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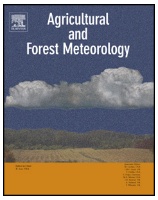

Modeling plant transpiration under limited soil water: Comparison of different plant and soil hydraulic parameterizations and preliminary implications for their use in land surface models

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ABSTRACT

Accurate estimates of how soil water stress affects plant transpiration are crucial for reliable land surface model (LSM) predictions. Current LSMs generally use a water stress factor, β, dependent on soil moisture content, θ, that ranges linearly between $\beta = 1$ for unstressed vegetation and $\beta = 0$ when wilting point is reached. This paper explores the feasibility of replacing the current approach with equations that use soil water potential as their independent variable, or with a set of equations that involve hydraulic and chemical signaling, thereby ensuring feedbacks between the entire soil–root–xylem–leaf system. A comparison with the original linear θ-based water stress parameterization, and with its improved curvi-linear version, was conducted. Assessment of model suitability was focused on their ability to simulate the correct (as derived from experimental data) curve shape of relative transpiration versus fraction of transpirable soil water. We used model sensitivity analyses under progressive soil drying conditions, employing two commonly used approaches to calculate water retention and hydraulic conductivity curves. Furthermore, for each of these hydraulic parameterizations we used two different parameter sets, for 3 soil texture types; a total of 12 soil hydraulic permutations. Results showed that the resulting transpiration reduction functions (TRFs) varied considerably among the models. The fact that soil hydraulic conductivity played a major role in the model that involved hydraulic and chemical signaling led to unrealistic values of β, and hence TRF, for many soil hydraulic parameter sets. However, this model is much better equipped to simulate the behavior of different plant species. Based on these findings, we only recommend implementation of this approach into LSMs if great care with choice of soil hydraulic parameters is taken.

1. Introduction

Most land surface models (LSMs), i.e. those models describing the land-surface atmosphere interactions in Numerical Weather Prediction (NWP) models or Global Circulation Models (GCMs), now employ coupled net assimilation (A_n)–stomatal conductance (g_s) descriptions (Sala and Tenhunen, 1996; Arora, 2003; Calvet et al., 2004; Keenan et al., 2009; Sellers et al., 1996; Best et al., 2011; Boussetta et al., 2013; Oleson et al., 2013; Van Den Hoof et al., 2013). These models ensure the most realistic representation of plant physiological processes, which in theory should lead to more accurate predictions of (global) water and carbon cycles, under current and future climatic conditions. For example, accurate model simulations of heat-wave related temperature anomalies over the European domain, crucially depend on accurate soil moisture predictions (e.g. Zampieri et al., 2009), which in turn rely on realistic descriptions of canopy exchange processes in LSMs, which includes plant water stress and related root water uptake.

How the current A_n–g_s models, with some of these embedded in LSMs, take account of plant water stress is described in detail in Egea et al. (2011a), for example. In almost all LSMs water stress will be determined by making use of a key soil hydraulic property: the soil water characteristic (SWC) which describes the relationship between soil matric potential, ψ_s (e.g. in MPa) and volumetric moisture content, θ ($m^3\ m^{-3}$). SWCs are generally calculated using both Brooks and Corey (1964), B&C, equations as well as Van Genuchten (1980)–Mualem (1976), VGM, parameterizations; we will get back to this in Section 2.2.

In the area of soil physics and plant science, it has long been known and widely accepted that plants respond to soil matric

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potential (suction) rather than to soil water content. For example, Marshall et al., 1996; (Section 14.2) discussed the closure of leaf stomata at particular leaf water potentials and the relationship between leaf and soil water potentials. Mullins (2001) led their article by stating that "in the absence of high concentrations of solutes, [soil matric potential] is the major factor that determines the availability of water to plants". The same point can be found in Gregory and Nortcliff (2013) and in many other sources.

By contrast, in a considerable number of LSMs plant water availability directly depends on θ, despite this wealth of literature; it decreases linearly when θ decreases from its value at field capacity (FC, also called critical point, generally at $\psi_s = -0.033$ MPa[1], see e.g. Veihmeyer and Hendrickson (1931), Saxton et al. (1986), Best et al. (2011), to its value at wilting point (WP, $\psi_s = -1.5$ MPa), respectively. θ_{FC} and θ_{WP} depend on soil textural composition, and on the type of hydraulic parameterization selected (B&C versus VGM) and parameter set used, as summarized in Section 2.2 and Table 2. The plant water stress factor (although plant water availability function would be a more appropriate name), generally referred to as β, is normalized by θ_{FC}–θ_{WP}, so that β becomes dimensionless and ranges between 1 (well-watered plants) and 0 (transpiration is zero, apart from cuticular transpiration):

$$\beta \begin{cases} 1 & \theta \geq \theta_{FC} \\ \left[\dfrac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}\right] & \theta_{WP} < \theta < \theta_{FC} \\ 0 & \theta \leq \theta_{WP} \end{cases} \tag{1a}$$

Many LSMs (e.g. Best et al., 2011, for the JULES UK community model, or Boussetta et al., 2013, for the CTESSEL model) use this linear decline function for their β parameterization.

The term $(\theta-\theta_{WP})/(\theta_{FC}-\theta_{WP})$ is also known as the fraction of transpirable soil water (FTSW). In most current LSMs, this type of β factor is being used to apply water stress directly to A_n or to the parameters of the photosynthesis model (Arora, 2003; Ronda et al., 2001; Calvet et al., 2004; Krinner et al., 2005; Best et al., 2011; Boussetta et al., 2013).

