Hydrology and Earth System Sciences Discussions

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Interactive comment on "An optimality-based model of the coupled soil moisture and root dynamics" *by* S. J. Schymanski et al.

S. J. Schymanski et al.

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We wish to thank the anonymous reviewer, Praveen Kumar, Francesco Laio and Salvatore Manfreda for contributing helpful comments and suggestions for improvement of the manuscript. We would also like to thank Thomas Wutzler, who communicated helpful comments directly to the first author. The contributions helped identify errors in the manuscript that escaped our attention previously as well as misunderstandings that we we did not anticipate. We apologise for the difficulties caused by errors and unclear formulations and we believe that the contributors' efforts will save many readers' valuable time at the end of the line. Therefore, the contributors deserve thanks also on behalf of the future readers of the article.

Before submitting a revised manuscript, we wish to respond to the comments and outline how the relevant issues will be addressed in the revised manuscript.

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Main Issues

Both reviewers commented on the use of "arbitrary" assumptions in the model, referring to page 69, line 21 in the manuscript, where we stated that the maximum daily root growth rate was "arbitrarily set to 0.1 m^2 per m^3 soil volume". Our formulation may be misleading, as the value of 0.1 m^2 m^{-3} d^{-1} was actually obtained by trial and error, considering the minimum flexibility of the root system needed to satisfy the canopy water demand. This will be clarified in the revised version of the manuscript.

Francesco Laio considered the value of 0.1 m^2 m^{-3} d^{-1} to be very large and suggested that the results would be very different if the value was decreased. The results would indeed be very different, as demonstrated by the simulations using a fixed root distribution in the manuscript. However, we do not agree that the value of 0.1 m^2 m^{-3} d^{-1} is unrealistically large. [Eissenstat (1991)] reported fine root growth rates of 0.07-0.15 cm cm^{-3} wk^{-1} for citrus fine roots with a specific root length of 2 cm mg^{-1}, as in our manuscript. This would translate to growth rates of 0.19-0.4 m^2 m^{-3} d^{-1}, which is more than double the maximum value prescribed in the model. Perhaps, we should also point out again that S_{Ar} only refers to the fine root surface area, which could indeed increase from 0 to 0.1 m^2 m^{-3} in one day provided that sufficient coarser roots are available as starting points for fine root growth. We conclude that the maximum root growth rate permitted in our model is more likely to be conservative than excessively large.

Eissenstat's values are given for roots growing into fresh soil and represent the behaviour after disturbance, not necessarily the response to natural variability in soil moisture. However, the values prove that roots have the capability to grow very fast, even faster than permitted in our model. The more important question is "under what conditions would plants have an advantage by rapidly adjusting their root distribution in the soil profile?". Our results suggest that a savanna with a highly seasonal soil moisture in the top soil represents such conditions. This is also consistent with observations referred to by [Jackson et al. (1997)], as pointed out in the manuscript. A

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recently published paper presents observations of fine root growth under natural conditions in the same vegetation type as the one at our study site [Janos et al. (2008)]. This paper shows an increase in fine root length in the top 1 m of soil from 10 to 120 m m^{-2} in 3 weeks, which is equivalent to an average increase in root surface area by 0.01 m^2 m^{-3} d^{-1} if the dominant fine root radius is assumed to be 0.3 mm. In comparison, the maximum fine root growth rate in our model occurred at the beginning of the simulation, when the root surface area increased from 0.1 to 0.7 m^2 m^{-3} in 40 days at the bottom of the root profile. This is equivalent to an average increase in root surface area by 0.015 m^2 m^{-3} d^{-1}. We conclude that Eissenstat's observations confirm that the maximum growth rate theoretically permitted in our model is realistic, while the observations by Janos et al. confirm that the maximum growth rate simulated by our model at the study site is realistic, too.

We find the concept of a seasonally changing vertical root distribution in an ecosystem composed of perennial deep rooting vegetation and seasonal shallow rooting vegetation very intuitive. In fact, we would suggest that models assuming a constant root profile should not be used in such ecosystems.

