths due to swelling and shrinking processes in Vertisols caused by the presence of three-layer-clay minerals;
- Good drainage in Ferralsols and Acrisols due to pseudo-aggregate formation from two-layer clay minerals and oxides, as well as in some Andosols exhibiting low bulk density;
- Low water storage capacity in Leptosols due to percentages of rock fragments, affecting both the soil hydraulic and thermal properties which are therefore frequently not effectively parameterized;
- High water storage capacity in Histosols due to high organic matter contents;
- Crust formation in, for example, Gypsisols or clayey Solonetzs and clayey Solonchaks, distorting infiltration patterns;
- Dense subsoil layers leading to stagnant water in Planosols, Stagnosols, or Plinthosols

Hence, next generation PTF will be required to integrate specific rock fragments, mineralogical, biological and chemical interactions that alter soil hydraulic properties[28,33]. To facilitate such progress current databases used to develop PTF must be expanded to include physical, chemical and biological properties of the above-mentioned soil groups, which are typically found in large parts of Africa, South America, India, the Middle East, Japan, China and Australia. First attempts have been made with a dedicated hydrophysical data base to develop PTF for tropical soils in Brazil[61]; unfortunately, adequate high-resolution data are frequently missing for other parts of the tropical and subtropical world, such as in Africa.



Text box 1 figure: **The concept of PTF**. It shows how PTF are being used to predict soil hydraulic properties from soil properties for Europe as a basis for estimating large scale soil hydrological processes, such as water storage, infiltration, evapotranspiration, drainage, and runoff. The hydraulic conductivity (bottom middle panel), *K*, indicates the ease with which water can flow in the soil: the value of this parameter will decrease rapidly with decreasing θ. Together with the gradient in hydraulic potential ($\nabla(h+z)$), with *h* being determined by the water retention curve and *z* the vertical coordinate, *K* determines the flow of water in the soil, thereby affecting the processes of infiltration, redistribution and drainage, as well as root water uptake and evaporation. The information contained in the water retention curve (top middle panel) also provides the models with parameters that determine how much water a certain soil can hold in its pore system (the available volumetric water content, AWC) and how easy it is for the roots to take up this water (that is, how tightly the water is being held in the pores).

Text box 2: Soil-plant hydraulics

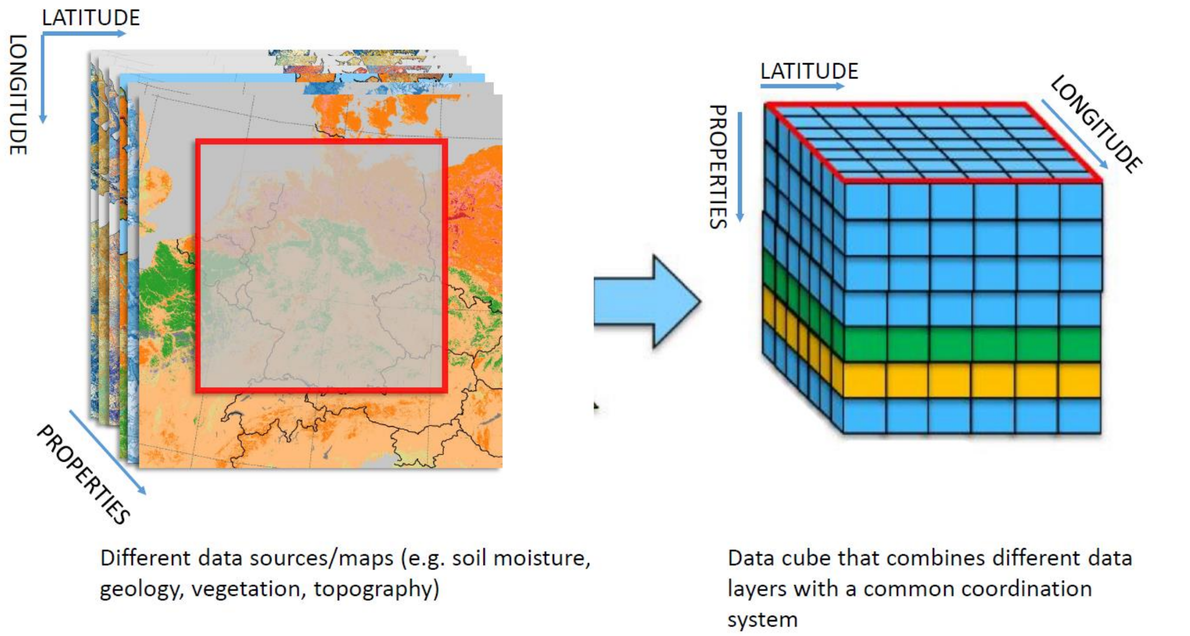
Parameterizing root hydraulic properties in plant hydraulic models remains challenging. A common simplification neglects the resistance to axial flow in the root system. But, for deep roots water uptake does not increase with root length since axial conductance becomes limiting[201]. Approaches to simulate RWU which account for the distribution of radial and axial conductance in root system networks[202] have been developed[203]. Using upscaling approaches, information about root architecture and root hydraulic traits can be ingested directly into larger scale soil-plant hydraulic models[204,205].

