



Plant Effective Conductance Fails to Predict Soil–Plant Hydraulics in Sandy Soils

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Abstract. Atmospheric and soil dryness impose increasing limitations in the hydraulic pathway of the soil–plant–atmosphere continuum (SPAC), leading to a decrease in the hydraulic conductivity of many elements, such as soil, soil–root interface, xylem, and leaves. Many SPAC models simplify the flow through this series of hydraulic conductances to a single effective conductance that varies as a function of the xylem water potential. This effective conductance is expected to implicitly account for soil characteristics, including soil texture-specific hydraulic limitations. However, it is unclear whether such an approach can properly reproduce the non-linear effects of soil texture-specific conductivities. This paper aims to explore under what conditions reducing the SPAC to a function of internal plant water status accurately captures the relation between transpiration rate and leaf and soil water potential, and when larger model complexity is required. For this purpose, a plant-only model, where the conductances along the SPAC solely depend on plant water potential, was compared to a more detailed model incorporating the hydraulics of varying soils. We demonstrate that the former simplification works well in fine-grained soils, such as clay and silt loam, but fails in more coarse-textured soils like sandy loam, where the pronounced non-linearity of its hydraulic functions requires explicit description. Additionally, a sensitivity analysis of key parameters within the full SPAC model reveals that the soil hydraulic properties have a significantly stronger impact on plant transpiration in sandy soils, as opposed to finer soils, where internal plant traits are more influential on plant–water relations.

1 Introduction

Water flow in the soil–plant–atmosphere continuum (SPAC) is driven by transpiration, which maintains a continuous water column from the soil to the leaves and is influenced by both internal (e.g., plant traits) and external factors such as light intensity, atmospheric humidity, temperature, and available soil water (Kochhar and Gujral, 2020). When plants transpire, the water potential in the leaves decreases, generating a suction in the xylem that propagates down to the roots. The reduced water potential on the root’s surface induces a pressure difference with the bulk soil, which causes the water in the soil to move to the roots. The water potential gradient across all components in the SPAC is the driving force of water flow.

Water flow through the plant from the soil to the atmosphere is mediated by the hydraulic conductance K , the ratio of water flux to water potential difference (Hunt et al., 1991). It is a function of the prevailing water potential and is the inverse of the hydraulic resistance, $K = \frac{1}{R}$. K describes how easily water can flow through the material. Many subdivisions of the pathway are possible; for example, plant resistance can be subdivided into root, stem, and leaf resistance. Eventually, the



overall conductance of the system is primarily dominated by the weakest element with the largest loss of conductance or the highest gain in resistance along the pathway, which depends on factors such as soil type, xylem vulnerability, and root length (Wankmüller et al., 2024).

As the soil and atmosphere in the plant's environment become drier, the soil's hydraulic resistance increases, making it more difficult for water to flow to the roots (Cai et al., 2022; Nimmo, 2009). Additionally, the plant's transpiration rate and water demand increase. This will put stress on the plant's vascular transport tissue due to a higher tension in the water column connecting the roots, stem, and leaves (Choat et al., 2018). With intensified drought, embolisms can occur – a sudden phase change from liquid water to gas that damages xylem conductivity, reducing its ability to transport water and limiting water movement (Tyree and Sperry, 1989; Choat et al., 2018; Lei et al., 2026). Choat et al. (2018) showed that stomatal conductance declines well before substantial xylem cavitation occurs to prevent further water loss at the leaf level and reduce the risk of hydraulic failure.

Currently, it remains unclear whether limitations in the plant hydraulic pathway or constraints imposed by the soil are the trigger for stomatal closure. The decline in plant transpiration was mainly associated with an increase in the hydraulic resistance of internal plant traits, particularly through xylem vulnerability (Sperry and Love, 2015; Anderegg et al., 2017). Stomata regulate the trade-off between meeting water demand and maximising photosynthetic carbon gain, while minimising the risk of xylem damage (Tyree and Sperry, 1989). Accordingly, stomatal closure is triggered by a decrease in leaf water potential (Wolf et al., 2016; Brodribb et al., 2017). However, it is not clear how to describe the conductivities that cause the leaf water potential to drop. Recent studies suggest that soil hydraulic properties, such as soil texture, strongly influence stomatal behaviour, especially when soil starts to be limiting, rather than internal plant damage (Rodriguez-Dominguez and Brodribb, 2020; Carminati and Javaux, 2020; Wankmüller et al., 2024; Di Bert et al., 2026). Soils with larger sand fractions, which have a steeply declining hydraulic conductivity curve, are characterised by a steeper, more drastic drop in soil water potential towards the roots. At a critical bulk soil water potential, soil resistance surpasses plant resistance, and the soil becomes the dominant factor limiting plant transpiration (Koehler et al., 2023). Consequently, the bulk soil water potential at which plant stress occurs and where plants transition from plant to soil limitation depends largely on soil texture: plants growing in sandy soils become soil-limited at a higher (less negative) water potential compared to soils with lower sand fractions, where plants maintain transpiration for longer (Koehler et al., 2022; Wankmüller et al., 2024). To qualitatively describe the limitation of plant transpiration E by bulk soil water potential $\psi_{s,b}$ and leaf water potential ψ_{leaf} , the Stress Onset Limit (SOL) framework was introduced by Carminati and Javaux (2020). The SOL illustrates a boundary on the $E(\psi_{s,b}, \psi_{leaf})$ surface, where plants transition from a linear transpiration zone with constant hydraulic constraints to a non-linear transpiration region with increased hydraulic resistance either in the xylem or the roots' vicinity. Carminati and Javaux (2020) suggested that this is the point where plants start to experience hydraulic stress and therefore close stomata to reduce transpiration.

Despite growing evidence that soil properties play a crucial role in transpiration modelling, many SPAC models still represent water flow using a single effective hydraulic conductance K_{eff} (Sperry et al., 2017; Anderegg et al., 2018; Sabot et al., 2020; Joshi et al., 2022). In these models, K_{eff} typically decreases in response to a reduction in xylem water potential. For instance, Anderegg et al. (2018) infers water flow through the plant, from the soil to the leaves, from the xylem conductance function