Another issue pointed out by both reviewers is the incomplete verification of the model outputs with observations at the site. Unfortunately, soil moisture was only measured in the top soil during the study period. These data have been presented in the manuscript and compared with the simulated soil moisture dynamics in the top soil layer. Soil moisture measurements at different soil depths are only available for the hydrological year 1998-1999 [Kelley (2002)]. We performed a comparison of these observations with the simulated soil moisture dynamics in the soil profile obtained using the empirical and optimised models in the hydrological year 2004-2005. Unfortunately, the 1998-1999 wet season was exceptionally wet (2600 mm of rain, as opposed to a mean of 1700 mm) and neither of the 2004-2005 simulations was found to have more similarities with the 1998-1999 observations than the other one. Therefore, we decided not to present the comparison in the paper. The main focus of the paper was to formulate

a model that uses the costs and benefits of roots in terms of respiration and water uptake to derive an optimally varying root profile given the canopy water demand and the soil water balance. A rigourous test of the soil water balance model would be beyond the scope of the paper. Further improvements of the water balance model (e.g. consideration of heterogeneity, macropores and fingering) and tests on sites with detailed soil moisture measurements in the soil profile could be presented in separate papers.

Francesco Laio commented that the vegetation water balance is modelled in great detail, while the soil water balance model follows a very simplified approach. We assume that the perceived simplicity of the water balance model originates from some confusion about the parameterisation of soil moisture in the model. We apologise for the confusion caused and will improve the revised manuscript accordingly (see the detailed comments below). The fact is that soil moisture was modelled for each soil layer 10 cm thick individually and the water fluxes between the soil layers were computed using a discretisation of Richards Equation. We believe that the assumption of a horizontal water table and the neglect of slope in the calculation of infiltration is justified in the modelled catchment, as the slopes on the study site are $< 1°$, as stated in the manuscript and acknowledged by Francesco Laio. During the derivation of both the soil water balance and root water uptake components we followed the same principle of parsimony in model parameterisation. Only processes that were necessary for capturing the characteristics of the feedback between the two components were considered. The vegetation water balance was deemed necessary for modelling the potential delay between root water uptake and transpiration as well as root-mediated hydraulic redistribution in the soil profile.

Salvatore Manfreda suggested to test different optimisation principles for driving the dynamically optimising root profile such as maximisation of water use efficiency. We believe that this principle is more useful to optimise the canopy water use than root water uptake. In fact, we used this principle in an earlier paper to dynamically

optimise stomatal conductance in conjunction with a canopy photosynthesis model [Schymanski et al. (2008)]. The present manuscript focuses on root water uptake only, assuming that the optimisation of canopy water use is implicit in the observed canopy water use, which has been prescribed as a driver for root water uptake.

Both Francesco Laio and Salvatore Manfreda requested a clarification of whether the optimality principle or the larger model complexity led to better results in the optimality-based model compared with the model based on a fixed root profile. Francesco Laio pointed out that the optimality-based model has more parameters than the empirically-based model because it requires an additional parameter (maximum root growth, see above) that is not needed in the empirical model. Strictly speaking, this statement is incorrect, as both models contain the same parameters. The only difference is that the maximum growth rate is 0 in the empirical model and 0.1 m^2 m^{-3} d^{-1} in the optimality-based model. Due to its sensitivity to the initial conditions, the empirical model requires even more input parameters, such as the root surface area in every soil layer, or at least the parameters defining the shape of the root profile and the root area index. In contrast, the optimality-based model is fairly insensitive to the initial root distribution and therefore needs fewer input parameters.

We agree with Salvatore Manfreda that the optimality-based model is more complex than the empirical model, because it has a dynamically varying root profile. However, the better results obtained by the optimality-based model are not only due to its increased complexity, but due to the optimisation itself. This is obvious in the dry season fluxes, where the empirical root profile led to water uptake rates that were below the observed transpiration rates and produced respiration rates that exceeded observed soil respiration rates by an order of magnitude (page 74, lines 18-23). The optimality-based model, on the other hand, resulted in a relatively static fine root profile in the dry season that produced water uptake and root respiration rates that were consistent with the available observations.

It is clear that the empirical model would generally perform better than the optimality-

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based model if the dynamics of the root system could be prescribed empirically. However, the dynamics of fine root distributions in the soil profile are largely unknown, which is why empirical models usually prescribe static root profiles. The optimality assumption allowed modelling fine root dynamics in the absence of empirical observations, which is particularly important for our understanding of root adaptation to environmental change (see the Discussion section in the manuscript).

