Short Comment on the discussion paper "A thermodynamic formulation of root water uptake"

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We thank the reviewers for their critical review of the paper, helpful remarks, and highlighting some errors and shortcomings, which we will address in the point-by-point response. There were some general points raised which we want to address before giving a point-by-point response.

Some of the major comments relate to the results of the conceptual root water uptake model, particularly regarding its simplicity and its assumptions, and our narrative might have been misleading with regard to the purpose of the paper. The focus of the paper is to be on some novel points that can be gained from a thermodynamic analysis of root water uptake, which are:

(1) Thermodynamics provides additional insights into the efficiency of heterogeneous root water uptake.
(2) The energy associated with water states and fluxes provides an evaluation tool to identify how much each flow process along the soil-root-continuum contributes to impeding water flow.
(3) Illustrating the balancing of the energy export against the change of energy and dissipation and thus paving the way for applications in more realistic and complex root water uptake models.

The reviewers raised some major concerns about the approach:

(4) Some of the model assumptions are invalid, especially regarding root water uptake being independent of local soil energy status.
(5) The model being too simple.
(6) The study lacks transferability to the real world.

We want to address these points below.

(1) *Thermodynamics provides additional insights into the efficiency of heterogeneous root water uptake.*

We propose and illustrate thermodynamics as a diagnostic tool to evaluate the place where the impediment to root water uptake lies. Applying thermodynamics to the soil-plant continuum illustrates its power, for example because it captures heterogeneous soil water conditions in a single number, something that cannot be done with the common approach that uses only potentials and water contents. Thermodynamics thus provides additional insights to better understand root water uptake. Please note, however, that this aggregated (average) soil energy state is only used to diagnose, and not to drive the flow or water uptake (see also point 4 below).

The main focus is equation 15, which captures all associated processes conveniently in a sum. We realize that the current text does not emphasize this point and that the focus on this aspect needs to be stronger. We will improve this in the revision. The terms of Eq. 15 allow us to understand the greatest contribution to the energy changes in the system and relate these to water fluxes and root water uptake. This brings us to point 2.

(2) *The energy associated with water states and fluxes provides an evaluation tool to identify how much each flow process along the soil-root-continuum contributes to impeding water flow*.

And

(3) *Illustrating the balancing of the energy export against the change of internal energy and dissipation and thus paving the way for applications in more realistic and complex root water uptake models.*

At the moment, we are not aware of any method for models of root water uptake that allows diagnosing at the plant scale on where the impediment to root water uptake lies. For example, is it the biotic or abiotic part of the overall flow path that most strongly impedes root water uptake? Also, how does this change in drying conditions?

We find that a thermodynamic view on the energy involved allows for exactly this insight, and cannot be provided by looking at fluxes and potentials. To our best knowledge, this aspect has not been considered. Our manuscript (i) shows how the equations can be formulated and implemented, and (ii) illustrates with a straightforward model to confirm that the proposed sum in Eq. 15 indeed works, that is, the energy balance is closed and the terms in Eq. 15 are balanced. We are aware that thermodynamic formulations have been used in hydrology before, with reference to thermodynamic optimization (e.g., Rinaldo et al. 1996, West et al., 1997, Zehe et al., 2013). In contrast, our study does not focus on optimization, but shows that thermodynamics provides a diagnostic tool by examining the associated energies in an energy balance that fully accounts for all terms, thus closing the balance. The latter has not been a focus in previous studies.

We do not want to draw any general conclusions on root water uptake except the one, that heterogeneity in soil potentials reflects on the impediment to root water uptake – a result which comes out of thermodynamics, not the simple model (see Fig. 2). We agree with Gerrit de Rooij that heterogeneous soil properties would affect this further, and it would be interesting to investigate this with complex (3-dimensional) models in the future.

(4) *Critique: Some of the model assumptions are invalid, especially regarding root water uptake being independent of local soil energy status*

We believe there might have been a misunderstanding regarding the model setup. It probably appeared as if the computation was conducted with average thermodynamic states. This is not the case. We will modify the description of the model in the revision along the following lines:

The water uptake model is distributed (not averaged), and calculates water flux based on potentials and conductances (Eq. 1, 3 and 4) in each compartment. In each time step the systems of equations is solved for the xylem potential (ψ_x), which is taken the same throughout the root system (corresponding to the assumption that axial resistance is small compared to the radial one, Steudle and Peterson, 1998):

$$\psi_x = \frac{-J_{wu} + \sum_{i=1}^{n} (\psi_{M,i} * K_{r,i})}{\sum_{i=1}^{n} K_{r,i}} \quad \text{(D1)}$$

where J_{wu} is the total plant transpiration, $\psi_{M,i}$ the matric potential on compartment i, $K_{r,i}$ the root conductivity in compartment i.

Root water uptake in each compartment ($J_{wu,i}$) can then be calculated based on Eq. 4, and water content is updated accordingly in each compartment. Thus, the model dynamically adapts the location of uptake based on the local water potential and root distribution in a typical, although simplified, resistance framework.

