

## Article (refereed) - postprint

---

This is the peer reviewed version of the following article:

Robinson, David A.; Hopmans, Jan W.; Filipovic, Vilim; van der Ploeg, Martine; Lebron, Inma; Jones, Scott B.; Reinsch, Sabine; Jarvis, Nick; Tuller, Markus. 2019. **Global environmental changes impact soil hydraulic functions through biophysical feedbacks**. *Global Change Biology*, 25 (6). 1895-1904, which has been published in final form at <https://doi.org/10.1111/gcb.14626>

This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

© 2019 John Wiley & Sons Ltd.

This version available <http://nora.nerc.ac.uk/522703/>

NERC has developed NORA to enable users to access research outputs wholly or partially funded by NERC. Copyright and other rights for material on this site are retained by the rights owners. Users should read the terms and conditions of use of this material at <http://nora.nerc.ac.uk/policies.html#access>

**This document is the authors' final manuscript version of the journal article, incorporating any revisions agreed during the peer review process. There may be differences between this and the publisher's version. You are advised to consult the publisher's version if you wish to cite from this article.**

The definitive version is available at <http://onlinelibrary.wiley.com/>

Contact CEH NORA team at  
[noraceh@ceh.ac.uk](mailto:noraceh@ceh.ac.uk)

Article type : Opinion

Global Environmental Changes Impact Soil Hydraulic Functions through Biophysical Feedbacks

Authors: David A. Robinson<sup>1</sup>, Jan W. Hopmans<sup>2</sup>, Vilim Filipovic<sup>3</sup>, Martine van der Ploeg<sup>4</sup>, Inma Lebron<sup>1</sup>, Scott B. Jones<sup>5</sup>, Sabine Reinsch<sup>1</sup>, Nick Jarvis<sup>6</sup>, Markus Tuller<sup>7</sup>

1. Centre for Ecology & Hydrology, ECW, Deiniol Road, Bangor, LL57 2UW, United Kingdom.
2. Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA
3. Dept. of Soil Amelioration, Faculty of Agriculture, University of Zagreb, 10000 Zagreb, Croatia
4. Dept. Environmental Sciences, Wageningen University, The Netherlands
5. Dept. of Plants, Soils and Climate, Utah State University, 4820 Old Main Hill, Logan Utah, USA.
6. Dept. of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, 750 07 Uppsala, Sweden
7. Dept. of Soil, Water and Environmental Science, The University of Arizona, 1177 E. 4<sup>th</sup> Street, Tucson, AZ, USA.

\*Correspondence:

David A. Robinson

Email: davi2@ceh.ac.uk

Running Head: Alternative stable soil moisture states

Keywords: soil water content, state shift, soil physics, infiltration, water repellency, biophysical feedbacks, hydraulic, environmental change

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/gcb.14626

This article is protected by copyright. All rights reserved.

## Abstract

Although only representing 0.05% of global freshwater, or 0.001% of all global water, soil water supports all terrestrial biological life. Soil moisture behaviour in most models is constrained by hydraulic parameters that do not change. Here we argue that biological feedbacks from plants, macro-fauna and the microbiome influence soil structure, and thus the soil hydraulic parameters and the soil water content signals we observe. Incorporating biological feedbacks into soil hydrological models is therefore important for understanding environmental change and its impacts on ecosystems. We anticipate that environmental change will accelerate and modify soil hydraulic function. Increasingly we understand the vital role that soil moisture exerts on the carbon cycle and other environmental threats such as heatwaves, droughts and floods, wildfires, regional precipitation patterns, disease regulation and infrastructure stability, in addition to agricultural production. Biological feedbacks may result in changes to soil hydraulic function that could be irreversible, resulting in alternative stable states (ASS) of soil moisture. To explore this, we need models that consider all the major feedbacks between soil properties and soil-plant-faunal-microbial-atmospheric processes, which is something we currently do not have. Therefore, a new direction is required to incorporate a dynamic description of soil structure and hydraulic property evolution into soil-plant-atmosphere, or land surface, models that consider feedbacks from land use and climate drivers of change, so as to better model ecosystem dynamics.

## Soil moisture and global environmental change

In the last 15 years, the importance of soil moisture has been recognized by earth system science involved with understanding the consequences of environmental change on the earth system (Green *et al.*, 2019, Seneviratne *et al.*, 2010). For example, soil moisture has been included in the list of the 50 most essential climate variables (Dorigo *et al.*, 2015) in order to support international organizations with the assessment of climate change impacts. In 2010, the Global Climate Observing System (GCOS) initiative has defined soil moisture as a fundamental climate variable (GCOS, 2010). Fundamentally, soil moisture provides the water resource for plants and primary food production, while it also affects a range of hydrological processes such as recharge of aquifers through the vadose zone. Soil moisture is also an important source of atmospheric water at continental scales as it is transpired by plants and evaporates from the soil surface, a proportion of which falls as precipitation back on the land surface downwind from the site of the original evapotranspiration (Entekhabi *et al.*, 1996, Koster *et al.*, 2004, Taylor *et al.*, 2011). Thus, soil moisture contributes to regulating the global energy balance of terrestrial ecosystems, also controlling soil temperature, air humidity and surface albedo (Robinson *et al.*, 2008, Seneviratne *et al.*, 2010, Vereecken *et al.*, 2008). A deficit of soil moisture leads to drought (Dai *et al.*, 2004, Sheffield & Wood, 2008); moreover, prior to deficit soil

moisture acts as a shock absorber reducing the magnitude of heatwaves (Rasmijn *et al.*, 2018, Seneviratne *et al.*, 2006).