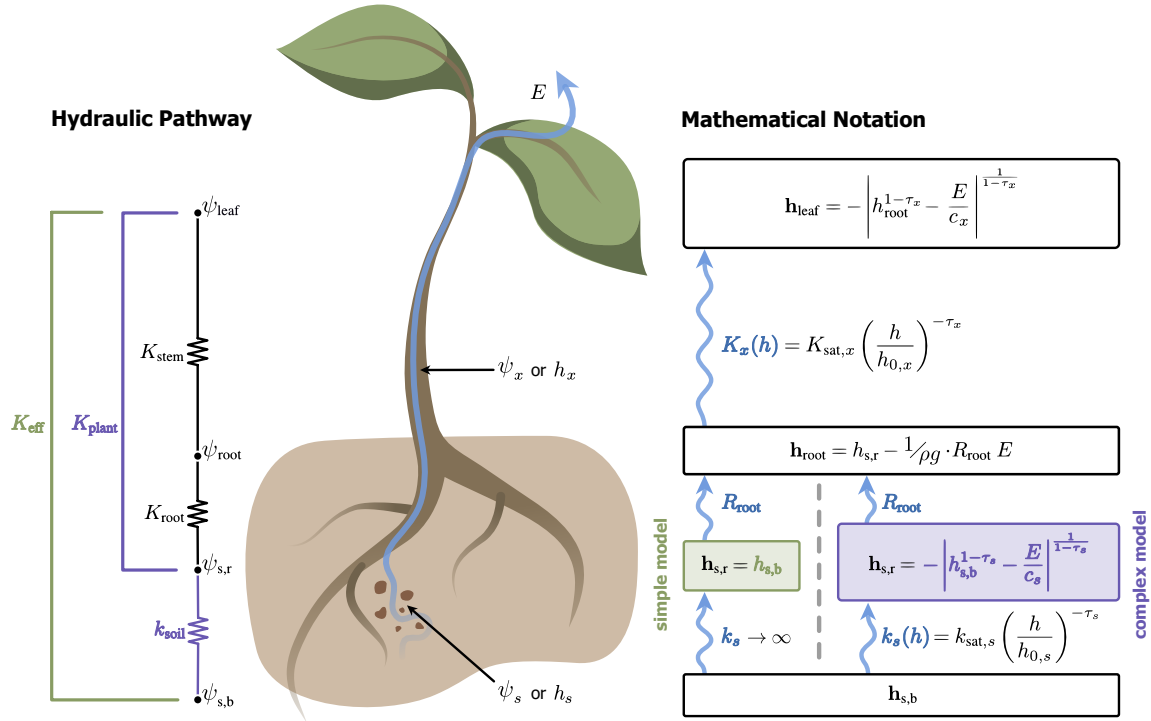


Figure 1. Comparison of hydraulic pathway and mathematical notation of two soil–plant hydraulic models. Water flows (blue arrows) through the soil with variable water potential and a specific soil texture to the roots, where it is taken up by plant roots. From there, water travels up through the stem to the leaves, until it evaporates through stomata into the atmosphere at a transpiration rate E . The flow is described using two models with different complexities, which are characterised as a series of resistances. The simple model (plant-only conductance model depicted in green) ignores the soil-specific hydraulic conductivity and is only expressed with a plant effective conductance K_{eff} directly connecting the tension in the bulk soil $\psi_{s,b}$ to the leaves ψ_{leaf} . The complex model describing the full SPAC (purple pathway) includes soil conductivity in series with plant conductance, where the latter is subdivided into root and stem conductance. The water flows from the bulk soil $h_{s,b}$ to the root surface water potential $h_{s,r}$, transmitted by the soil conductivity, $k_{soil} \equiv k_s$, further up the plant with conductance K_{plant} into the leaves, where it evaporates with transpiration rate E . Both K_{eff} and K_{plant} in the two model setups are considered to be a series of root conductance $K_{root} = 1/R_{root}$ and xylem conductance as a function of stem xylem water pressure head $K_x(h)$, where $K_{sat,x} = K_{root}$. The simple model (green) omits soil hydraulics by setting $h_{s,r} = h_{s,b}$, resulting from an infinite soil hydraulic conductivity $k_s \rightarrow \infty$. The complex model (purple) incorporates soil-specific hydraulic properties, where k_{soil} depends on h , $k_{soil} \equiv k_s(h)$. The variable c_s in the equation of $h_{s,r}$ stems from the equation of flow in unsaturated soils and is proportional to the root length, $c_s \propto L_{root}$. For convenience, the pressure head h was used in the calculations, and it only differs by a constant from the water potential ψ . A more detailed mathematical description can be found in Sect. 2.



K_x , driven by water loss through transpiration, but does not explicitly incorporate the strong decline in hydraulic conductivity during soil drying. Similarly, Sabot et al. (2020) represents the water pathway by a single effective segment where the model parameters explicitly depend on properties of the entire plant but not on those of the surrounding soil. As a result, these models generally neglect the non-linear effects of soil hydraulic conductivity losses on transpiration. It remains unclear whether a series of non-linear conductances across the SPAC, such as those found in soils, can be successfully replaced by a uniform or effective soil–plant conductance without losing predictive accuracy.

A second challenge concerns the appropriate level of model complexity. Simplifying model complexity can decrease computational demands, whereas more extensive plant hydraulic models can also introduce more uncertainty through poorly described hydraulic parameters like xylem vulnerability curves and root hydraulic traits (Yang et al., 2025; Paschalis et al., 2020; Feng, 2020). Determining the necessary conditions in which a given level of model complexity is sufficient remains an ongoing task. Existing model comparison studies have largely focused on alternative representations of plant hydraulic parametrisations while neglecting how soil texture influences the appropriate level of model complexity (Sloan et al., 2021; Yang et al., 2025).

Our work addresses both of these knowledge gaps by investigating the consequences of neglecting soil hydraulic conductivity variations in plant transpiration modelling and by evaluating model complexity from a soil hydraulic perspective. Specifically, we compared two hydraulic models (see Fig. 1): one that includes a detailed description of soil and plant hydraulic properties along the SPAC (purple) and one that omits soil characteristics by representing water flow solely with an effective plant hydraulic conductance (green). Subsequently, by conducting a sensitivity analysis (SA), the impact of key parameters within the full SPAC model on the model’s outcome – and thus plant–water relations – will be analysed as a function of soil type. Together, these analyses assess under which soil conditions the plant-only conductance model is sufficient and when the full description of the SPAC is necessary to accurately describe plant–water relations by investigating how soil texture shapes plant–water relations. We hypothesise that the simple, plant-only model can capture plant hydraulics only when the soil is not limiting, such as in wet and fine-grained (i.e. clayey) soils. However, in sandy and dry soils, a model incorporating soil characteristics is necessary to correctly describe plant–water relations.

2 Methods

2.1 Model description

We used the single-root, single-leaf hydraulic model described in Carminati and Javaux (2020). This section briefly describes the model approach and the most important equations implemented. For more details, please refer to Carminati and Javaux (2020).

The calculations were conducted expressing the tension experienced in hydraulic pathways in pressure head h (cm) to follow the typical notation of soil physics. The discussion, on the other hand, was written using the concept of water potential ψ (MPa) to keep consistency with the terms used in plant physiology. An overview of the most important terms and abbreviations can be found in Table 1.



Table 1. Summary of variables used in the paper. Note that the water potential ψ and water pressure head h can easily be converted using $\psi = \rho g \cdot h$, where ρ is the water or sap density and g is the gravitational acceleration.

Variable	Description	Units
$q(r)$	Water flux; function of radial distance r to root axis	cm s^{-1}
E	Actual transpiration rate	$\text{cm}^3 \text{s}^{-1}$
$E_{\max}$	Maximal transpiration rate	$\text{cm}^3 \text{s}^{-1}$
$E_{\min}$	Minimal transpiration rate	$\text{cm}^3 \text{s}^{-1}$
$E_{\text{rel}} = E/E_{\max}$	Relative or normalised transpiration rate	–
$\psi_{s,b}$	Bulk soil water potential	MPa
$\psi_{s,r}$	Soil–root interface water potential	MPa
ψ_{leaf}	Leaf water potential	MPa
$h_{s,b}$	Bulk soil water pressure head	cm
$h_{s,r}$	Soil–root interface water pressure head	cm
h_{leaf}	Leaf water pressure head	cm
R_{root}	Single-root hydraulic resistance; inverse of K_{root}	$\text{hPa cm}^{-3} \text{s}$
$k_{\text{soil}} \equiv k_s(h)$	Soil hydraulic conductivity	cm s^{-1}
$K_x(h)$	Xylem hydraulic conductance	$\text{cm}^3 \text{s}^{-1} \text{hPa}^{-1}$
K_{root}	Single-root hydraulic conductance; inverse of R_{root}	$\text{cm}^3 \text{s}^{-1} \text{hPa}^{-1}$
$K_{\text{sat},s}$	Soil saturated hydraulic conductance	$\text{cm}^3 \text{s}^{-1} \text{hPa}^{-1}$
$K_{\text{sat},x}$	Xylem saturated hydraulic conductance; assumed equal to K_{root}	$\text{cm}^3 \text{s}^{-1} \text{hPa}^{-1}$
$h_{0,s}$	Soil air-entry water pressure head	cm
$h_{0,x}$	Xylem air-entry water pressure head	cm
τ_s	Soil Brooks–Corey exponent	–
τ_x	Xylem Brooks–Corey exponent	–
L_{root}	Effective root length active in water uptake; single-root approach	cm

Water flow is modelled using a series of resistances, or rather conductivities. The SPAC is composed of flow from the bulk soil to the soil–roots interface and from the roots through the xylem into the leaves, where water evaporates into the atmosphere.

95 In both the soil and the xylem, the hydraulic conductivity $k(h)$ depends on the water pressure head h and is described by the semi-empirical Brooks–Corey model (Van Genuchten, 1980).

$$k(h) = k_{\text{sat}} \left(\frac{h}{h_0} \right)^{-\tau} \quad (1)$$



The saturated hydraulic conductivity k_{sat} describes the hydraulic conductivity in the fully saturated medium, and h_0 is the air-entry pressure head. The empirical coefficient τ (–) represents a dimensionless parameter that depends on the water transport medium. In soils, it is related to pore-size distribution (Brooks and Corey, 1964), whereas in the xylem, it includes xylem sensitivity (Tyree and Sperry, 1989). Generally, in the soil, the decline in hydraulic conductivity with soil drying is steeper with larger sand fractions, and it begins at less negative water potentials compared to finer-textured soils (Wankmüller et al., 2024).

