

Interactive comment on “Parameterizing complex root water uptake models – the arrangement of root hydraulic properties within the root architecture affects dynamics and efficiency of root water uptake” by M. Bechmann et al.

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Note to reviewer #1, referee comments

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Introduction

The anonymous reviewer #1 raises a couple of important issues that need clarifications. In this note, we address the three major issues raised by the reviewer, while we provide a point-by-point response to the review when we submit the revised version of the manuscript.

The major issues that were raised are:

1. A misunderstanding regarding the applicability of the efficiency measures to transient root water uptake scenarios.
2. The reviewer finds that the two measures used for evaluating efficient root parameterizations seem inappropriate, since they are correlated.
3. A misunderstanding on our background section and the concept of “axial limitation” and how it is addressed in our paper.

In the following, we address these issues and show that these are misunderstandings. In the revised manuscript we will include additional information to state these points more clearly.

1 Applicability of the measures of root water uptake on transient conditions

The reviewer commented in “general comments”:

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“Moreover, the indices require the plant transpiration rate to be constant until water stress is reached, which makes their calculation for real plants implausible. On total, these points make the perspective of using these indices to parametrize complex root water uptake models illusory.”

It is important to notice that neither of the indices requires root water uptake to be time constant. This can be seen in Fig. 1 (c) (attached to this note), where we calculate, as an example, the index “effort” for both constant and for sinusoidal transpiration flux at the root collar. In our manuscript, we chose to present data for the time constant scenario for simplicity in the interpretation, as pointed out in Sect. 2.4 and Appendix A of our manuscript. In the revision we will re-arrange equations between appendix and the main text to bring out this fact and to avoid misinterpretation.

Water yield is proportional to the sum of the water transpired during an evaluation period. We chose to evaluate the unstressed water uptake, this is water uptake during times when the xylem potential at the root collar lies below a critical threshold. This does not require the uptake to be constant in time.

Concerning the “effort” - index: The complete form of the introduced “effort” index is (Eqs. A1, A2 and A3 of the manuscript):

$$w(t) = \frac{\int_{\tau=0}^t Q(\tau) \cdot \psi_x^0(\tau) d\tau}{\int_{\tau=0}^t Q(\tau) d\tau} \quad (1)$$

where Q (m^3/s) is the time dependent transpiration rate or total root water uptake rate at the root collar, ψ_x^0 (m) is the time dependent xylem water potential at the root collar and $w(t)$ (m or 9810 Pa or 9810 J m^{-3}) is the effort at the current time step t (s).

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We simplified $w(t)$ to the average xylem potential only because we decided to work with a constant transpiration flux scenario. Only in this specific case, the effort $w(t)$ is related to the time average xylem potential (see eqs. (10) and (11) in the Methods section of this note). However, the only requirement for the application of both criteria is a continuous drying scenario. Also, as already mentioned in the manuscript, we repeated the investigations with periodic boundary conditions (day night cycles), which did however not affect the results. Figure 1 shows model results obtained for a complex root system of a plant. It compares collar potentials obtained with a time constant transpiration rate (Fig. 1 (a)) with those obtained with a sinusoidal transpiration rate (Fig. 1 (b)). Figure 1 (c) shows the temporal evolution of effort for both scenarios.

In the revised manuscript, we will clarify the appendix and change the nomenclature to make this more transparent. We will also discuss the units and comment on the functional form of $w(t)$ and its relation to work. Finally, we will attach a table with all variables and their units.

2 Choice of measures for efficient root water uptake

The reviewer comments in “general comments”:

“The choice of the efficiency indices is not convincing, since they appear to be quite correlated to each other, sensitive to the chosen scenario, not very sensitive to root topology and maturity (especially water yield).”

We use the two indices for very good reasons. While water yield is strongly related to overall transpiration, which has widely been used before, we introduce a new measure, we call effort, which is much more relevant to how whole plants function. Effort

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integrates information about the temporal evolution of water potentials within the root xylem. Since xylem water potential is critical for maintaining xylem conductivity and avoidance of cavitation, we believe effort is better related to whole plant functioning. By comparison of water yield and effort, we find that the new measure (effort) is consistent with previous measures (water yield) but provides additional sensitivity and more of a plant physiological foundation.