Egea et al. (2011a), from hereon referred to as EVV11, introduced a more versatile β function which varies curvi-linearly (with flexibility in degree of curvature, via parameter q, see Eq. (1b)), when θ ranges between θ_{FC} and θ_{WP}:

$$\beta \begin{cases} 1 & \theta \geq \theta_{FC} \\ \left[\dfrac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}\right]^q & \theta_{WP} < \theta < \theta_{FC} \\ 0 & \theta \leq \theta_{WP} \end{cases} \tag{1b}$$

EVV11 also introduced alternative ways to exert water stress on canopy exchange processes, i.e. not just via stomatal (multiplication of g_s by β) or biochemical pathways (by multiplying maximum carboxylation rate, V_{cmax}, and maximum photosynthetic electron transport rate, J_{max}, with β) but also through multiplication of mesophyll conductance, g_m, by β (see also Calvet, 2000) or a combination of the above.

There are some models that calculate β as a function of soil matric potential, ψ_s. One of the earliest water stress equations of this kind is the one by Feddes et al. (1978), used in the hydrological SWAP model (Van Dam et al., 2008). Focusing on LSMs (SWAP is not a LSM; it is not embedded in a NWP or GCM), Oleson et al. (2013), from here on referred to as OEA13, for the Community Land Model (CLM), define a plant wilting factor, equivalent to β in Eqs. (1a) and (1b), by:

$$\beta = 0 \leq \frac{\psi_{s,c}-\psi_s}{\psi_{s,c}-\psi_{s,o}} \leq 1 \tag{2}$$

where $\psi_{s,c}$ is the soil water potential at which stomata close and $\psi_{s,o}$ is the soil water potential when the stomata are fully open. In Eq. (2) the independent variable is ψ_s, not θ. Furthermore, whereas in Eqs. (1a) and (1b) parameters θ_{FC} and θ_{WP} are dependent on soil texture, $\psi_{s,o}$ and $\psi_{s,c}$ are dependent on plant functional type (PFT).

Table 1
Parameter values used in model equations, and explanation of abbreviations.

Parameter	Explanation	Default value
a_1	Parameter of D02 model, see Eq. (5)	6.0
a_{ABA}	Effective ABA sequestration rate [mol H_2O m^{-2} s^{-1}]	0.0001
$b(-)$	B&C: slope of the soil water characteristic	See Table 2
D_0	Parameter of D02 model, see Eq. (5) [kPa]	1.67
K_{sat}	B&C & VGM: saturated hydraulic conductivity [m s^{-1}]	See Table 2
$l(-)$	VGM: empirical pore-connectivity parameter	See Table 2
L_{max}	Max. xylem hydraulic conductivity [mol m^{-2} s^{-1} MPa^{-1}]	0.00667
$n(-)$	VGM; measure of the pore-size distribution	See Table 2
$R_{sr,min}$	Min. soil-root hydraulic resistance [MPa mol^{-1} H_2O m^2 s]	0.1
α	VGM; inverse of the air-entry matric potential [m^{-1}]	See Table 2
γ	ABA synthesis parameter [m^3 mol^{-1} ABA]	1.48×10^{-4}
δ	Increase in stomatal sensitivity to [ABA] [MPa^{-1}]	−2.0
θ_{sat}	Soil moisture at saturation [m^3 m^{-3}]	See Table 2
θ_{FC}	Soil moisture at field capacity (−0.033 MPa) [m^3 m^{-3}]	See Table 2
θ_{WP}	Soil moisture at wilting point (−1.5 MPa) [m^3 m^{-3}]	See Table 2
λ_r	Root ABA synthesis coefficient [MPa^{-1} m^{-2} s^{-1}]	4×10^{-6}
λ_e	Leaf ABA synthesis coefficient [MPa^{-1} m^{-2} s^{-1}]	1×10^{-6}
ψ_{tL}	Threshold value of ψ_e at which L_{re} starts to decline [MPa]	−1.0
ψ_{xL}	Value of ψ_e at which L_{re} falls to zero [MPa]	−7.0*
$\psi_{s,sat}$	B&C: soil matric potential at air entry [MPa or m]	See Table 2
$\psi_{s,max}$	Value of ψs at field capacity [MPa]	−0.033

Abbreviation	Explanation
ABA	Abscisic acid
B&C	Brooks and Corey (1964)
BL	Biochemical limitation
C&H	Clapp and Hornberger (1978)
CEA	Cosby et al. (1984)
CLM	Community Land Model
D02	Dewar (2002)
EVV11	Egea et al. (2011a)
FC	Field capacity
FTSW	Fraction of transpirable soil water
LSM	Land surface model
ML	Mesophyll limitation
OEA13	Oleson et al. (2013)
PFT	Plant functional type
RT	Relative transpiration
S05	Sinclair (2005)
SL	Stomatal limitation
SWC	Soil water characteristic
SVG	Schaap and Van Genuchten (2006)
TRF	Transpiration reduction function (*RT* versus FTSW)
VGM	Van Genuchten-Mualem hydraulic parameterization
WEA	Wösten et al. (1999)
WP	Wilting point

* D02 used −3 MPa.

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[1] Note that 10 kPa is another widely used value to denote FC (see, e.g. Verhoef and Egea, 2013).