Starting in the soil, water flow is described using the Richards equation based on conservation of mass (Richards, 1931)

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r k(h) \frac{\partial h}{\partial r} \right] = -\frac{q}{r} - \frac{\partial q}{\partial r} \quad (2)$$

with the volumetric water content θ ($\text{m}^3 \text{m}^{-3}$), water head h (m), hydraulic conductivity $k(h)$ (m s^{-1}) as a function of pressure head h , radial coordinate r (m), and Darcy's flow $q = -k(h) \frac{\partial h}{\partial z}$ along a path segment ∂z . The Richards equation can be linearised using the matric flux potential Φ (cf. Schröder et al., 2008; Carminati and Javaux, 2020)

$$\Phi_i = \int_{-\infty}^{h_i} k(x) dx \quad (3)$$

where h_i is the current pressure head. The matric flux potential Φ combines the two flow-defining parameters – hydraulic conductivity and water potential – into a single parameter (Shaykewich and Stroosnijder, 1977).

When the flow at the outer radius is assumed to be zero, $q(r = r_b) = 0$, and the uptake at the soil–root interface is considered to be uniform, $q(r = r_0) = \frac{E}{2\pi r_0 L_{\text{root}}}$, the solution of Φ_i to Eq. (2) can be used to calculate the matrix flux potential at the soil–root interface

$$\Phi_{s,r} = -\frac{E}{2\pi r_0 L_{\text{root}}} \left(\frac{r_0}{2} - r_0 r_b^2 \frac{\ln(r_b/r_0)}{r_b^2 - r_0^2} \right) + \Phi_{s,b} \quad (4)$$

with r_b being the bulk soil radius, where the bulk soil matric flux potential $\Phi_{s,b}$ and the bulk soil pressure head $h_{s,b}$ are defined, r_0 is the root mean radius. Equation (4) describes the water flow from the bulk soil to the roots (i.e., a single root), where the water is transported through the xylem up to the leaves (i.e., a single leaf). Using Eq. (1), the pressure head at the root–soil interface $h_{s,r}$ at a given transpiration demand E and prevailing bulk soil pressure head $h_{s,b}$ can be calculated (Carminati and Javaux, 2020).

$$h_{s,r} = - \left| h_{s,b}^{1-\tau_s} - \frac{E}{c_s} \right|^{\frac{1}{1-\tau_s}}, \quad \text{with } c_s \propto \frac{L_{\text{root}} \cdot k_{\text{sat},s}}{h_{0,s}^{-\tau_s}} \quad (5)$$

τ_s is the Brooks–Corey parameter describing how soil hydraulic conductivity changes with water pressure head. c_s is a parameter incorporating water flow in unsaturated soil (see Eq. (4)) and is proportional to single root length L_{root} . The water propagates from the soil–root interface into the plant's vascular transport system, mitigated by the xylem hydraulic conductance of the root $K_{\text{root}} = \frac{1}{R_{\text{root}}}$ as described by the Couvreur model (Couvreur et al., 2012).

$$h_{\text{root}} = h_{s,r} - \frac{1}{\rho g} \cdot R_{\text{root}} \cdot E \quad (6)$$



The Couvreur model is formulated using water potentials ψ . Hence, a conversion factor of ρg is added.

Acknowledging that the conductivity along the xylem can decline with increasingly negative potentials, using the xylem vulnerability curve from Eq. (1), we can finally express the leaf water head as a function of transpiration demand E and soil water head $h_{s,b}$

$$h_{\text{leaf}} = - \left| h_{\text{root}}^{1-\tau_x} - \frac{E}{c_x} \right|^{\frac{1}{1-\tau_x}}, \quad \text{with } c_x = \frac{K_{\text{sat},x}}{1-\tau_x} \cdot h_{0,x} \quad (7)$$

with the saturated xylem hydraulic conductance $K_{\text{sat},x}$ (assumed to be equal to K_{root} , meaning that K_x would be larger than K_{root} for h_{leaf} less negative than $h_{0,x}$) and the xylem Brooks–Corey coefficient τ_x .

The model connects the transpiration demand E , bulk soil water potential $\psi_{s,b}$, and leaf water potential ψ_{leaf} . It results in a three-dimensional surface in the $(\psi_{s,b}, \psi_{\text{leaf}}, E)$ space, which describes the hydraulic states the plant can attain physically. However, plants operate (or ‘surf’) on this three-dimensional surface, avoiding unfavourable hydraulic conditions, that is, the strong hydraulic non-linearities under high transpiration and in dry soil (Carminati and Javaux, 2020). To delineate these non-linearities and to better compare the different model outputs, we compute the SOL. It is defined as the boundary where the gradient of $E(\psi_{s,b}, \psi_{\text{leaf}})$ at constant bulk soil water potential $\psi_{s,b}$, $\left. \frac{\partial E(\psi_{s,b}, \psi_{\text{leaf}})}{\partial \psi_{\text{leaf}}} \right|_{\psi_{s,b}=\text{const.}}$, reaches 70% of its maximum value (Carminati and Javaux, 2020).

2.1.1 Setup of the two compared soil–plant hydraulic models

Two model configurations were used to describe water flow in the soil–plant–atmosphere continuum (SPAC): A comprehensive SPAC model (referred to as *complex model*, adopted from Carminati and Javaux (2020)) and a simplified plant-only model (denoted *simple model*, modified version of the complex model). For both models, steady-state transpiration was assumed, which means that water supply equals water loss, and therefore plant capacitance was neglected (Carminati and Javaux, 2020).

- The **complex model** includes both soil conductivity k_{soil} and plant conductance K_{plant} (see purple pathway in Fig. 1). The water flow equations were solved separately for each SPAC component and coupled to represent the hydraulic pathway from soil to leaves. Soil-specific model parameters were specified for three different soil types – clay, silt loam, and sandy loam – to cover a broad range of soil textures (see Table 3 for detailed values). The plant parameters were held constant for all soil types (see Table 2 for detailed values), except when performing the SA (more details in Sect. 2.3), to isolate the effect of soil properties on the model behaviour. The model output was analysed using the SOL defined above, representing a plant stress boundary on the three-dimensional $(\psi_{s,b}, \psi_{\text{leaf}}, E)$ surface.
- The **simple model** was obtained by removing soil-specific hydraulics in the complex model. The root surface water pressure head is set equal to the bulk soil water pressure head, $h_{s,r} = h_{s,b}$, which eliminates the soil’s resistances by letting the soil hydraulic conductivity approach infinity $k_s \rightarrow \infty$ (see green pathway in Fig. 1). All other parameters in the model remained unchanged.

To compare the two approaches, the simple model will be fit to the transpiration SOL curves generated by the complex model for each soil type. This allows us to evaluate in which soil type it is possible to describe plant transpiration without using



a full description of belowground hydraulics. This comparison treats the full SPAC model as the ground truth to isolate and
160 assess the role of soil texture in plant transpiration modelling.

2.1.2 Model parametrisation

The plant hydraulic pathway was parametrised by the root resistance R_{root} , the xylem air-entry water head $h_{0,x}$, the saturated
hydraulic conductance in the xylem $K_{\text{sat},x}$, and the xylem Brooks–Corey parameter τ_x . The soil-to-root pathway was described
by the root length L_{root} and the root radius r_0 . The saturated hydraulic conductance is set to be the inverse of the root resistance,
165 $K_{\text{sat},x} = \frac{1}{R_{\text{root}}}$, and is therefore not treated as an independent parameter. The root resistance R_{root} determines the slope of
 $E(\psi_{\text{leaf}})$ at a constant $\psi_{s,b}$ in wet soils (the slope of the $\psi_{s,b}$ iso-lines in Fig. 2a). The xylem air-entry water head $h_{0,x}$ dictates
the onset of the SOL drop in wet soils, i.e. when hydraulic conductance starts to decline due to more negative water potentials
and the plant enters stress regime. The Brooks–Corey parameter for the xylem hydraulic conductance τ_x controls how fast
transpiration declines with decreasing (more negative) water potentials along the pathway and therefore how steeply the SOL
170 drops from maximal transpiration ($E_{\text{rel}} = 1$). An infinite τ_x represents a plant that experiences total loss in plant hydraulic
conductance at a specific leaf water potential. Additionally, τ_x also partially influences when the SOL starts to drop, i.e. a larger
 τ_x will shift the onset of the SOL drop to a more negative ψ_{leaf} . In general, plant hydraulic constraints like xylem embolism
determine the shape of $E(\psi_{s,b}, \psi_{\text{leaf}})$ in wet conditions with large transpiration rates, whereas soil resistances influence it under
dry conditions (Carminati and Javaux, 2020). To more effectively compare the soil texture’s influence, the plant parameters to
175 compute transpiration in Eq. (5 - 7) were kept constant across all soils during the optimisation part (see Table 2).

