Dear Erwin Zehe,

we herewith submit the revised manuscript “A thermodynamic formulation of root water uptake” for your consideration.

We have taken the reviewers comments very seriously and have substantially changed the manuscript. The major changes are as follows:

- We formulated more clearly the contribution of the paper, which is to propose a tool for assessing the several impediments to root water uptake.
- We clarified that the conceptual model is not meant to draw general conclusions about root water uptake or plant evolution. We emphasized the nature of the conceptual water uptake model as a tool for demonstrating the application of the thermodynamic diagnostic to investigate the impediment to root water uptake. For this we removed ambiguous statements, re-arranged the order of the presented methods and explicitly state this throughout the text.
- We revised the mathematical notation for consistency and added an additional equation to show how uptake is calculated from the distributed, transient model.
- We added a section “Scenarios”, where we give references for the model parameters and show that they are representative of real systems.
- We have also performed additional model simulations as you suggested. While we agree that this is important to show, we decided to place these in the supplementary material as they are not that different compared to the case shown in the main manuscript.

In the following we give a detailed list of the changes done in response to each reviewer comment. In the revised manuscript, changes are marked in blue.

We thank you and the reviewers for the effort made in the review and we believe the revision has much improved this manuscript.

Sincerely,
Anke Hildebrandt

Changes during the revision

Changes in the manuscript are marked by blue.

Specific responses to the editor comments:

Both reviewers particularly pointed out that your main conclusion: "that uniform root water uptake is most efficient as it minimizes dissipative losses" is misleading, because it is based on spatially uniform soil water retention properties in your four box model. In case the soil water retention properties are not constant, the energetic minimum will likely neither correspond to the spatially uniform extraction nor to a spatially uniform "root density". This could and should be investigated using additional test simulations. Thereby you should as recommended by Uwe Ehret use a realistic set of 2 to 3 end members, preferably based on soil water retention properties that have been observed in real systems to assure realism of the underlying parameter sets.

We have erased the sentence "that uniform root water uptake is most efficient as it minimizes dissipative losses" from the abstract, as this was not the main message of the manuscript. However, we do refer to this later in the manuscript. We also state explicitly throughout the paper that we aim at demonstrating how thermodynamics can be used to discern separate impediments on the flow path between bulk soil and root collar.

We have also re-structured and substantially revised the paper to emphasize that the simple model is meant for demonstration purposes only. Finally, have also added a simulation with other soil types to the set of simulations, and added them to the supplement. All soil parameters are taken from observation.

We agree that heterogeneous soil properties affect the model results, but this can be evaluated easily be extending the diagnostics of the paper to more complex scenarios. The main purpose was to demonstrate that, amongst others, heterogeneity in water potentials affects the impediment to water uptake by plants, a fact which has not been considered so far.

The statement "we ignore soil water redistribution in our model, and thus changes in water content are due to root water uptake alone" suggest that you do not use a fully coupled model for soil water flow and root water uptake? This simplification is valid if root water uptake is faster than lateral redistribution in soil. This can and should be shown.

Our purpose in the manuscript is to show that heterogeneity affects the thermodynamics of root water uptake even though the mean properties of the system are the same. As our goal is not to explain the conditions under which heterogeneity develops, we kept the setup as it is, but focused on explaining our motivation for doing so in the revision.

In case of heterogeneous retention properties soil water redistribution crucially affects the ratio between dissipation within the soil and within the plant. I am not sure, whether it makes sense, to pool both dissipation terms into an overall uniform dissipation.

This may be a misunderstanding, the dissipation terms are not pooled, but separated out. These can, however, be aggregated to a total dissipation term, or separated by each compartment, depending on purpose. This is because in any case, they are additive, as shown in Eq. 11- which is a great advantage of this approach.

Personally I think the plant has an advantage by minimizing the necessary work that has to be performed to extract water from the environment. This might even include that it takes advantage from lateral distribution of water towards the plant, which as the roots do not grow for nothing.

Last not least I think the model could be used to investigate the energetic tradeoffs in the vertical pattern of root water uptake, which is known to be non-homogeneous. I guess the tradeoff between the amount of work that has to be performed to extract water from an increasingly drier top soil or to from the wetter sub soil is the key to understand how forests extract their water from variable depths.

Yes, we also think this may be further implications which would best be addressed with comprehensive root water uptake models diagnosed thermodynamically. We added a remark on this to the discussion.

Minor point: Your notion of Darcy's law is a little different to what is usually used in hydrology. Darcies law determines a flux (m/s) based on the potential gradient (m) and a hydraulic conductivity (m/s). You use a bulk formulation which combines the potential difference (m) with a hydraulic conductivity (m^2/s) to a flow (m^3/s). With this the flux becomes independent from the spatial separation between both boxes, which is unphysical.

Yes, this is true, thank you! We added a clarifying remark where the equation is introduced.

Specific responses to the review comments (GdR = Gerrit de Rooij, UE=Uwe Ehret):

GdR01: Mathematical formulation

Mathematical notation was made more consistent and more of the assumptions were explained in sections 2 and 3. We nevertheless kept sums for the integration over the soil volume, as a meaningful evaluation of energy as done in the manuscript requires a scale of at least the representative elementary volume (REV), i.e., a scale where porosity and the soil water retention curve are defined. This explanation is an important criterion and we added this to the end of section 2.1. Integrals and differentials were maintained for the integration over the soil water content to obtain the binding energy as well as for describing the temporal evolution of the soil water balance.

GdR02: Averaging procedure

In the revision, we now describe how we perform the averaging in greater detail to avoid confusion. To do so, we introduced section 4 that describes the setup of the scenarios and how the averaging was done.