From a biogeochemical perspective, soil moisture influences redox conditions (Keiluweit *et al.*, 2017, Veneman *et al.*, 1998) thereby changing the availability of nutrients for plants, fauna and microbes. Soil moisture indirectly influences microbial activity and respiration as it changes carbon and nutrient availability (Evans & Wallenstein, 2014, Frank *et al.*, 2015, He & Dijkstra, 2014, Vicca *et al.*, 2014), and directly by soil moisture availability and excess (Davidson *et al.*, 1998, Orchard & Cook, 1983, Reinsch *et al.*, 2017, Skopp *et al.*, 1990). Among the important processes, soil moisture regulates nitrification, denitrification and CO<sub>2</sub> production via soil microbial and plant root respiration (Homyak *et al.*, 2017, Manzoni *et al.*, 2012, Vicca *et al.*, 2014).

Long-term changes in soil moisture can have drastic impacts on the biosphere (Manzoni *et al.*, 2012, Wu *et al.*, 2011). Long-term reductions in soil moisture can cause desertification and tree mortality (Van Mantgem *et al.*, 2009), thereby completely changing the landscape. Soil moisture is also linked to wildfires, often in complex ways (Westerling *et al.*, 2003). Soil, and associated ecosystem degradation and accelerated desertification can also cause severe dust storms, which can lead to respiratory diseases and other health problems (Stacy *et al.*, 2012). Given the importance of soil moisture dynamics within the biosphere, the objective of this opinion paper is to highlight the links between environmental change, impacts on biological systems and potentially irreversible or slowly reversible alterations in soil hydraulic function. Our work considers feedbacks between the soil-plant-faunal-microbial system and soil structure, which modify soil hydraulic function in response to environmental change.

Here we define soil hydraulic function as the ability of soils to infiltrate and retain water to provide the moisture pool that sustains the soil-plant-faunal-microbial system. Mathematically, soil hydraulic functions are usually described with static values of hydraulic parameters, such as those governing hydraulic conductivity and soil water retention. This simplification neglects the co-evolution of the soil-plant-faunal-microbial system; especially the different strategies that living soil organisms adopt, to modify or adapt to soil structural and moisture changes. Thus, physico-chemical processes and biological activity can modify the soil properties resulting in a shift from one soil moisture regime to another. Before going further, it is important to stress that these phenomena, which lead to permanent alterations of the soil pore structure, should be distinguished from the hysteresis (i.e. the non-uniqueness of water/air distributions in soil) due to soil structure at the pore-scale that arises from the

Accepted Article

history of wetting and drying (Dane & Lenhard, 2005). This classical phenomenon of hysteresis, which has been studied in soil physics for nearly a century (Haines, 1930), is not the subject of this opinion paper. Here, we examine biological factors and processes that change the soil architecture (i.e. the geometry and topology of soil pore space and solid matter) or the properties of the solid surfaces (e.g. hydrophobicity) that influence the soil hydrology. The focus of this opinion piece is therefore on physico-chemical and biological processes mediated by environmental change that have irreversible or slowly reversible direct or indirect impacts on soil structure and therefore soil moisture states and hydraulic behaviour.

Biology has a number of direct effects on hydraulic function. Given that soils and vegetation often co-evolve, it is unsurprising that changes to vegetation through land use or climate change affect soil properties. Broadly, we might recognise four primary pathways through which flora (Rabbi *et al.*, 2018), fauna (Smettem, 1992) and soil microbes (Hallett, 2008) alter hydraulic function through changes in:

- 1) organic matter inputs changing bulk density, porosity and/or pore size distribution (Franzuebbers, 2002, Jarvis *et al.*, 2017, Rawls *et al.*, 2004, Yang *et al.*, 2014);
- 2) rooting structure and decreases in porosity through compression induced by new root growth, or macropore generation when roots decay (Bodner *et al.*, 2014, Fischer *et al.*, 2015, Koestel & Schlüter, 2019);
- 3) biopore characteristics and abundance resulting from the activity of macrofauna, the 'ecosystem engineers' (Berry, 2018, Smettem, 1992); and
- 4) microbial activity, especially in the rhizosphere, which impacts hydrophobicity (Hallett, 2008).

Biology is also involved in a variety of indirect climate-mediated impacts. Pedotransfer functions traditionally use soil texture as the only model input to estimate hydraulic properties in landscape- and global scale models. However, although biological and climatic factors are rarely considered, the ability of organisms to modulate soil hydrology may overwrite these intrinsic soil properties. Jarvis *et al.* (2013) found that saturated and near-saturated hydraulic conductivity could be better explained by land use, organic carbon content, bulk density and climatic factors (average annual precipitation, temperature), rather than the classical emphasis on soil texture (i.e. sand, silt and clay contents). More recent, continental scale research has also established links between climate and soil hydraulic function. Hirmas *et al.* (2018) provided evidence that macroporosity increases in drier climates on decadal time scales, which they suggest may lead to 'unexplored feedbacks between climate and the land surface.' Robinson *et al.* (2016) presented evidence of a connection between climate change and

soil hydraulic function through a long-term drought manipulation experiment, with a shift to an alternative, more permanent, soil moisture state. The soil moisture state shift was attributed to a drought-induced alteration of soil structure. Climate and other environmental stresses may initiate these soil responses. It is critical to consider the effects of biological processes on soil hydrology if the key drivers (climate and land use) change. Therefore, developing a new 'dynamic' paradigm for soil hydraulic functioning by linking biological and climate feedbacks to soil hydraulic behaviour must be an important direction for understanding impacts of global environmental change, as well as for developing policies that mitigate soil threats such as erosion, compaction or salinization.