Table 2. Detailed values for plant hydraulic conductivity modelling. Note that for E_{max} , L_{root} , r_0 , and $R_{\text{root}} = 1/K_{\text{root}}$, their relative
dependencies rather than their absolute values dictate the model results. The maximum plant conductance (in our case, the root conductance)
and maximum transpiration rate were set to fulfil $\psi_{\text{leaf,max}} = E_{\text{max}}/K_{\text{root}} \approx -1$ MPa in well-watered conditions ($\psi_{s,b} = 0$ MPa) (Mencuc-
cini, 2003). The root length was set to obtain a reasonable root surface hydraulic conductivity using $k_{s,r} = K_{\text{root}}/A_{\text{root}} \approx 10^{-8} \text{ m s}^{-1} \text{ MPa}^{-1}$
(Draye et al., 2010). The remaining parameters were set to default values (Carminati and Javaux, 2020).

Parameter	Description	Value	Unit
L_{root}	Active Root Length	30000	cm
r_0	Root radius	0.05	cm
R_{root}	Root Hydraulic Resistance	$1.2 \cdot 10^6$	$\text{hPa cm}^{-3} \text{ s}$
$h_{0,x}$	Xylem Air-Entry Water Pressure Head	$-2.5 \cdot 10^4$	cm
τ_x	Brooks–Corey coefficient	5	–
E_{max}	Maximal Transpiration Rate	$9 \cdot 10^{-3}$	$\text{cm}^3 \text{ s}^{-1}$

The soil hydraulic pathway in the complex model was parametrised using the soil air-entry water head $h_{0,s}$, the soil saturated
hydraulic conductivity $k_{\text{sat},s}$, and the soil Brooks–Corey coefficient τ_s . The soil-specific values used to compute Eq. (7) of the
complex model are shown in Table 3. The bulk soil radius r_b is a function of L_{root} to keep the cylindrical root soil volume



Table 3. Detailed values for soil hydraulic conductivity modelling. The parameter values of the air-entry water pressure head $h_{0,s}$, saturated soil hydraulic conductivity $s_{sat,s}$, and Brooks–Corey coefficient τ_s are the basis for the Brooks–Corey conductivity in Eq. (1) and were chosen from W. J. Rawls et al. (1982).

Soil Textural Class	$h_{0,s}$ (cm)	$k_{sat,s}$ (cm s ⁻¹)	τ_s (-)
Clay	-37.31	$1.667 \cdot 10^{-5}$	2.393
Silt Loam	-20.75	$1.889 \cdot 10^{-4}$	2.633
Sandy Loam	-14.66	$7.194 \cdot 10^{-4}$	2.966

constant, i.e. $r_b = \sqrt{\frac{V_{root}}{\pi L}}$, where $V_{root} = \pi L_0 r_{0,b}^2$ with $L_0 = 3000$ cm and $r_{b,0} = 1$ cm. The values of $r_{b,0}$ and L_0 were taken from Carminati and Javaux (2020).

Finally, ψ_{leaf} was calculated for the complex and simple model with $\psi_{s,b}$ ranging from -0.001 to -1.5 MPa and transpiration rates E running from 0 to E_{max} .

2.2 Optimisation

The simple model was fit to the complex model by minimising the root mean squared error (RMSE) between the SOL curves generated by the two models. The SOL is a three-dimensional curve in the $(\psi_{s,b}, \psi_{leaf}, E)$ space with $\psi_{s,b}$ as input and the SOL curve generated by the complex model served as a ground truth. The RMSE to be minimised was taken as a weighted sum of the RMSE in E and the RMSE in ψ_{leaf} :

$$\text{RMSE}_{\text{tot}} = \frac{1}{|E_{\text{max},c} - E_{\text{min},c}|} \cdot \text{RMSE}_E + \frac{1}{|\psi_{\text{leaf,max},c} - \psi_{\text{leaf,min},c}|} \cdot \text{RMSE}_{\psi_{\text{leaf}}},$$

$$\text{with } \text{RMSE}_{\text{VAR}} = \sqrt{\frac{\sum_{j=1}^n (\text{VAR}_{s,j} - \text{VAR}_{c,j})^2}{n}} \quad (8)$$

where VAR with the subscripts s and c refer to the parameters E and ψ_{leaf} of the simple and complex models, respectively. The sum was weighted to account for the differences in scales between E and ψ_{leaf} . The minimisation was conducted using the stochastic, population-based optimisation algorithm `differential_evolution` by the open-source Python library `SciPy`. It is suitable for functions that are noisy, non-differentiable, or have many local minima. The method is based on the algorithm by Storn and Price (1997). The free parameters in the simple model were chosen to be the root resistance R_{root} , the xylem air-entry water head $h_{0,x}$, and the xylem Brooks–Corey parameter τ_x , according to the model parametrisation in Sect. 2.1.2. The root length L_{root} can be associated with soil influence (see Sect. 2.3) and is therefore held constant. To estimate the precision of the optimal solution obtained, the algorithm was run a total of 25 times per soil. The error bars in Fig. 3 are the standard deviation of all optimisation runs.



2.3 Sensitivity Analysis of plant and soil hydraulic parameters

We performed a global SA to quantify the influence of specific parameter values. This approach allowed us to explore the entire input space and reveal the global effects of each varied input parameter on the model output. Global SAs are primarily used for non-linear models (Reed et al., 2022).

To this end, we used the open-source Python library SALib (Herman and Usher, 2017), based on the method proposed by Saltelli et al. (2002). Its output is sensitivity indices of multiple orders for each parameter. First-order indices measure the global influence of the variance of a single parameter alone. Second-order indices describe the contribution to the output variance caused by the interaction between two parameters. The total-order indices incorporate first, second, and higher-order effects to determine the total contribution of the model's input to the output variance (Herman and Usher, 2017). The SA was performed on four different parameters: root resistance R_{root} , xylem Brooks–Corey coefficient τ_x , xylem air-entry water head $h_{0,x}$, and root length L_{root} , for three different soils, clay, silt loam, and sandy loam.

Note that the soil's influence is evaluated by analysing the impact of root length on the model's output. As in the considered plant hydraulic model, the root length can be associated with soil influence. An infinite root length corresponds to an infinite hydraulic conductivity and thus negligible resistance, which cancels out the soil's water potential dissipation (see Eq. (4)). Consequently, the soil matric flux potential at the root surface is equal to that of the bulk soil.

$$\lim_{L_{\text{root}} \rightarrow \infty} \Phi_{s,r} = \lim_{L_{\text{root}} \rightarrow \infty} \left[-\frac{E}{2\pi r_0 L_{\text{root}}} \left(\frac{r_0}{2} - r_0 r_b^2 \frac{\ln(r_b/r_0)}{r_b^2 - r_0^2} \right) + \Phi_{s,b} \right] = \Phi_{s,b} \quad (9)$$

The detailed values for the intervals used to compute the SA can be found in the Supplementary Information. The total sensitivity index for each parameter is then plotted against the soil water potential of each soil.

3 Results

The first step was to evaluate whether the simple model – excluding an explicit soil representation by describing water flow solely using a single effective hydraulic conductance (see K_{eff} in Fig.1) assuming that it would implicitly account for soil characteristics – could approximate the more complex model serving here as ground truth and which includes explicit soil hydraulic parameters across the three different soil textures of clay, silt loam, and sandy loam.