In the below sections, we will address all of the submitted comments and point out what changes will be made in the revised manuscript to correct errors and improve clarity. We believe that the paper will be a significant contribution to Hydrology and Earth System Science and we wish to thank all the contributors for helping to improve the paper.

Issues raised by the anonymous Referee #2

Adaptations of the above-ground vegetation properties were not part of this study but they are treated in a follow-up paper [Schymanski et al .(2008)]. In the present study, all above-ground adaptations are assumed to be expressed in the observed canopy water use that was used as a driver for root water uptake.

When talking about arbitrary assumptions, we assume that the reviewer refers to the maximum root growth rate (page 69, line 21 in the manuscript). We will clarify in the revised manuscript that the value of this parameter was obtained by trial and error with the aim to give enough flexibility to the root system for satisfying the canopy water demand, while preventing excessive oscillations of root surface area due to exaggerated daily increments.

As discussed above, there was not enough data available from the study site for a detailed validation of the water balance model. However, the main objective of the study was an improved root water uptake and dynamics model that would give a realistic coupling between root water uptake and respiration costs. We will make this a bit clearer in the introduction of the revised manuscript.

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We thank the reviewer for pointing out the word confusion on page 56. This will be corrected in the revised manuscript.

Issue raised by Praveen Kumar

We thank Praveen Kumar for pointing out to us the error on page 76 and we apologise for misquoting [Amenu and Kumar (2007)]. The paragraph will be changed in the revised manuscript to:

"Existing models assume that when stomata close, there is no movement of water through the plant system resulting in the abrupt shut-down of root water uptake. Recently, [Amenu and Kumar (2007)] formulated a root water uptake model that enables the simulation of simultaneous efflux of water from the plant to the soil in layers of dry soil and root water uptake in layers of wet soil at night, when stomata are assumed to be closed. However, observations of prolonged sap flow after the shut-down of canopy transpiration [Silberstein et al. (2001), Unsworth et al. (2004)] and the finding that tree water storage can be important for tree water use suggest that there can be significant net water uptake at night when the plant water store is being filled up [Goldstein et al. (1998), Meinzer et al. (2003), Zweifel and Häsler (2001), Zweifel et al. (2001)]."

Issues raised by Francesco Laio

Under point 1, Francesco Laio pointed out potential deficiencies of the soil water balance model:

On page S98, he claimed that the assumption of a horizontal water table and the neglect of the influence of terrain slope on the infiltration process constitute overly simplified assumptions. Given that the model was actually applied in a flat study site (slopes $< 1°$), the above claim does not appear relevant. Francesco Laio was aware of this fact, as he acknowledged on page S100 that the terrain of the study site was flat. Therefore, we do not see the need to address this point in the manuscript.

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Still on page S98, Francesco Laio points out that the decline in elevation of the water table is formulated in Equation 13 as a function of soil porosity and the average soil moisture content in the unsaturated zone and that this formulation neglects the influence of variations in the vertical soil moisture profile on the water table position. The fact is that Equation 13 formulates changes in the water table elevation as a function of the fluxes in and out of the saturated zone, including $Q_{nlayers}$, which is a function of the pressure head gradient between the saturated zone and the bottom layer of the unsaturated zone (Equation 4 in the manuscript). The division by $\varepsilon\left(s_u(t) - 1\right)$ in Equation 13 merely reflects the fact that the saturated zone can only expand into the air-filled volume of the unsaturated zone. This will be clarified in the revised version of the manuscript. For the fluxes between the unsaturated and the saturated zones, only the local head gradient at the interface between the two zones is relevant, not the shape of the whole soil moisture profile, as suggested by Francesco Laio on page S98.

As pointed out by Francesco Laio, there are some inconsistencies with the subscripts related to soil moisture (s_u) in the manuscript, potentially leading to confusion about whether the average soil moisture in the whole profile is referred to or the soil moisture within a single layer. Except for the description of the original REW model and Equation 13, s_u refers to the local soil saturation degree and should have the subscript i. This will be fixed in the revised manuscript, and a notation table will be provided to improve clarity.