### **Alternative stable states in relation to soil hydraulic function**

Rapid global change, through either land use or climate, raises the concern that hydrological systems may begin to experience abrupt state shifts. About 40 years ago, ecologists (Beisner *et al.*, 2003, Holling, 1973, Lewontin, 1969) first proposed that communities or ecosystems can be found in one of several possible alternative stable states (ASS). The theory of ASS (Petraitis, 2013) predicts that under the same environmental conditions an ecological system can potentially exist in different, but stable, states following a 'disruptive' perturbation (Carpenter *et al.*, 2011, Scheffer *et al.*, 2012, Schröder *et al.*, 2005). This has been explored in soils research in the context of fire-vegetation-soil (Wood & Bowman, 2012) and in ecohydrology to explain abrupt changes of plant communities (Borgogno *et al.*, 2007, D'Odorico *et al.*, 2007, Zeng & Zeng, 1996, Zeng *et al.*, 2004). Feedback mechanisms between vegetation and soil moisture may induce a transition between soil moisture states. The existence of ASS has profound implications for management with a seemingly stable vegetated state suddenly, following a perturbation, crossing a critical threshold and moving to a new, often degraded, state. Once this has occurred, the system does not return to the former state after the perturbation has ceased, resulting in an irreversible state change. The existence of such states has been proposed for a variety of ecosystems and a useful conceptual framework is presented in (Bestelmeyer *et al.*, 2011). It is particularly relevant to the world's rangelands, where the threat of a shift from a state that sustains life, to a degraded one that does not, is a constant concern.

There is only limited evidence for shifts for different ecosystems Schröder *et al.* (2005). They argued that evidence of state shifts has been largely derived from analyses of historical records and rarely from manipulation experiments, thus offering only indirect evidence, which remains open to alternative explanations. They found 13 experiments showing direct evidence of ecological state shifts. Much of the work on dryland ecohydrology (Borgogno *et al.*, 2007, D'Odorico *et al.*, 2007, Zeng & Zeng, 1996) is based on modelling, as manipulating ecosystems experimentally is a considerable challenge. The 'tipping point' concept, where a change at the tipping point sets in motion

mutually reinforcing feedback loops that force the system on a new course, is garnering interest. Aligned with this are studies that suggest the need to search for “critical slowing down points” in modelling that will indicate a regime shift; see for example (Van Nes & Scheffer, 2007). Given that modelling and experimental evidence of shifts in soil hydraulic function are emerging (Robinson *et al.*, 2016, Zeng *et al.*, 2004), largely connected to alterations in biological factors, we must determine the processes leading to such changes and ASS.

### **Evidence for alternative states in soils: some illustrative examples**

We propose that it is important to identify and gather evidence for ASS in soils (Dekker *et al.*, 2007, Rietkerk *et al.*, 2004, Robinson *et al.*, 2016, Zeng *et al.*, 2004), which we now consider. Soil structure may deform by exertion of outside force by machinery or livestock trampling, leading to a change in infiltration response of the soil (Logsdon, 2012, Messing & Jarvis, 1993, Moret & Arrúe, 2007). Reversing such deformation by for example no-tillage practices may take years (Horn, 2004). If soils contain clay, they may exhibit shrink and swell behaviour because of soil moisture availability. Te Brake *et al.* (2013) provides an example of a loam soil where very dry spring conditions resulted in shrinkage of 20 mm over a soil depth of 60 cm. For marshes and wetlands seasonal elevation changes have been observed, while drought led to increased consolidation of the soil, thereby reducing the resilience of these ecosystems (Cahoon *et al.*, 2011). Such soils may exhibit hysteresis effects through multiple drying/wetting or freezing/thawing cycles, thereby impacting soil water storage, root water uptake, and the ability of roots to penetrate the soil. Roots themselves impact soil structure (Fischer *et al.*, 2015, Koestel & Schlüter, 2019) and vegetation changes such as deforestation may lead to irreversible changes in soil water retention (Ramírez *et al.*, 2017). For soils containing high organic matter, such as peat soils, ponding of surface water upstream from hummocks combined with positive feedbacks between hummock occurrence and water table depth can lead to string patterns (Swanson & Grigal, 1988).

Water resource concentration mechanisms can lead to ASS (Rietkerk *et al.*, 2004). In particular, feedbacks and self-organized pattern development have been documented and modelled, explaining the occurrence of vegetation patterns (e.g., tiger bush) in dryland ecosystem functioning (Rietkerk *et al.*, 2002, Rietkerk *et al.*, 2004). Another water concentration mechanism widely studied in soil science is soil hydrophobicity (Doerr *et al.*, 2000, Hallett, 2008). Extensive work has been conducted on soil hydrophobicity, which was initially associated with wildfires (DeBano, 2000). Increasingly, hydrophobicity is observed across soil types and across biomes globally, although the exact extent remains unclear (Doerr *et al.*, 2000). Hydrophobicity changes solid-water contact angles and thus the way water infiltrates into soil (Filipović *et al.*, 2018, Ritsema *et al.*, 1998). Water infiltrates into dry