As shown in Fig. 2, this proved only partially successful. In wet conditions, with $\psi_{s,b} \rightarrow 0$ MPa, the simple model (dashed, light green curve) closely reproduced the SOL trajectory of the complex model (solid, dark green curve) across all soils with only minor deviations in clay and silt loam. The point where the transpiration rate calculated by the complex model reaches its maximum value ($E_{\text{rel}} = 1$) is at $\psi_{\text{leaf}} \approx -1$ MPa for all soil types, due to the choice of plant parameters (see Sect. 2.1.2), and it starts to decline from its maximum at $\psi_{s,b} \approx -0.5$ MPa. This behaviour was successfully reproduced by the simple model, except for the decline in transpiration rate in sandy loam, which contrastingly already starts in wet conditions at $\psi_{s,b} \rightarrow 0$ MPa. Upon soil drying, the simple model is challenged with increasing resistance imposed by the soil. In clay and silt loam, the SOL trajectories calculated by the simple model are very similar to the complex model's output. However, the simple model deviates a lot from the complex model in sandy loam, which is a soil type with a steeper and more non-linear SOL drop. The complex

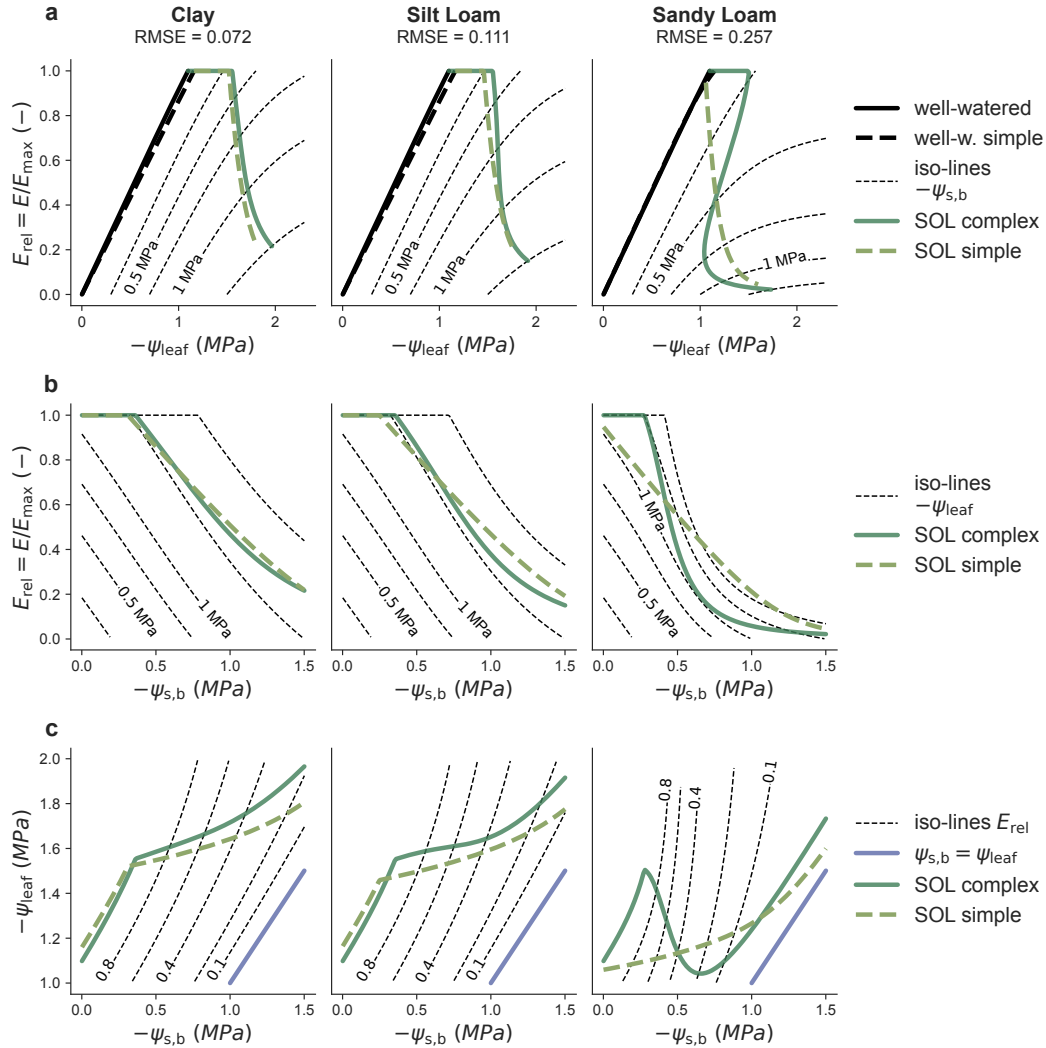


Figure 2. Comparison of the simple and the complex models for three different soil textures. Transpiration E is normalised by the maximally experienced transpiration $E_{\max}$, $E_{\text{rel}} = E/E_{\max}$. At zero transpiration ($E = 0$), soil and leaf water potential are assumed to be at equilibrium ($\psi_{\text{leaf}} = \psi_{\text{s,b}}$). The simple model (light green dashed curve) is fitted to the complex model (dark green curve). The Root Mean Squared Error (RMSE) between both curves is shown for each soil (see Eq. (8)). It is apparent that the simple model closely reproduced the SOL trajectory of the complex model in fine but not coarse soils. Panels **a–c** show the three perspectives of $(\psi_{\text{s,b}}, \psi_{\text{leaf}}, E)$: **a.** $E(\psi_{\text{leaf}})$ describes the plant physiological perspective. Bold black lines show transpiration with maximally wet soil (iso-line $\psi_{\text{s,b}} = 0$ MPa) for the complex (solid) and simple (dashed) model. The thin, dashed black lines show the iso-lines of constant $\psi_{\text{s,b}}$. This perspective highlights potential differences in $\psi_{\text{leaf,max}} = E_{\max}/K_{\text{root}}$ (onset of stomatal closure) and $\psi_{\text{leaf,full}}$ (full stomatal closure) between the two models. **b.** $E(\psi_{\text{s,b}})$ shows the soil hydrological and land–climate perspective. The dashed black lines show the iso-lines of constant ψ_{leaf} . This view highlights the critical soil water potential $\psi_{\text{s,b,crit}}$ at which transpiration starts to decline. **c.** $\psi_{\text{leaf}}(\psi_{\text{s,b}})$ describes the transpiration perspective with link to an/isohydricity (Martínez-Vilalta et al., 2014). The bold purple line represents equal soil and leaf water potential ($E = 0$). The dashed lines are iso-lines of constant E_{rel} . This perspective highlights the convergence and divergence of ψ_{leaf} and $\psi_{\text{s,b}}$ during drying.

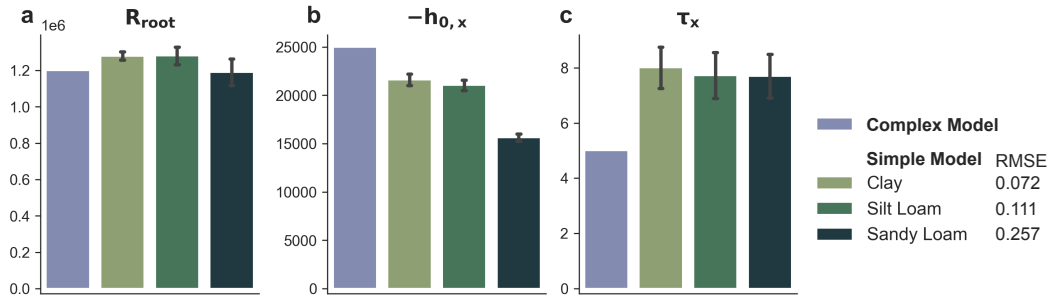


Figure 3. Comparison of fitted parameters for three different soil textures. The plant parameters used in the complex model (purple) to calculate transpiration are compared to the plant parameters fitted with the simple model (green hues). The simple model was fit to the complex model output of three different soils, resulting in three different sets of parameters of root resistance R_{root} , xylem air-entry water head $h_{0,x}$, and Brooks–Corey coefficient τ_x . The simple model adjusted these plant hydraulic parameters to closely reproduce the complex model output (see Fig. 2) via minimising the RMSE between the SOL trajectories of the simple and complex model using a population-based optimisation algorithm. For each soil, the simple model was fit a total of 25 times to get an estimate of the precision. The standard deviation is shown as error bars. For each soil, the Root Mean Squared Error (RMSE) between the complex and the simple model of the respective soil is shown. **a.** The values for the root resistance R_{root} are robust across all compared soils and the complex model and don't vary significantly. **b.** There's a clear drop in the absolute value of the xylem air-entry water head $h_{0,x}$ for the simple model in comparison to the complex model, most pronounced for sandy loam. $h_{0,x}$ accounts for the lack of increasing non-linearities in soil hydraulic resistance with increasing soil coarseness. **c.** In comparison to the complex model, the xylem Brooks–Corey parameter τ_x (–) increased uniformly for all three soils, but does not differ significantly across soils. The simple model needs to adjust xylem vulnerability to account for the missing soil hydraulic non-linearities.