The reviewer suggests that it is a drawback of our choice that the efficiency index depends on the chosen scenario (for example specifically uptake rate, as pointed out in RC 26 and RC32). We disagree. Plant performance depends on the scenario as well. For example, plants may suffer from water stress and reduce transpiration at higher water contents, when subject to higher transpiration demand (Denmead and Shaw, 1962). Thus, it is intuitive for the efficiency index to behave the same way.

Finally, the low sensitivity regarding effort between different scenarios of root system maturation is a result of this study. It shows that from a hydraulic perspective the plant suffers little disadvantage between different distributions of mature to young roots, and neither does the simulation result. This is an interesting result for further work on coupling root models to xylem transport and stomatal functioning. On the other hand, parameterization strongly influences bleeding, and the effort index is a suitable tool for discovering that those scenarios with strong bleeding are unlikely.

3 The concept of “axial limitation“

The reviewer comments in “general comments“:

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"[..] some of the concepts defined in this paper are misused. Most of the background section being affected by the artefact reported in RC7, it should be considered as misleading, and removed from the paper. Many figures, the result and discussion sections, should also be corrected accordingly."

A more detailed explanation is given in reviewer comment RC7:

"[..] Unfortunately, the increasing part of the function is an artefact due to the simplifying assumption of the authors (see the figure attached to this document, in which "n seg" is the number of segments in which the same unbranched root is discretized). The authors might want to characterize the shape of the function for different discretizations of the same uniform unbranched root. They will first notice that the function is sensitive to the number of segments in which the root is divided, and then that the increasing part of the function tends to disappear with refinement of the root discretization. This artefact undoubtedly affects a large part of the results and of the discussion. [..]"

It is incorrect that concepts are being misused. Our figures, results and discussions are correct. Our result is not an artifact of the number of segments used, but depends on the boundary condition, as is shown in Figure 2. In the following, we discuss where the misunderstanding of the reviewer likely came from. We are however left to some speculation, because the way that his figure was generated is not clearly explained in the review. We think the reviewers arguing comes from the assumption that soil water remains homogeneously distributed while a root system extracts water from the soil. In particular this would be the case under constant and homogenous soil water potential boundary conditions, in a steady state root water uptake scenario with an unlimited soil water reservoir.

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For this specific case, we have reproduced the reviewers results in Fig. 2 (a). On the y-axis, we replaced the resistance by the collar potential, which results in the same shape as long as transpiration is taken constant in time. We have stated all equations we used to create the plots in a methods section below. With homogenously distributed soil water potential, most of the root water uptake is provided from the region near the collar, and less from distances further away, as shown in Fig. 2 (b). Furthermore this allows the calculation of the root resistance in analogy to Ohms law, that is by dividing the difference between uniform soil matric potential and root collar potential by the transpiration flux.

It is important to notice that the uptake behavior shown in Fig. 2 (b) is strictly limited to situations where the soil water potential is distributed homogenously along the root. Since the soil water reservoir is limited in our manuscript this uptake pattern is of limited duration. Soon, the spatially confined root water uptake leads to a selective drying of soil near the collar. Thus, soil water content and matric potential are no longer homogeneous within the soil and the region of root water uptake subsequently moves further away into root regions surrounded by wet soil. This can be seen from Figs. 2 (b) and 2 (d). When starting the simulation with homogenous soil water potentials, the initial uptake corresponds to the one obtained in the unlimited reservoir (Fig. 2 (b)). Figure 2 (d) shows how the uptake has moved after half time before reaching water stress. The movement of the uptake area along the root forces water to travel increasingly longer distances within the xylem and thus to be subject to greater axial resistance. Thus, over a period of time the root length activated for uptake increases because uptake fronts move along the root.

Within the background section of our manuscript we have simplified this movement by assuming that water uptake is located approximately mid distance along the root length. While showing this only on a single segment is clearly a simplification,

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this simple model nevertheless captures a more complex representation with many segments. As Fig. 2 (c) shows the number of segments used for the model has no influence on the fact that an optimal root length exists with regard to the effort. Only the location of the optimal root length differs somewhat depending on the number of segments. Please note that with the time constant transpiration rate used here, effort corresponds to an average collar potential (see eqs. (10) and (11) in the Methods section of this note). However, the index "effort" can also be calculated under arbitrary transpiration rates (see Sect. 1 and 2).