soil due to capillary and gravitational forces, normally with small pores filling first and large pores last. Hydrophobicity reverses this sequence with large pores filling first and small ones last, or not at all. This creates both non-homogeneous wetting through preferential flow, as well as increased air entrapment, infiltrating (or channelling) water further downwards into the soil without wetting the surface soil (Jarvis *et al.*, 2016). There is growing consensus that hydrophobicity derives from multiple sources (Hallett, 2008). These include geochemical, e.g. through alteration by fire (DeBano, 2000, Stoof *et al.*, 2010, Weninger *et al.*, 2019); biochemical; leaf litter, plant degradation products, root exudates (Doerr *et al.*, 2000, Hallett, 2008); biological where the organisms themselves are hydrophobic like fungi (Unestam, 1991, Wessels, 1993), and physical, simply through microscopically rough, rugose, or wrinkled surfaces (Quére, 2008). However, the mechanisms that stimulate the development and persistence of soil hydrophobicity remain poorly understood; especially links to climate change (Goebel *et al.*, 2011). The role of soil organisms and their contribution to the development and persistence of hydrophobicity and soil structure are only now being uncovered. Pioneering work on mycorrhizae (Unestam, 1991) indicated some organisms are hydrophilic, some aren't, and some change, making the study of such phenomena challenging.

In a study in Utah, Robinson *et al.* (2010) found that hydrophobic compounds were associated with pinyon - juniper woodlands, resulting in a water concentration mechanism under the trees (Figure 1). Anecdotal evidence indicated that soils under trees further away from water flow paths were more hydrophobic, suggesting a feedback of increasing hydrophobicity with increasing stress. Hydrophobicity could have several beneficial effects; i) leaving topsoil like a dry mulch, creating an evaporation barrier and reducing competition from seed germination; ii) altering the infiltration behaviour of the soil and so effectively increasing the amount of moisture infiltrating deeper into the soil, developing a potential soil moisture maintenance pool for vegetation. For example, the way in which hydrophobicity impacts water infiltration is illustrated based on Hydrus 2D simulations depicted in Figure 1 (adapted from Robinson *et al.* (2010)). The left side of Figure 1 illustrates infiltration under a tree canopy where hydrophobic conditions dominate, whereas the right side shows infiltration into hydrophilic bare soil conditions. The water infiltrates twice as deep in the 24 hr simulation period under hydrophobic conditions forming small wet bulbs. Furthermore, these wetted bulbs are less connected to the soil surface, thus reducing evaporative losses. Understanding the link between the soil-plant-faunal-microbial system in response to environmental stress and the development and persistence of hydrophobicity represents a distinct research gap.



Plants, through their rooting behaviour, can modify the soil below plants and in their immediate vicinity, thereby altering the hydraulic conductivity and infiltration behaviour of the soil leading to water concentration. Franz *et al.* (2011) was able to demonstrate with a combination of measurements and modelling that the proliferation of the undesirable succulent, *S. volkensii* in central Kenya was a result of a positive feedback. Increased grazing led to smaller above-ground forage biomass and bare soil patches, such that water infiltrated preferentially where the remaining grass swards were growing. *S. volkensii* was then able to exploit this, growing water in run-on rather than runoff zones, developing self-organized patterns in the landscape with islands of *S. volkensii*. In addition to enhancing local infiltration, plants also shade soil, thereby locally reducing evaporation from the soil surface. Once established, plant islands preferentially concentrate water resources, whereas the bare soil patches in-between represent a drier, hotter, and more hostile environment for other plants to establish. This supports that the present state of the vegetation depends on its history (Rietkerk *et al.*, 2004).

Changes to the hydraulic conductivity of an organo-mineral soil with perched water have also been proposed as a mechanism to explain the observed change in the soil moisture patterns recorded during a long-term climate change experiment subjected to drought (Robinson *et al.*, 2016). The soil moisture storage in the top 10 cm (O horizon) of a podzol, with a 10 cm organic layer overlying an 18 cm thick mineral layer resulted in a substantial hydraulic contrast. The O horizon stopped rewetting fully after a summer drought (Figure 2). The figure shows two organic ( $O_f$  and  $O_h$ , 10 cm) horizons over a mineral layer (18 cm). The grey (before intense drought) and black (after intense drought) lines reflect the soil moisture storage in the O horizon (10 cm). The organic horizon transitions from fermented ( $O_f = 5$  cm), to humic ( $O_h = 5$  cm) then to a mineral horizon (18 cm). The hydraulic conductivity of the  $O_h$  horizon was adjusted, from 1 cm day<sup>-1</sup> prior to the drought, to 10 cm day<sup>-1</sup> post drought, reflecting an increase in  $O_h$  soil horizon hydraulic conductivity brought about by drought-induced soil structural change. What we do not know is whether this response to drought is a permanent shift to an ASS, or whether the soil will recover in the long-term.

Data from similar soils from long-term soil moisture storage monitoring programme at the Plynlimon experimental site (Hudson, 1988) provide some insight into the roles of vegetation and soil (Figure 3). A major drought occurred in 1976 and a minor one in 1984 in Wales (Hudson, 1988). The data for peat soils show that they dry and then rewet (Figure 3A), whereas the podzolic soil dries and rewets under grass, but not under forest (Figure 3B). We suggest that the latter is evidence of a shift to an ASS induced by the drought, cracking the subsoil and facilitating drainage of any perched soil water. The upward trajectory of the recovery in the forested soil, following the 1976 drought, suggests that the soil structure might rebound and perched water again collect, but a subsequent drought in 1984

appears to stop this recovery. Hence, the data show intriguing patterns in soil moisture response to drought for different soils and vegetation. Clearly, there are feedbacks from the drought affecting the soil moisture retention through alteration of the soil structure.