230 model's SOL approaches $\psi_{\text{leaf}} \approx -1$ MPa again during soil drying in sandy loam, whereas leaf water potential computed by the complex model in finer-grained soils remains well below $\psi_{\text{leaf}} \approx -1.25$ MPa. From the soil hydrological perspective, the SOL drop is very steep in sandy loam, where stomata seem to close largely at a single $\psi_{s,b}$, as opposed to the SOL trajectory in finer soils, which declines more gradually. Therefore, sandy soil represents a particular challenge for the simple model, which fails to represent the SOL trajectory by the complex model in sandy loam entirely in dry conditions (further elaboration in the

235 Supplemental Information). The simple model seems to struggle capturing the non-linear transpiration decline in dry, sandy soils for any of the three perspectives of $(\psi_{s,b}, \psi_{\text{leaf}}, E)$.

Across all soils, the root resistance R_{root} did not change from the complex model to the simple model (see Fig. 3a), which is also indicated by the close fit of the well-watered transpiration curve in Fig. 2. $h_{0,x}$ and τ_x cross-coordinate, such that $h_{0,x}$ continues to decline from complex over fine to coarse soil, whereas τ_x increases significantly for the simple model, but only

240 decreases slightly from fine to coarse grained soils. This indicates a general need for increased hydraulic resistance imposed by the plant to account for the lack of soil hydraulic limitations.

Performance-wise, the simple model overall achieved lower RMSE values in fine-grained soils, as opposed to sandy soils (see Fig. 4). In clay and silt loam, the simple model can estimate the complex model's output relatively well, meaning that the

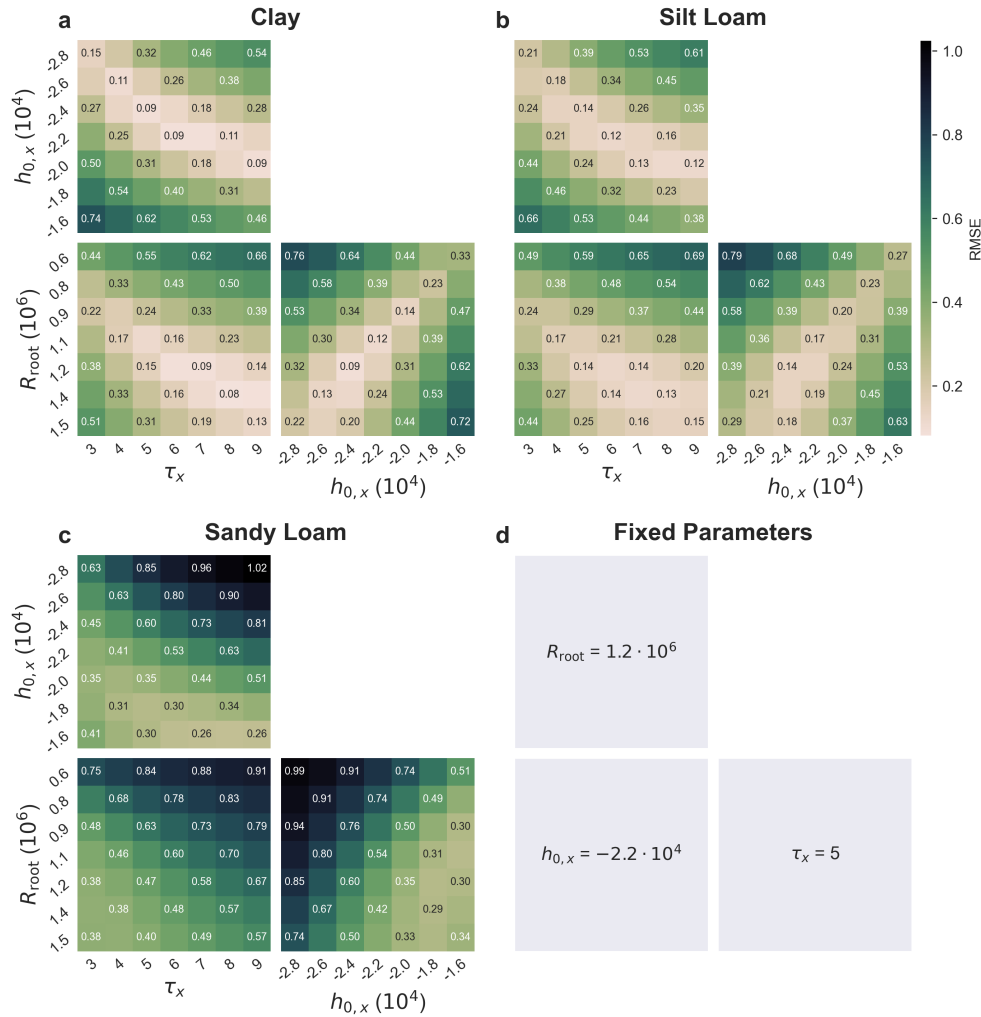


Figure 4. Root Mean Squared Error (RMSE) Heatmaps comparing the general trend of the simple and complex model outputs between three different soil textures. Each heatmap shows the RMSE between the Stress Onset Limit (SOL) of the complex and the simple model. The SOL of the complex model is computed once for each soil and then remains unchanged, whereas the simple model is computed for different parameter combinations, with one of the three free parameters held constant as indicated in panel **d**. The three varying parameters are the root resistance R_{root} , xylem water head $h_{0,x}$, and xylem coefficient τ_x . Lower RMSE values (lighter colours) indicate better agreement between SOL curves. **a-b**. In clay and silt loam, the simple and complex models show very similar heatmap patterns with RMSE values below 0.20 for several parameter combinations (light brown). This indicates that the optimisation algorithm manages to reproduce the complex model using the simple model parametrisation in fine soils. **c**. The comparison between the simple and complex models in sandy loam shows consistently higher RMSE values, indicating reduced prediction performance of the simple model in coarse soils. For lower RMSE, the simple model has to go to the edges of the parameter values to compensate for missing resistance in the system.