The resistance to flow from bulk soil to root surfaces through the so-called rhizosphere becomes increasingly important when the soil dries out[206]. Root exudates and mechanical effects of root growth influence the hydraulic properties of the rhizosphere and consequently RWU[207,208]. An additional complexity is that the conductivity of the root-soil interface is reduced when roots and soil shrink during soil drying and contact to the soil is lost[209]. How plants engineer the rhizosphere and its impact on SHP is a multifaceted problem that includes micro-scale soil and root mechanics and hydraulics. These small-scale processes are key to understanding how plants affect soil structure and infiltration processes, which are important feedback mechanisms that structure and sustain vegetation in water limited ecosystems.

The adaptation of vegetation and its hydraulic properties to environmental conditions referred to as plant plasticity can be predicted based by invoking optimisation principles, but it remains unclear why they apply when natural selection is not a mechanism for optimisation. Unravelling the mechanisms that couple growth and stress physiology and plant hydraulics will be crucial for a mechanistic modelling of plant and vegetation plasticity. This coupling entails the coupling of phloem carbon transport and xylem water flow, and how they respond to changing environmental conditions[210] as well as a comprehensive understanding of how changing environmental conditions in the soil are sensed by plants[211] and signalled between the plant organs or individual plants.

Text box 3: The soil data hypercube

The confluence of rapidly expanding Earth observing platforms at all scales, availability of massive computational resources and the urgent need to provide information for increasingly complex and highly resolved Earth system models create unprecedented opportunities for individual characterization of every grid of the Earth surface[212]. The hypercube approach stacks gridded geospatial data according to standardized global coordinates such as DGSS (DGGSs)[213] and adding a z-dimension for various information layers that incorporate localized legacy-data, vegetation, geomorphic, climate and other environmental attributes, and, of course, soil variables at different depths (Fig. 5). This data structure provides unique opportunities for data fusion and temporal information assimilation to derive parameters or variables, and enhance the quality of inputs to EMS applications especially as novel machine learning approaches can be used to impose physical constraints and extract auxiliary information for the representation of SHP. Combined with modern data cube geospatial data management and analysis software, such as provided by the Open Data Cube (ODC) initiative, and unique indexing of grid cells down to 150 m resolution[214]. This realizes the vision of Digital Earth and populating of every grid cell with soil and hydrologic information unique to each grid cell and location on the planet[215].



Text box 3 Figure **Basic principle of a data cube**. It links different data layers (e.g. soil moisture, geology, vegetation, topography) with a common coordinate system.

For example, we envision the development of the next generation PTF and geomorphic functions in their geo-referenced and local attribute-based context to greatly enhance SHP-related information and offer a path for continual improvement as more information enters into the local hypercube. The richness of information and advanced analytical methods will supersede our present non-referenced generic attribute-based PTFs and offer local and updatable referenced hydrologic and surface information at an ever-increasing resolution and expanding temporal record[215]. For effective exploration, management, querying, and updating the massive geospatial information, the community will need to embrace hypercube-based visualization[216], that extends traditional space-time cubes into higher dimensions spanned by contemporary soil and environmental information (Fig. 5). Recent developments point to the central role of cloud computing in management, extraction and direct simulation of spatial data (Google Earth Engine)[217]. The potential for rich soil (and environmental) information unique to a location, where local and extrapolated new measurements and observations are harmonized and integrated using ensemble machine learning tools to continuously update and improve data quality and derived parameters, holds great promise for reducing uncertainties of present Earth system models.