All of the simulations presented in the results section of our manuscript have been obtained with models which have at least 100 segments, just as the reviewer suggests. In the revised manuscript we will however make more explicit in the background section, that this is a simplified model for a root in a limited reservoir subject to moving uptake fronts. Also, in order to avoid misunderstanding, we will state the number of model segments used for the model in the methods section.

In summary: Our results are not an artifact of the number of segments used, but depend on the boundary condition, as is shown in Figure 2. The figure presented in the comment by reviewer #1 is likely obtained assuming a root surrounded by an unlimited soil water reservoir and steady state conditions, while we work with a limited soil water reservoir and transient conditions. In a limited soil water reservoir and taking into account moving uptake fronts, both an optimal root length with respect to effort and axial limitation exist.

This also addresses another comment (RC 35) by the reviewer:

"Here the authors mention the classic concept of axial limitation (i.e. root water uptake is expected to be reduced at the outer ends of the root due

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to the longer, and thus, more resistive axial pathway to reach the collar), which is different of the definition of axial limitation given in the background section (i.e. the overall root resistance decreases with length due to the axial resistance). They should be careful not to use the same expression for different concepts.“

(We believe the reviewer means *”(i.e. the overall resistance increases with length ..“*)

In a limited water reservoir, these concepts are both true, at different times during the uptake process, as shown in Fig. 2. When the soil water potential is distributed homogenously along the root, root water uptake is expected to be reduced at the outer ends of the root due to the longer, and thus, more resistive axial pathway to reach the collar. After moving uptake fronts have developed overall root resistance increases with length due to the axial resistance.

4 Methods

Within this section we give the equations used to produce Figure 2 of this note. It was produced with the simple model for an unbranched root strand described in the methods section of our manuscript but varying the number of root segments between 1 and 1000. Within the simple model each root segment is surrounded by a soil cylinder of radius $r_{Soil} = 1.2$ cm providing the finite soil water reservoir. Water flow between adjacent soil cylinders is neglected within this simplified model.

The central equation is the water mass balance, which has to hold hold for each segment i :

$$Q_{Ax;out}^{(i)} = Q_{Ax;in}^{(i)} + Q_{Rad}^{(i)} \quad (2)$$

$Q_{Ax;out}^{(i)}$ (m^3/s) denotes the rate of water transport out of segment i towards the collar, $Q_{Ax;in}^{(i)}$ (m^3/s) denotes the inflow from the preceding segment, and $Q_{Rad}^{(i)}$ (m^3/s) denotes for the radial inflow (root water uptake) from the soil into the root.

At a sufficiently short time interval, the water potential within each root segment and the matric potential within the soil compartments is assumed to be constant. Under this assumption, the rates of water flow can be calculated in analogy to Ohm's law:

$$Q_{Ax;out}^{(i)} = \frac{\psi_x^{(i)} - \psi_x^{(k)}}{R_{Ax}^{(i)}} \quad (3)$$

$$Q_{Ax;in}^{(i)} = \frac{\psi_x^{(j)} - \psi_x^{(i)}}{R_{Ax}^{(j)}} \quad (4)$$

$$Q_{Rad}^{(i)} = \frac{\psi_{Soil}^{(i)} - \psi_x^{(i)}}{R_{Rad}^{(i)}} \quad (5)$$

$\psi_x^{(i)}$ (m) denotes the xylem water potential within segment i , $\psi_x^{(k)}$ (m) denotes xylem water potential within segment k succeeding segment i , $\psi_x^{(j)}$ (m) denotes xylem water potential within segment j preceding segment i , and $\psi_{Soil}^{(i)}$ (m) denotes the soil matric potential (m) within the soil compartment surrounding segment i .

$R_{Ax}^{(i)}$, $R_{Ax}^{(j)}$ and $R_{Rad}^{(i)}$ are the axial resistance of root segment i and j , and the radial resistance of root segment i , all given in (s / m^2).