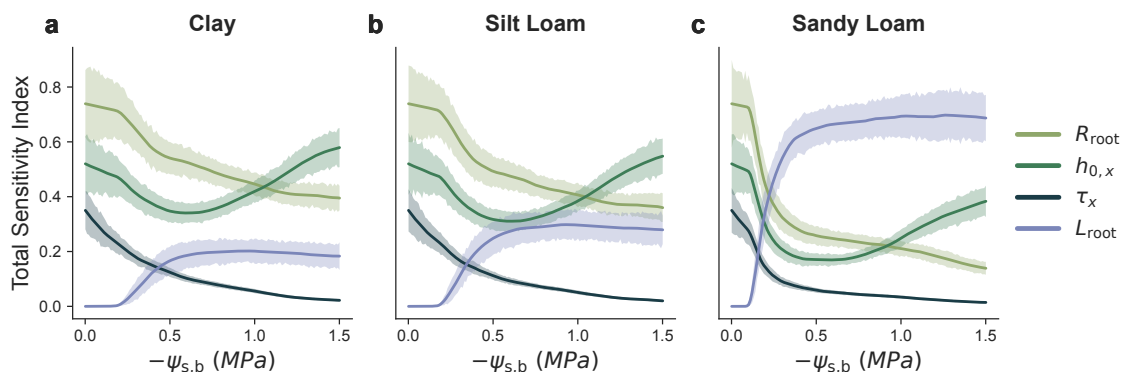


Figure 5. Sensitivity Analysis (SA) on the Stress Onset Limit (SOL) comparing plant internal and soil-specific parameters for clay, silt loam, and sandy loam across different soil water potentials. The total sensitivity index incorporates first and higher-order sensitivity indices and was computed for different soil water potentials $\psi_{s,b}$ individually. The parameters describing the influence of plant hydraulics in the stem and the root (green hues) were root resistance R_{root} , xylem air-entry water head $h_{0,x}$, and xylem Brooks-Corey coefficient τ_x . Root length L_{root} (purple line) was used as a measure of soil influence (more details in Sect. 2.3). The shaded areas display the 95% confidence intervals for the respective parameter. **a.** The SA of clay indicates that the variance of the root resistance explains a large portion of the output variance in the SOL across most soil water potentials. The xylem coefficient τ_x only plays a role in wet conditions, where the root length variance is negligible. The influence of the xylem air-entry water head $h_{0,x}$ plays a non-negligible role in wetter soils and increases in very dry soils. **b.** For silt loam, the relative importance of the different parameters is similar to clay. In drier conditions, the influence of root length increases and almost matches the sensitivity of $h_{0,x}$ and the root resistance. **c.** In wet soils, the sensitivity indices are very similar to the findings for clay and silt loam. However, the total sensitivity index clearly shows a dominance of the root length in dry soil conditions. The general trend across the different soil types shows a decrease in the importance of the root resistance R_{root} and xylem air-entry water head $h_{0,x}$ and an increase in the significance of root length L_{root} with more coarse-textured, sandy soils.

belowground hydraulic mechanisms can be substituted by plant constraints, which is also visible in Fig. 4a and b, where clay and silt loam exhibit relatively low RMSE values across several parameter combinations. Still, the performance is slightly but not significantly better in clay, achieving a lower RMSE than in silt loam. In Fig. 4a and b, it is apparent that there is no unique combination of best-fit parameters in clay and silt loam, which is not necessarily an issue. The aim is not to find physically accurate parameters but to approximate the complex model's behaviour. In sandy loam, the RMSE shows consistently higher values, decreasing towards the parameter value edges. There is no apparent local minima or optimal solution, indicating a failure of the simple model to accurately represent the complex model's behaviour in sandy soils.

Finally, the complex model's output was tested for its sensitivity to input variance of four different parameters: the root length L_{root} acts as a proxy for soil influence, and the root resistance R_{root} , xylem air-entry water head $h_{0,x}$, and the xylem coefficient τ_x describe the plant's limitation. The SA across different soil types in Fig. 5 clearly shows how soil characteristics – particularly texture and moisture – affect the sensitivity to root length under varying soil water potentials. The first- and second-order sensitivity effects are shown and analysed in the Supplemental Information. The xylem coefficient has a noticeable effect



on plant transpiration under wet conditions, but its influence reduces substantially with soil drying, across all soil textures. The influence of root resistance R_{root} is also more pronounced in wet conditions and remains relatively constant in finer soils such as clay and silt loam, but declines noticeably in coarser-grained soils with lower soil water potentials. The influence of the xylem air-entry water head $h_{0,x}$ evolves similarly to R_{root} , but with a further increase of importance in very dry soils. Overall, the influence of R_{root} and $h_{0,x}$ decreases with increasing sand fraction. The importance of root length L_{root} is negligible in very wet soils for all soil textures. Upon soil drying, however, the total sensitivity index of L_{root} increases significantly, which is especially pronounced in coarser soils. This is due to its strong influence on model output and an increased interaction with other parameters such as R_{root} and $h_{0,x}$, which is further discussed in the Supplementary Information.

4 Discussion

4.1 Sand content dictates when it is necessary to explicitly include soil-specific properties

The findings of the SA can be directly linked to the conducted optimisation. The simple model parametrises the hydraulic pathway only using three parameters – root resistance R_{root} , xylem air-entry water head $h_{0,x}$, and xylem coefficient τ_x – out of the four tested in the SA. In finer soils like clay and silt loam, the influence of those three parameters is sufficiently strong such that a large part of the variance in the output can be explained by them. In clay and silt loam, the influence of root length L_{root} – and therefore the soil’s hydraulic properties – is smaller than that of R_{root} and $h_{0,x}$ (Fig. 5a and b) and the SOL trajectories of the simple and the complex model (Fig. 2) exhibit only minor differences. Consequently, the RMSE values between the model outputs of the simple and complex models are low (Fig. 4a and b). The success of the simple model to match the complex model relatively closely suggests that the lack of soil resistance considered in the simple model can be implicitly compensated for by adjusting plant hydraulic resistance. In particular, by lowering the absolute value of the xylem air-entry water head $h_{0,x}$ and increasing the xylem conductivity coefficient τ_x , as shown in Fig. 3b and c. Both adjusted plant parameters resulted in a steeper decrease in xylem hydraulic conductance at higher (less negative) soil water potentials, with a more pronounced increase in hydraulic limitation. In general, the simple model produces SOL curves with shapes that are similar to those of the complex model, allowing it to effectively replicate the complex model’s behaviour. In such soils, focusing solely on plant hydraulics might be sufficient, and a detailed description of soil properties is not necessary to describe transpiration dynamics. This might reduce computational demand and parameter uncertainty in plant hydraulic models.

However, in coarser and more non-linear soils like sandy loam, the soil’s influence cannot be ignored. The simplified plant-focused model fails to accurately describe the system’s behaviour in these conditions, as shown in Fig. 2 and 4c, where the simple model breaks down, and RMSE values between the model outputs differ significantly for the lastly tested soil. Figure 4c may suggest that extending the parameter range of the simple model would have helped to better reproduce the SOL trajectory of the complex model. However, the failure of the simple model has a more fundamental explanation and stems from the ways the two models describe hydraulic resistance. In the simple model, the decline in transpiration upon soil drying is mainly influenced by xylem vulnerability, whereas the hydraulic resistance in the complex model is, in addition, influenced by the hydraulic conductivity decline around the roots as the soil dries. In sandy loam, the pores are of more uniform size distribution,



and therefore empty at nearly the same soil water potential, leading to a near-simultaneous loss of conductivity across all pores.

290 Downstream water potential declines rapidly and non-linearly. To reproduce this behaviour in a plant-only model, the plant's xylem hydraulic conductivity must be reduced drastically at a specific soil water potential. However, this is not possible in the simple model. The mathematical framework describes the slope of the SOL drop only with a single parameter τ_x . Letting τ_x approach infinity only leads to a vertical hydraulic conductivity drop in the system, but not a non-linear drop observed in sandy loam. This means that for coarse-textured soils, the simple model cannot replicate the complex interaction between

295 plant and soil hydraulics. Generally, the simple and complex models display a larger deviation in sandy loam with a greater correspondence at more extreme parameter values (compare with Fig. 4c). As a result, the parameter trends observed for sandy loam in Fig. 3 should be interpreted qualitatively rather than quantitatively. They indicate that the resistance in the plant must increase significantly to compensate for the non-linear behaviour of the coarse-textured soil. Additionally, the SA in Fig. 5c shows that plant transpiration is far more sensitive to root length L_{root} and consequently to soil properties than to plant

300 characteristics. This indicates that most of the variance in the model output arises from the soil-specific processes rather than plant internal characteristics like xylem vulnerability. As the sand content of the soil increases, it is not sufficient to rely solely on plant properties, and it is essential to incorporate accurate soil properties to model gas exchange correctly.