### **Synthesis and future direction**

Climate change is causing diverse effects, higher summer temperatures, droughts, fewer frost days and more intense rain events (Frich *et al.*, 2002, Thornton *et al.*, 2014). Based on the evidence compiled in this work, we propose that drier periods are likely to cause a number of biophysicochemical feedbacks to soil that alter the soil hydraulic function and moisture states. This is conceptualised at the top of

Figure 4, where the climate gradient, or frequency of drought, leads to soils being subjected to longer and more intense dry spells (A, B, C). At the bottom, soil wetting scenarios and changes to the hydraulic function are shown as drying becomes stronger and more prolonged. Figure 4A is a soil profile with no macropores that is hydrophilic and exhibits uniform matrix flow, with winter wetting and summer drying. Figure 4B shows macropores developing, where, as summers become drier, plant roots penetrate deeper in search of water and the soil develops cracks. During rainfall, water infiltrates into the soil preferentially in macropores, resulting in a heterogeneous wetting of the soil profile (Jarvis *et al.*, 2016). Figure 4C highlights a more severe drought condition, inducing the ecosystem to a hydrophobic state. This alters the infiltration process so that even in an unsaturated state soil preferential flow may occur in macropores, capturing scarce water resources that would otherwise be quickly lost to evaporation from the soil surface. This may allow for the development of a soil moisture pool deeper in the soil profile that could form a maintenance moisture pool for vegetation during dry periods (4C). This conceptual framework proposes a number of feedbacks that result in changes to soil structure, hydrophobicity and moisture retention. The drought-induced feedbacks result in soil moisture shifts with ASS as a result. What we are yet to determine are the time scales over which these phenomena and feedbacks might occur, and how quickly the soil moisture state will recover, if at all. The evidence from Figure 3 suggests that these shifts might be long-term. These examples illustrate how climate, and especially drought, as a driver can lead to reinforcing feedback mechanisms and thus ASS. Land use and soil management may also alter soil hydraulic function, for example changes in cropping systems and soil management practices and systems can affect soil properties with consequences for hydraulic functions, water storage and movement, carbon cycling, biological activity, transport of nutrients and pollutants, and plant growth (Alletto *et al.*, 2015, Franzluebbers, 2002, Strudley *et al.*, 2008). These temporal changes are particularly seen in the near-

saturated range, where soil structure strongly influences water storage and flow (Daraghmeh *et al.*, 2008, Or & Ghezzehei, 2002).

We need to change and develop models to meet the challenges of incorporating soil bio-physical feedbacks. Predicting the impacts of environmental change on soil functions and ecosystem services requires appropriately parameterized models that can account for the dynamic nature of soil hydraulic properties. However, applications of models in the literature generally make use of time invariant hydraulic parameters (Figure 5). The grey box shows the current approach to modelling soil hydraulic functions and soil moisture processes, which assumes they are 'static' and unresponsive to changes in environmental conditions. The required future direction is to move towards a dynamic concept of the soil so that soil processes susceptible to environmental change result in biophysical feedbacks to the soil system altering the hydraulic function. Modelling studies accounting for time-variable hydraulic properties in tilled soils have shown improved simulations of near-surface soil water storage (Alletto *et al.*, 2015, Schwen *et al.*, 2011). However, we know little about which parameters are constant, which change, and how. Alletto *et al.* (2015) observed that both hydraulic conductivity and saturated water content decreased with time in a tilled cropping system. They also refer to work indicating that the  $\alpha$  parameter in the Van Genuchten (1980) water retention curve changes but the value of  $n$  related to pore size distribution does not. However, tilled systems likely represent transient behaviour brought about by management rather than a switch to an ASS.

Understanding i) the dynamics of environmental processes, ii) bio-physical feedbacks on soil, iii) the subsequent soil moisture state behaviour, and iv) impact on environmental processes, together represent a major challenge for modelling soil functions under future environmental change, as does the collection of data from long-term monitoring and manipulation experiments. The need for this new understanding is supported by recent calls to bring together biological and physical modelling of the soil system (Blagodatsky & Smith, 2012, Vereecken *et al.*, 2016). If ecosystems respond as we propose, it suggests a continued dynamic co-evolution of hydrological properties and processes mediated by bio-physical-soil feedbacks, driven by global environmental change.

Acknowledgements: David Robinson and Sabine Reinsch were supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCaPE programme delivering National Capability.