The axial and radial resistances of each root segment i are calculated as follows:

$$R_{Ax}^{(i)} = \zeta^{(i)} \cdot l^{(i)} \quad (6)$$

$$R_{Rad}^{(i)} = \frac{\rho^{(i)}}{A_{surf}^{(i)}} \quad (7)$$

The root hydraulic resistivities $\zeta^{(i)}$ (s / m³) and $\rho^{(i)}$ (s) are material properties which are combined with the length of the root segment $l^{(i)}$ (m) and the surface area of the root segment $A_{surf}^{(i)} = 2 \cdot \pi \cdot r^{(i)} \cdot l^{(i)}$ m². Values of $\zeta^{(i)}$ and $\rho^{(i)}$ correspond to mature roots in our manuscript, and the root radius $r^{(i)}$ is uniformly set to 1 mm.

Closure of this underdetermined system of linear equations is achieved in terms of boundary condition at the root collar. This might either be a flux boundary condition

$$Q_{Ax;in}^{(0)} = Q \quad (8)$$

which mimics a constant transpirational demand, or a potential boundary condition

$$\psi_x^{(0)} = \psi_{crit} \quad (9)$$

which is used to model a plant under water stress. The presented simulations use a constant flux boundary condition. We run the model for two scenarios: Option A with an "unlimited soil water reservoir", that is soil matric potential $\psi_{Soil}^{(i)}$ is constant in time and equal for all segments $i = 1 \dots n$. Option B: With a limited soil water reservoir. The soil matric potential in the cylinder surrounding the root decreases corresponding to root water uptake and to the soil water retention curve (see manuscript, Table 2, and Table 1 of this note). We believe that the results presented by reviewer # 1 correspond to option A, whereas the results of our manuscript focus on option B, which makes the difference in interpreting our results.

Effort at a given time t is calculated for arbitrary transpiration rates via

$$w(t) = \frac{\int_{\tau=0}^t Q(\tau) \cdot \psi_x^0(\tau) d\tau}{\int_{\tau=0}^t Q(\tau) d\tau} \quad (10)$$

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and relates to a time average collar potential only under a time constant flux rate

$$w(t) = \frac{Q \cdot \int_{\tau=0}^t \psi_x^0(\tau) d\tau}{Q \cdot t} = \bar{\psi}_x^0(t) \quad (11)$$

in which $\bar{\psi}_x^0(t)$ is the time average xylem water potential at the root collar, evaluated between $\tau = 0 \dots t$.

In a drying scenario and with a time constant transpiration rate a unique point \tilde{t} in time exists at which water stress occurs. For producing Figs. 3 and 4 and Tables 3 and 4 of our manuscript, as well as Fig. 2 (c) of this note, we evaluated effort at this time, which is thus given by $w(\tilde{t})$. Please note that Fig. 1 of this note was instead produced by calculating effort at all times t and for both a time constant and a transient (sinusoidal) transpiration rate.

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Tables

Table 1. Parameters and important features of the simple model used to produce Fig. 2

Root properties for mature roots	
Critical collar potential ψ_{crit}	-150 m
Flux boundary condition $Q(t)$ (24 h Average)	$4.32 \times 10^{-3} \text{ dm}^3 \text{ d}^{-1}$
Total root length l_{total}	0.01–5 m
Number of segments n	1 . . . 1000
Branching	No
Root Radius r_{root}	1 mm
Root Axial Resistivity ζ_{Ax}	$8 \times 10^{10} \text{ s m}^{-3}$
Root Radial Resistivity ρ_{Rad}	$5 \times 10^8 \text{ s}$
Soil properties	
Soil cylinder radius r_{Soil} (including the root)	1.2 cm
Redistribution of soil water	No
Soil porosity	0.46
Initial water content	0.4
Residual water content	0.02
n_{VG}	1.534
α_{VG}	1.44 m^{-1}

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References

Denmead, O. T. and Shaw, R.H.: Availability of Soil Water to Plants as Affected by Soil Moisture Content and Meteorological Conditions, *Agronomy Journal*, 54, 385-390, 1962.

Interactive comment on *Hydrol. Earth Syst. Sci. Discuss.*, 11, 757, 2014.