GdR3: It is not intuitive that given the prevalence of heterogeneity in natural systems, we claim that homogenous uptake is most efficient.

We erased this line here and formulated this conclusion more carefully later in the paper. We emphasize still that heterogeneity in soil water potential *affects* root water uptake. And in situations where roots are equally distributed in areas with low and high potential and hydraulic properties do not change substantially, heterogeneity causes earlier water stress. This scenario is common in many modelling studies for root water uptake.

GdR04: Abstract suggests that we claim to predict evolution (using thermodynamics)

In the revision we emphasize the diagnostic (not predictive) nature of the thermodynamic evaluation. This starts in the abstract, but continues throughout the text. In particular, we added an extra section describing that the hydrological model was run first and thermodynamic evaluation perfomed *a posteriori* on the results of the process model. Only at the end of the discussion we also draw parallels to studies dealing with optimization, to which the thermodynamic approach may contribute informative evaluation measures.

GdR 05: Comparison between water retention and flow over a resistance is possible with some adjustments, while we claim it is not.

We formulated this instance more precisely.

GdR 06a, GdR 07: Incomplete equations formulated

We have reformulated the equation to make them consistent

GdR 08, GdR 06b: Formulation caused misunderstanding – integral was understood to be in space.

We have re-formulated all equations to make it more obvious, where we aggregate over space and where we integrate the water retention function (internal state) to yield binding energy. In the new version, all aggregation in space is given in form of sums, since the thermodynamic formulations given in the paper requires the minimum scale of the representative elementary volume (i.e. where the soil water retention function is defined), thus we need to imply discrete soil compartments. We also added a note to this at the beginning of the thermodynamics section.

GdR 09: Wording is too general, as comment only applies to homogenous soil properties

We reformulated accordingly.

GdR 10, GdR 11: The red arrow in the old Figure 2 (new Figure 1) suggested a predefined trajectory of water uptake implied by the thermodynamics

First, we removed the arrow. Second, we realized more information was needed to explain the setup better. We added a paragraph explaining the model procedure that is the thermodynamic formulations are not used as a process model describing root water uptake, but rather that they are used *a posteriori*, after water fluxes have been calculated with the conventional gradient driven distributed flow model. We also stated the thermodynamics first and the processes model second to support this. The latter also helped to remove some inconsistencies with the formulations of the equations.

GdR 12: Time stepping though the processes model was not stated

First, we added an equation and additional information explain how the processes model updates soil states between time steps. This also improved the processes model section and made it more consistent in general. Second, we performed a transient model run with time varying boundary conditions and added it to the supplement, to support this.

GdR 13: Add additional equations for water balance and heat

We added more information on the water balance (see above) and a paragraph addressing the relevance of the heat term.

GdR 14: Unclear how energy and water balance relate to each other

We addressed this together with GdR 10,11 above and laid out explicitly the sequence of model and diagnosis procedure.

GdR 15a: Not convinced that water uptake is hindered by heterogeneity of soil potential distribution – it is needed to model water flow first and aggregate afterwards

This comment is addressed by stating the distributed model more explicitly and showing that aggregation is done after evaluation of the process model. Also, we added an additional paragraph to the discussion to more clearly address the role of heterogeneity for impeding water uptake and how this relates to root growth and other adaptations.

GdR 15b, 16, 17 Some simplifying assumptions comprise the validity of the study – are they needed? (time constant boundary condition, no soil water flow between compartments, no root adaptation)

In the revision we added text at several instances to make it clear that we wish to demonstrate a powerful method to evaluate models, but we do not (here) wish to draw general conclusions. We explain that the demonstration is performed on a simple model, in order keep the focus on the thermodynamic diagnosis, not the model results.
In order to show that models can be adjusted, we added modelling results with fluctuation boundary conditions and different textures for demonstration to the supplement.

GdR 18: Need a clearer explanation of the contribution of the paper

We have added a text to the discussion and conclusion and abstract to lay out more clearly the contribution of the paper.

GdR 19: Would like to see simulations with day-night-cycles

We have added simulations with diurnal boundary conditions to the supplement.

GdR 20: Does the plant expend energy? Also, under non stressed conditions – is there at all an advantage to minimization of energy dissipation?

We show in the outlook that a minimization of dissipative losses is an interesting follow up topic, which is not addressed here. We also add that the functional role of this minimization is to delay of the arrival of water stress.

GdR 21: What does "export" mean?

We clarified the term "export" in the abstract and "Thermodynamics" section

GdR 23, 24: Small edits

done

GdR 25 – confusing Figure caption of Fig 1

Was edited to be more clear.

UE01, UE02 need to show that model parameters are realistic

We have added a paragraph to explain the origin of parameters of the hydrologic model, including soil parameters, transpiration rate, plant hydraulic conductivity, root length density. We also performed additional simulations to show how results are affected by more extreme (high and low) water retention., and added them to the supplement.

UE03, 04 Why is water flow between reservoirs stated and then neglected, it is an important omission.

We added a note to state that we state it for completeness, but maintain heterogeneity by isolating the compartments and artificially enhancing heterogeneity to demonstrate its effect on root water uptake.

UE05 Diurnal cycle of transpiration is missing, need to show that heterogeneity persists long enough to matter for transpiration

We performed additional simulations with diurnal cycles and explicitly allowing for hydraulic redistribution via the plant roots between compartments. Those results are included to the supplement in order to demonstrate that qualitatively results do not change.
Also, we included a note in the manuscript indicating that we deliberately maintain heterogeneity to show its role for impeding root water uptake.

UE 06 Clarify why the water retention cannot be formulated in a resistance analogue

We changed the wording of this part of the introduction.

UE 07, 08, 09 Text edits

Done as suggested