4.2 The critical bulk soil water potential where soil–plant limitation changes depends on soil texture

The relative importance of soil and plant hydraulics across different soil textures is intertwined with moist and dry soil conditions. The SA in Fig. 5 indicates where the plant–soil dominance changes as a function of soil moisture. Clay shows the least

305 drastic drop in SOL upon soil drying as well as the lowest sensitivity index for root length (see purple curve in Fig. 5a), while sandy loam displays the steepest, most non-linear decline together with the largest root length influence across a large soil water potential range (see purple curve in Fig. 5c). Consequently, soil characteristics become a dominant factor in sandy loam in dry conditions. There's a critical water potential where the influence of plant properties on transpiration decreases, while

310 soil properties start to play a larger role. In wet soils with less negative water potentials, plant-related parameters dominate water flow, and soil influence is minimal. However, with lower water potentials, the soil starts to impact plant transpiration more prominently, with its magnitude depending on soil texture. When comparing the sensitivity to plant-specific versus soil-specific properties across different soil types, it is apparent that the soil water potential at which soil properties start influencing transpiration more significantly shifts to less negative values for more sandy, non-linear soils. This has also been found by

315 Wankmüller et al. (2024). Overall, plant resistance causes most water potential dissipation in wet soils, whereas the soil tends to be the limiting factor in drier conditions, especially in sandy soils.

The sensitivity to plant parameters, R_{root} , $h_{0,x}$, and τ_x , generally decreases with soil drying. Interestingly, in all soils at water potentials below -1 MPa, the total sensitivity index of $h_{0,x}$ increases again. This could be due to its increasing interaction with root length sensitivity in particularly dry soils (compare to the second-order indices in the Supplemental Information).

320 Additionally, previous studies indicate that plant limitations increase again under extremely dry conditions (very dry soils at high transpiration demand). In such cases, xylem cavitation occurs widely and drastically reduces hydraulic conductivity, potentially below that of the already dry soil (Wankmüller and Carminati, 2023).



4.3 Root physiological adaptation as explanation for strong soil sensitivity in sandy soils

At the roots' level, Nobel and Cui (1992) showed that root resistance imposes the largest constraint on water flow across the soil–root interface in wet soils. Therefore, under these conditions, water uptake is not expected to vary substantially with different soil textures (Cai et al., 2021). This finding is consistent with our SA, in which the SPAC model exhibits very similar sensitivities to plant parameters in wet soils across all soil types, with plant transpiration being most sensitive to root resistance R_{root} . Additionally, because R_{root} is the most influential parameter in wet soils, the optimisation algorithm identified a similar value for R_{root} across all soils to closely reproduce the SOL in wet conditions and avoid large RMSE penalties. Consequently, the trajectory of the simple model in well-watered conditions is nearly indistinguishable from the complex one. Upon soil drying, however, the soil hydraulic conductivity continues to impose a larger constraint on water flow, especially in coarse soils, where the non-linear decrease in hydraulic conductivity is most pronounced. Roots tend to adapt to growing in sandy soils: they grow generally longer and thicker in wet conditions (Adamczewski et al., 2026), and their root hairs take a larger role in water uptake than in finer soils in the range of approx. -0.01 to -1 MPa soil matric potential to increase the active root surface and consequently alleviate the pronounced and non-linear loss in hydraulic conductivity of coarse-textured soils during drying (Duddek et al., 2023; Stoll et al., 2026). During drought-onset, the soil hydraulic conductivity around the roots reduces significantly in sandy soils, such that a small change in L_{root} and A_{root} accordingly would have a large impact on the experienced surface hydraulic conductivity and consequently transpiration. This is visible in Fig. 5c, where the root sensitivity greatly increases with drying soil in sandy soils. The increasing hydraulic limitation imposed by the soil and the root adaptations to growing in sandy soils point towards a physiological explanation for the theoretical results obtained in this work.

4.4 Potential shift in relative difference between the simple and complex model due to modelling limitations

Some phenomena not covered in this work could potentially shift the relative difference between the simple and the complex model, notably the effect of plant capacitance, where plants pull water from their own internal water storage system along the hydraulic pathway rather than directly from the soil (Steppe et al., 2006). Plant hydraulic capacitance might buffer imbalances between water supply and transpiration demand (Fuchs, 2025), allowing plants to remain in regions of leaf water potentials where they normally operate at (cf. Martinetti et al., 2026). Consequently, the full SPAC model may become less sensitive to declining soil hydraulic conductivities, because part of the transpiration demand is met by plant internal water. By including plant capacitance, the complex model might display a different hydraulic response during soil drying, potentially even approaching the transpiration behaviour of the simple model. All together, this could motivate further research towards the importance of plant capacitance and individual stomatal strategies in determining the relative importance of soil and plant hydraulic limitations and required model complexity to accurately predict soil–plant water relations.

During soil drying, larger constraints by hydraulic limitations in the soil are mainly due to a decrease in the effective contact area between the roots and the surrounding soil (Krounbi and Lazarovitch, 2011), where the amount of contact loss increases with increasing sand fractions (Koch et al., 2025). Our model did not explicitly take this effect into account, and we would expect an even more pronounced trend of increased root length sensitivity in coarse-grained soils than observed in Fig. 5c.



Finally, in this work, the complex model is considered the ground truth to which the simple model was compared. It is acknowledged that even detailed soil–plant hydraulic models may contain errors and might not fully capture all underlying physical processes. It was not the goal of this work to verify the validity of the full SPAC model. Moreover, the SA highlights where the risk of uncertainty related to the model output is most pronounced. In sandy loam, the large sensitivity to soil and root parameters in drying soils emphasises the importance of correctly describing these properties to reduce output uncertainty. It might be interesting to investigate whether incorporating a root architecture model improves the accuracy of the simulated plant transpiration or shifts the disparity between the simple and the complex models. A combined model could help to better describe transpiration dynamics in soils with larger sand content. For instance, a three-dimensional root model based on the 3D Richards equation, where the root system is represented using connected root nodes, all contributing individually to the water uptake, as described in Javaux et al. (2008).

5 Conclusions

This work evaluated whether plant transpiration in a soil–plant–atmosphere model can be parametrised solely using plant-specific parameters, which should implicitly account for soil hydraulic properties. The results demonstrate that, in fine-textured soils (e.g., clay and silt loam), soil–plant water relations can be modelled accurately without explicitly including detailed soil characteristics. The SOL curves produced by the simple model closely resemble those of the complex model. This suggests that the soil’s resistance can largely be compensated for by adjusting internal plant traits. The SA supports this result, showing that soil characteristics, represented by root length sensitivity, only have a minor impact on the complex model output, whereas plant-specific properties, such as xylem vulnerability and root resistance, have a much larger effect on plant transpiration. Therefore, it may be sufficient to implement a soil–plant hydraulic model without explicitly describing soil characteristics, while still adequately capturing the relation between transpiration rate and leaf and soil water potential. This might help reduce model complexity and parameter uncertainty. In contrast, for dry, coarse-grained soils (e.g., sandy loam), a straightforward, plant-only model fails to reproduce a more complex, full SPAC model. This demonstrates the need to integrate detailed soil-specific characteristics to accurately describe soil–plant–water relations. Soil–plant hydraulics cannot be substituted by a single effective plant hydraulic conductance because the effects of soil texture-specific drying are significant. The SA further identifies the impact of soil on transpiration as most pronounced in dry, coarse-textured soils, leading to the conclusion that it is insufficient to rely solely on plant parameters to sufficiently describe plant transpiration. Additionally, the system in sandy loam undergoes a transition from being plant-limited in wet conditions to being soil-limited in dry conditions. In the latter scenario, the impact of soil resistance becomes dominant in determining water flow, surpassing the sensitivity of plant internal parameters.

Overall, this qualitative analysis shows that soil texture has a large influence on whether soil properties are crucial to be included in an SPAC model. To further support the analysis empirically, it would be beneficial to compare plant transpiration from field sites of different soil textures. This could further deepen our understanding of soil water limitations and soil texture influences, and connect theoretical hypotheses with real-world data.



390 *Code and data availability.* The code used in this work are archived in the *Zenodo*, <https://doi.org/10.5281/zenodo.22093434>. The code was run in Visual Studio Code 1.103.2 on Python 3.11.11. The data used in the code is embedded in the repository, but the code for data generation is also provided (where applicable) if the reader wishes to produce it themselves. Further information can be provided upon request.

Author contributions. EW: Conceptualisation, Formal Analysis, Methodology, Software, Visualisation, Writing (original draft); FJPW: Supervision, Writing (review and editing); SDB: Conceptualisation, Supervision, Writing (review and editing); AC: Conceptualisation, Funding acquisition, Methodology, Supervision, Writing (review and editing).

395 *Competing interests.* The authors declare that they have no conflict of interest.

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