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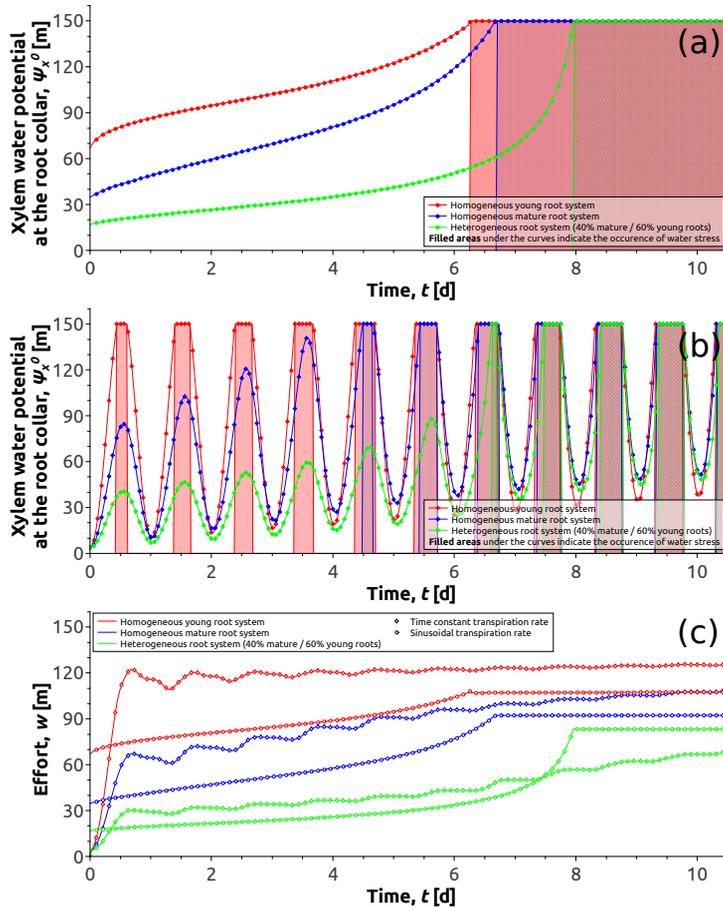


Fig. 1. Comparison of variable vs constant boundary condition. Evolution of collar water potential for transpiration rate being (a) time constant, (b) sinusoidal. (c) Evolution of effort for (a) and (b).

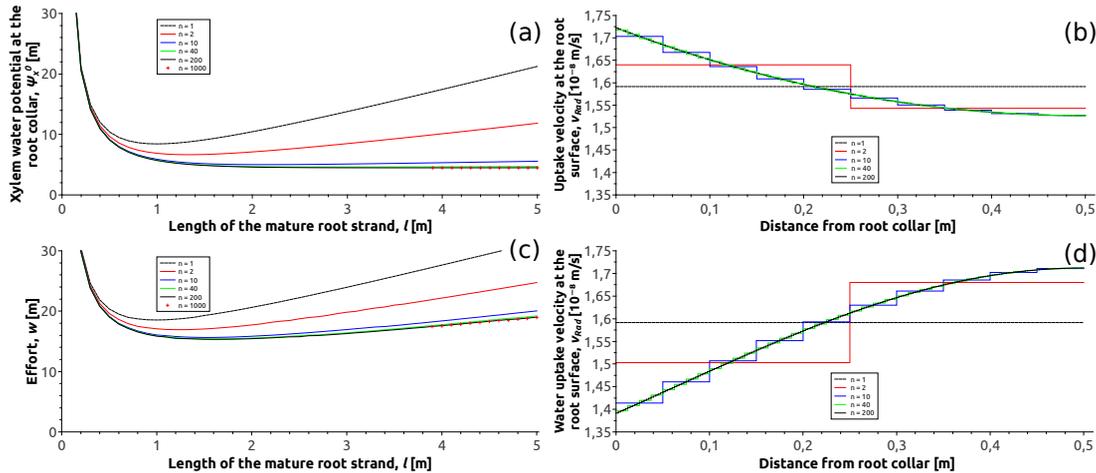


Fig. 2. Effect of number of root segments. Soil water reservoir (a,b) unlimited (steady state), (c,d) limited (transient). Shown is (a) root collar potential, (b,d) uptake along the root, (c) effort.

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