## References

- Alletto L, Pot V, Giuliano S, Costes M, Perdrieux F, Justes E (2015) Temporal variation in soil physical properties improves the water dynamics modeling in a conventionally-tilled soil. *Geoderma*, **243**, 18-28.
- Beisner BE, Haydon DT, Cuddington K (2003) Alternative stable states in ecology. *Frontiers in Ecology and the Environment*, **1**, 376-382.
- Berry EC (2018) Earthworms and other fauna in the soil. In: *Soil Biology*. pp Page., CRC Press.
- Bestelmeyer BT, Ellison AM, Fraser WR *et al.* (2011) Analysis of abrupt transitions in ecological systems. *Ecosphere*, **2**, 1-26.
- Blagodatsky S, Smith P (2012) Soil physics meets soil biology: towards better mechanistic prediction of greenhouse gas emissions from soil. *Soil Biology and Biochemistry*, **47**, 78-92.
- Bodner G, Leitner D, Kaul H-P (2014) Coarse and fine root plants affect pore size distributions differently. *Plant and Soil*, **380**, 133-151.
- Borgogno F, D'odorico P, Laio F, Ridolfi L (2007) Effect of rainfall interannual variability on the stability and resilience of dryland plant ecosystems. *Water resources research*, **43**.
- Cahoon DR, Perez BC, Segura BD, Lynch JC (2011) Elevation trends and shrink–swell response of wetland soils to flooding and drying. *Estuarine, Coastal and Shelf Science*, **91**, 463-474.
- Carpenter SR, Cole JJ, Pace ML *et al.* (2011) Early warnings of regime shifts: a whole-ecosystem experiment. *Science*, **332**, 1079-1082.
- D'odorico P, Caylor K, Okin GS, Scanlon TM (2007) On soil moisture–vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. *Journal of Geophysical Research: Biogeosciences*, **112**.
- Dai A, Trenberth KE, Qian T (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, **5**, 1117-1130.
- Dane J, Lenhard R (2005) Hysteresis. In: *Encyclopedia of Soils in the Environment*. pp Page.
- Daraghmeh O, Jensen JR, Petersen C (2008) Near-saturated hydraulic properties in the surface layer of a sandy loam soil under conventional and reduced tillage. *Soil Science Society of America Journal*, **72**, 1728-1737.
- Davidson EA, Belk E, Boone RD (1998) Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology*, **4**, 217-227.
- Debanò LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology*, **231**, 195-206.
- Dekker SC, Rietkerk M, Bierkens MF (2007) Coupling microscale vegetation–soil water and macroscale vegetation–precipitation feedbacks in semiarid ecosystems. *Global Change Biology*, **13**, 671-678.
- Doerr S, Shakesby R, Walsh R (2000) Soil water repellency: its causes, characteristics and hydrogeomorphological significance. *Earth-Science Reviews*, **51**, 33-65.
- Dorigo W, Gruber A, De Jeu R *et al.* (2015) Evaluation of the ESA CCI soil moisture product using ground-based observations. *Remote Sensing of Environment*, **162**, 380-395.
- Entekhabi D, Rodriguez-Iturbe I, Castelli F (1996) Mutual interaction of soil moisture state and atmospheric processes. *Journal of Hydrology*, **184**, 3-17.
- Evans SE, Wallenstein MD (2014) Climate change alters ecological strategies of soil bacteria. *Ecology letters*, **17**, 155-164.
- Filipović V, Weninger T, Filipović L, Schwen A, Bristow KL, Zechmeister-Boltenstern S, Leitner S (2018) Inverse estimation of soil hydraulic properties and water repellency following artificially induced drought stress. *Journal of Hydrology and Hydromechanics*, **66**, 170-180.
- Fischer C, Tischer J, Roscher C *et al.* (2015) Plant species diversity affects infiltration capacity in an experimental grassland through changes in soil properties. *Plant and Soil*, **397**, 1-16.

- Frank D, Reichstein M, Bahn M *et al.* (2015) Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. *Global Change Biology*, **21**, 2861-2880.
- Franz TE, King EG, Caylor KK, Robinson DA (2011) Coupling vegetation organization patterns to soil resource heterogeneity in a central Kenyan dryland using geophysical imagery. *Water resources research*, **47**.
- Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage research*, **66**, 197-205.
- Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Tank AK, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate research*, **19**, 193-212.
- Gcos (2010) Implementation plan for the Global Observing System for Climate in support of the UNFCCC.
- Goebel MO, Bachmann J, Reichstein M, Janssens IA, Guggenberger G (2011) Soil water repellency and its implications for organic matter decomposition—is there a link to extreme climatic events? *Global Change Biology*, **17**, 2640-2656.
- Green JK, Seneviratne SI, Berg AM, Findell KL, Hagemann S, Lawrence DM, Gentile P (2019) Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*, **565**, 476.
- Haines WB (1930) Studies in the physical properties of soil. V. The hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith. *The Journal of Agricultural Science*, **20**, 97-116.
- Hallett PD (2008) A brief overview of the causes, impacts and amelioration of soil water repellency—a review. *Soil and Water Research*, **3**, S21-S29.
- He M, Dijkstra FA (2014) Drought effect on plant nitrogen and phosphorus: a meta-analysis. *New Phytologist*, **204**, 924-931.
- Hirmas DR, Giménez D, Nemes A, Kerry R, Brunsell NA, Wilson CJ (2018) Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. *Nature*, **561**, 100.
- Holling CS (1973) Resilience and stability of ecological systems. *Annual review of ecology and systematics*, **4**, 1-23.
- Homyak PM, Allison SD, Huxman TE, Goulden ML, Treseder KK (2017) Effects of Drought Manipulation on Soil Nitrogen Cycling: A Meta-Analysis. *Journal of Geophysical Research: Biogeosciences*, **122**, 3260-3272.
- Horn R (2004) Time dependence of soil mechanical properties and pore functions for arable soils. *Soil Science Society of America Journal*, **68**, 1131-1137.
- Hudson J (1988) The contribution of soil moisture storage to the water balances of upland forested and grassland catchments. *Hydrological sciences journal*, **33**, 289-309.
- Jarvis N, Forkman J, Koestel J, Kätterer T, Larsbo M, Taylor A (2017) Long-term effects of grass-clover leys on the structure of a silt loam soil in a cold climate. *Agriculture, Ecosystems & Environment*, **247**, 319-328.
- Jarvis N, Koestel J, Larsbo M (2016) Understanding preferential flow in the vadose zone: Recent advances and future prospects. *Vadose Zone Journal*, **15**.
- Jarvis N, Koestel J, Messing I, Moeys J, Lindahl A (2013) Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrology and Earth System Sciences*, **17**, 5185-5195.
- Keiluweit M, Wanzek T, Kleber M, Nico P, Fendorf S (2017) Anaerobic microsites have an unaccounted role in soil carbon stabilization. *Nature communications*, **8**, 1771.
- Koestel J, Schlüter S (2019) Quantification of the structure evolution in a garden soil over the course of two years. *Geoderma*, **338**, 597-609.
- Koster RD, Dirmeyer PA, Guo Z *et al.* (2004) Regions of strong coupling between soil moisture and precipitation. *Science*, **305**, 1138-1140.
- Lewontin R (1969) The meaning of stability. paper presented at Brookhaven symposia in biology.