Next, in each time step, we calculate the change of internal energy, dissipation and flow in each compartment (Eq. 7, 10) and sum them over the entire domain to yield the total change of energy (Eq. 5) and dissipation (Eq. 11) per time step. This is compared to the energy export to (i) demonstrate the closure of the energy balance by comparing two independent ways of calculating it and (ii) demonstrating the information content of the energy export.

(5) Critique: Model is too simple

It was not the goal of the paper to draw general conclusions about root water uptake based on the conceptual model.

We are fully aware that the model is conceptual and is held at a very simple level on purpose. We think that keeping it simple is critical because a thermodynamic approach is still rarely used in hydrology and thus not intuitive to apply (some of the comments in the reviews actually show this as well).

For this, we would like to advocate the usefulness of simple ("toy") models for illustrating the application of theory and the exact balancing of terms, here in the energy balance. We have chosen this model type, because it can be solved easily (see Eq. D1 above), and the soil water dynamics can intuitively be grasped. Also, this simple model allows us to illustrate the sign of the total energy and why it becomes more negative in a moist soil.

We deliberately omitted and simplified the representation of processes. We do not consider soil water flow between compartments because (i) we want to allow for the built up of heterogeneity and (ii) because the implementation of unsaturated flow requires appropriate discretization to avoid numerical errors. Numerical errors reflect on whether or not the energy balance is closed, as it should be. This is because, the dissipation is calculated based on the gradients in one time step, but the change in binding energy based on two consecutive time steps. In the current version, however, we do not elaborate on this numerical aspect, but will expand on this in the revision. Ideally, unsaturated flow and related dissipation is best accounted for in a sophisticated numerical scheme for flow and root water uptake like RSWMS or OGS. Such an application would sacrifice the intuitive character of the paper and take away the focus from the thermodynamics.

As stated above, the model is only used to illustrate that Eq. 15 works and how it can be used to evaluate the impediments to the flow path.

(6) Critique: Study lacks transferability to the real world

Our model is inspired by split root experiments, which have yielded great insight into plant water uptake in the past (Green et al., 1997, Simonneau and Habib 1994, Yao et al., 2001), and at the larger scale by a model on the role of heterogeneous infiltration on soil water, root uptake and ground water recharge (Guswa 2012). In those cases soil compartments are connected only by the root system. We will add this motivation on the choice of root parameters etc. in the revision.

Also, energy export has been successfully applied to discern efficient root systems in a 3-dimensional complex root water uptake model (Bechmann et al., 2014), but because of the model's complexity, the thermodynamic formulation and its numerical implementation are difficult to evaluate and understand. In this paper, we essentially use the same formulations of soil hydrology and root water uptake as in that study (or, generally, in hydrologic models), so that we believe that the formulations and insights we demonstrate should easily be transferable to other models. In the revision, we will provide details more explicitly about how the thermodynamic formulation can be applied in more complex models.

References

Bechmann, M., Schneider, C., Carminati, A., Vetterlein, D., Attinger, S. and Hildebrandt, A.: Effect of parameter choice in root water uptake models – the arrangement of root hydraulic properties within the root architecture affects dynamics and efficiency of root water uptake, Hydrol. Earth Syst. Sci., 18(10), 4189–4206, doi:10.5194/hess-18-4189-2014, 2014.

Green, S.R., Clothier, B.E., McLeod, D.J.: The response of sap flow in apple roots in response to localised irrigation. Agric Water Manage, 33, 63–78, 1997.

Guswa, A. J.: Canopy vs. roots: Production and destruction of variability in soil moisture and hydrologic fluxes, Vadose Zo. J., 11(3), doi:10.2136/vzj2011.0159, 2012.

Rinaldo, A., Maritan, A., Colaiori, F., Flammini, A., Rigon, R., Rodríguez-Iturbe, I., Banavar, J. J. J. R., Rodriguez-Iturbe, I. and Banavar, J. J. J. R.: Thermodynamics of Fractal Networks, Phys. Rev. Lett., 76(18), 3364–3367, doi:10.1103/PhysRevLett.76.3364, 1996.

Simonneau T. and Habib R.: Water uptake regulation in peach trees with split-root systems, Plant, Cell and Environment 17, 379–388. 1994.

Steudle, E. and Peterson, C. A.: How does water get through roots ?, J. Exp. Bot., 49(322), 775–788, 1998.

West, G. B., Brown, J. H. and Enquist, B. J.: A general model for the origin of allometric scaling laws in biology, Science, 276(4), 122–126, doi:10.1126/science.276.5309.122, 1997.

Yao, C., Moreshet, S., Aloni, B.: Water relations and hydraulic control of stomatal behaviour in bell pepper plant in soil drying. Plant Cell Environ.24, 227–35, 2001.

Zehe, E., Ehret, U., Blume, T., Kleidon, A., Scherer, U. and Westhoff, M.: A thermodynamic approach to link self-organization, preferential flow and rainfall-runoff behaviour, Hydrol. Earth Syst. Sci., 17, 4297–4322, doi:10.5194/hess-17-4297-2013, 2013.