- Logsdon SD (2012) Temporal variability of bulk density and soil water at selected field sites. *Soil Science*, **177**, 327-331.
- Manzoni S, Schimel JP, Porporato A (2012) Responses of soil microbial communities to water stress: results from a meta-analysis. *Ecology*, **93**, 930-938.
- Messing I, Jarvis N (1993) Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. *Journal of Soil Science*, **44**, 11-24.
- Moret D, Arrúe J (2007) Dynamics of soil hydraulic properties during fallow as affected by tillage. *Soil and Tillage research*, **96**, 103-113.
- Or D, Ghezzehei TA (2002) Modeling post-tillage soil structural dynamics: a review. *Soil and Tillage research*, **64**, 41-59.
- Orchard VA, Cook F (1983) Relationship between soil respiration and soil moisture. *Soil Biology and Biochemistry*, **15**, 447-453.
- Petraitis P (2013) *Multiple stable states in natural ecosystems*, OUP Oxford.
- Quéré D (2008) Wetting and roughness. *Annu. Rev. Mater. Res.*, **38**, 71-99.
- Rabbi SM, Tighe MK, Flavel RJ, Kaiser BN, Guppy CN, Zhang X, Young IM (2018) Plant roots redesign the rhizosphere to alter the three-dimensional physical architecture and water dynamics. *New Phytologist*.
- Ramírez BH, Van Der Ploeg M, Teuling AJ, Ganzeveld L, Leemans R (2017) Tropical Montane Cloud Forests in the Orinoco river basin: The role of soil organic layers in water storage and release. *Geoderma*, **298**, 14-26.
- Rasmijn L, Schrier G, Bintanja R, Barkmeijer J, Sterl A, Hazeleger W (2018) Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints. *Nature Climate Change*, **8**, 381.
- Rawls WJ, Nemes A, Pachepsky Y (2004) Effect of soil organic carbon on soil hydraulic properties. *Developments in soil Science*, **30**, 95-114.
- Reinsch S, Koller E, Sowerby A *et al.* (2017) Shrubland primary production and soil respiration diverge along European climate gradient. *Scientific reports*, **7**, 43952.
- Rietkerk M, Boerlijst MC, Van Langevelde F *et al.* (2002) Self-organization of vegetation in arid ecosystems. *The American Naturalist*, **160**, 524-530.
- Rietkerk M, Dekker SC, De Ruiter PC, Van De Koppel J (2004) Self-organized patchiness and catastrophic shifts in ecosystems. *Science*, **305**, 1926-1929.
- Ritsema CJ, Dekker LW, Nieber JL, Steenhuis TS (1998) Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. *Water resources research*, **34**, 555-567.
- Robinson D, Campbell C, Hopmans J *et al.* (2008) Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. *Vadose Zone Journal*, **7**, 358-389.
- Robinson DA, Jones SB, Lebron I *et al.* (2016) Experimental evidence for drought induced alternative stable states of soil moisture. *Scientific reports*, **6**, 20018.
- Robinson DA, Lebron I, Ryel RJ, Jones SB (2010) Soil water repellency: A method of soil moisture sequestration in pinyon–juniper woodland. *Soil Science Society of America Journal*, **74**, 624-634.
- Scheffer M, Carpenter SR, Lenton TM *et al.* (2012) Anticipating critical transitions. *Science*, **338**, 344-348.
- Schröder A, Persson L, De Roos AM (2005) Direct experimental evidence for alternative stable states: a review. *Oikos*, **110**, 3-19.
- Schwen A, Bodner G, Scholl P, Buchan GD, Loiskandl W (2011) Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. *Soil and Tillage research*, **113**, 89-98.
- Seneviratne SI, Corti T, Davin EL *et al.* (2010) Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99**, 125-161.



- Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land–atmosphere coupling and climate change in Europe. *Nature*, **443**, 205.
- Sheffield J, Wood EF (2008) Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate*, **21**, 432-458.
- Šimůnek J, Van Genuchten MT, Šejna M (2008) Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal*, **7**, 587-600.
- Skopp J, Jawson M, Doran J (1990) Steady-state aerobic microbial activity as a function of soil water content. *Soil Science Society of America Journal*, **54**, 1619-1625.
- Smettem KR (1992) The relation of earthworms to soil hydraulic properties. *Soil Biology and Biochemistry*, **24**, 1539-1543.
- Stacy PK, Comrie AC, Yool SR (2012) Modeling valley fever incidence in Arizona using a satellite-derived soil moisture proxy. *GIScience & remote sensing*, **49**, 299-316.
- Stoof CR, Wesseling JG, Ritsema CJ (2010) Effects of fire and ash on soil water retention. *Geoderma*, **159**, 276-285.
- Strudley MW, Green TR, Ascough II JC (2008) Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil and Tillage research*, **99**, 4-48.
- Swanson DK, Grigal DF (1988) A simulation model of mire patterning. *Oikos*, 309-314.
- Taylor CM, Gounou A, Guichard F, Harris PP, Ellis RJ, Couvreur F, De Kauwe M (2011) Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. *Nature Geoscience*, **4**, 430.
- Te Brake B, Van Der Ploeg M, De Rooij G (2013) Water storage change estimation from in situ shrinkage measurements of clay soils. *Hydrology and Earth System Sciences*, **17**, 1933-1949.
- Thornton PK, Ericksen PJ, Herrero M, Challinor AJ (2014) Climate variability and vulnerability to climate change: a review. *Global Change Biology*, **20**, 3313-3328.
- Unestam T (1991) Water repellency, mat formation, and leaf-stimulated growth of some ectomycorrhizal fungi. *Mycorrhiza*, **1**, 13-20.
- Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil Science Society of America Journal*, **44**, 892-898.
- Van Mantgem PJ, Stephenson NL, Byrne JC *et al.* (2009) Widespread increase of tree mortality rates in the western United States. *Science*, **323**, 521-524.
- Van Nes EH, Scheffer M (2007) Slow recovery from perturbations as a generic indicator of a nearby catastrophic shift. *The American Naturalist*, **169**, 738-747.
- Veneman P, Spokas L, Lindbo D (1998) Soil moisture and redoximorphic features: a historical perspective. *Quantifying soil hydromorphology*, 1-23.
- Vereecken H, Huisman J, Bogaen H, Vanderborght J, Vrugt J, Hopmans J (2008) On the value of soil moisture measurements in vadose zone hydrology: A review. *Water resources research*, **44**.
- Vereecken H, Schnepf A, Hopmans JW *et al.* (2016) Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal*, **15**.
- Vicca S, Bahn M, Estiarte M *et al.* (2014) Can current moisture responses predict soil CO<sub>2</sub> efflux under altered precipitation regimes? A synthesis of manipulation experiments. *Biogeosciences*, **11**, 3307-3308.
- Weninger T, Filipović V, Mešić M, Clothier B, Filipović L (2019) Estimating the extent of fire induced soil water repellency in Mediterranean environment. *Geoderma*, **338**, 187-196.
- Wessels JG (1993) Tansley Review No. 45 Wall growth, protein excretion and morphogenesis in fungi. *New Phytologist*, **123**, 397-413.
- Westerling AL, Gershunov A, Brown TJ, Cayan DR, Dettinger MD (2003) Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society*, **84**, 595-604.
- Wood SW, Bowman DM (2012) Alternative stable states and the role of fire–vegetation–soil feedbacks in the temperate wilderness of southwest Tasmania. *Landscape Ecology*, **27**, 13-28.



Wu Z, Dijkstra P, Koch GW, Peñuelas J, Hungate BA (2011) Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. *Global Change Biology*, **17**, 927-942.

Yang F, Zhang G-L, Yang J-L *et al.* (2014) Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes. *Journal of Hydrology*, **519**, 3086-3093.

Zeng Q-C, Zeng X-D (1996) An analytical dynamic model of grass field ecosystem with two variables. *Ecological Modelling*, **85**, 187-196.

Zeng X, Shen SS, Zeng X, Dickinson RE (2004) Multiple equilibrium states and the abrupt transitions in a dynamical system of soil water interacting with vegetation. *Geophysical Research Letters*, **31**.

Figure 1. Successive numerical simulations (from top to bottom) of infiltration and subsequent water redistribution: left hand side in hydrophobic soil and right hand side in none hydrophobic bare soil using Hydrus 2D (Šimůnek *et al.*, 2008). The water infiltrates deeper in the soil profile in the hydrophobic soil forming wet bulbs. The reduced connectivity with the surface makes the water less likely to evaporate.

Figure 2. Soil moisture data (points) and Hydrus 1D modelling output (lines) for a soil moisture state shift (01/01/2004) at the Clocaenog (UK) long-term climate change experiment. The grey and black lines use three soil horizons, where the hydraulic conductivity of the  $O_h$  horizon is adjusted to 1 cm day<sup>-1</sup> for the first 3 years, and 10 cm day<sup>-1</sup> after that reflecting an order of magnitude increase in hydraulic conductivity following drought that caused cracking of the  $O_h$  horizon.

Figure 3. Soil moisture deficits measured on Peat and Podzol under different land uses at the long-term field site Y Foel (Neutron probe tubes 35-38) in Plynlimon, UK. A) The peat dries during the drought year of 1976 (pink bar) but recovers to its winter soil moisture values within a few years, the drying is greatest under the forest (black) and the recovery slower than under rough grass (red). B) The podzol on the other hand is not impacted by the same drought under the rough grass/heather/seedlings but appears to show an ASS under the forest which never returns to its original soil moisture state.

Figure 4. Conceptual model of soil moisture processes in response to increasingly drier summers. A) is characteristic matrix flow in non-hydrophobic soils, B) droughts may cause increased macroporosity and saturation resulting in excess infiltration that causes preferential flow, C) further drying induces feedback from plants (root exudates) and microbes producing hydrophobic compounds that allow for unsaturated preferential flow in cracks or biopores, as modelled in Figure 2.

Figure 5. Schematic view of both current modelling of soil hydraulic function (grey) and the proposed future direction that incorporates dynamic, time varying soil hydraulic parameters that result in ecosystem feedbacks (orange).