With respect to Francesco Laio's comment about the detailed treatment of the water fluxes in the plant system, we wish to point out that the consideration of the plant water store was helpful for investigating phenomena like nocturnal root water uptake and hydraulic redistribution. In fact, the buffer introduced by the plant water store allows peak transpiration rates that would not be possible otherwise, or at least not without a substantially increased root surface area. This has been demonstrated in Figure 7 in the manuscript and we are confident that the discussion will encourage similar treatments in future models. It is also not clear to us what Francesco Laio intends to suggest by his

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comment at the top of page S100 with respect to the detailed treatment of infiltration and exfiltration dynamics. His acknowledgement of the fact that the model is indeed applied in a flat terrain somehow disarms his previous critique about neglecting slope effects, so we do not know what else we could improve in the manuscript in this regard.

Under point 2, Francesco Laio expressed the following doubts about some of the results:

On page S100, he suggested that the choice of the maximum fine root growth of 0.1 m^2 m^{-3} d^{-1} in the model is too large and results in an unrealistically dynamic root system. He asks for more supporting empirical data (e.g. root biomass measurements at different times in the dry and wet season) supporting the simulated dynamics. As the dynamics of the root distribution in the soil profile may be surprising to many readers familiar with models based on static root distributions, we will mention the findings by [Eissenstat (1991)] and [Janos et al. (2008)] in the revised manuscript to support the choice of the maximum root growth rate and the resulting dynamics. See also our discussion of this issue under "Main Issues" in this document. The literature cited in the manuscript supports the dynamic root distribution in the soil profile at the site and the interested reader can follow up references given by [Schenk and Jackson (2005)] and [Jackson et al. (1997)] to find more empirical evidence for other sites. As mentioned above, under Main Issues, we find it intuitive that the vertical root distribution changes seasonally in an ecosystem composed of perennial deep rooting and seasonal shallow rooting vegetation. Assuming that it does not change, in fact, would mean either that the seasonal vegetation has no roots or that the perennial vegetation produces and sheds roots with an exactly opposite timing to the growth and decay of the seasonal vegetation.

Further along on page S100, Francesco Laio stated that the better performance of the optimality-based model was only based on a comparison of the reproduction of the measured surface soil moisture time series. This is not correct, as the main point of the paper was to demonstrate that the optimality-based model gave a more realistic

relation between root water uptake capacity and respiration costs than a model with an empirically prescribed, fixed root system. This was discussed at length in the Discussion section of the manuscript and it was pointed out that the empirically-based model over-estimated root respiration by an order of magnitude while under-estimating root water uptake during the dry season (page 75, lines 12-17). We are not able to provide a comparison of the model results with observed fine root or soil moisture dynamics in the soil profile, as such observations are not available for the studied period, but we will provide a comparison of the observed and simulated dynamics of transpiration in the revised manuscript. This comparison will illustrate that failures of the models to match the observed water use are mostly limited to the late dry season (when soil moisture is most depleted).

On page S101, Francesco Laio suggested that the better fit of the optimality-based model could be an effect of the increased number of model parameters and not a result of a better representation of the physical processes. He refers to the use of the maximum fine root growth rate that was "arbitrarily set" in the optimality-based model. The representation of the physical processes is identical in all model runs, the only differences are related to the biological process of root dynamics. The value of the maximum fine root growth rate limits the temporal flexibility of the root system, with a value of 0 leading to a static root profile and increasing values leading to potentially stronger variability of fine root surface area in the soil profile. It is intuitive that the fine root abundance in the different soil layers changes dynamically due to the presence of deep rooting perennial and shallow rooting seasonal vegetation. Therefore, parameterisation of a dynamic root system should lead to improved simulation of root water uptake, if the dynamics represented in the model are realistic. Empirical parameterisation of the fine root dynamics at the site is not possible, as appropriate observations are not available. This is the case for most sites. Therefore, the use of the optimality-based model constitutes a major advance in the modelling of dynamic root systems. This will be pointed out more explicitly in the Discussion of the revised manuscript. The estimation of the maximum fine root growth rate will also be clarified in the revised

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manuscript and a comparison with field observations that justifies the estimated value will be presented, as discussed above under Main Issues.

Under minor points, Francesco Laio pointed out the following issues:

- Non-intuitive derivation of Equation (2). The equation for Z suggested by Francesco Laio is incorrect, as it should be: $Z = y_s + y_u * \omega_u$ [Reggiani et al. (2000)]. The correct derivation was given in A.3.2.1 in [Schymanski (2007)], which is publicly available from the University of Western Australia's web site. For convenience, the direct link to the file will be provided in the references section of the revised manuscript.

- Reference to [Laio et al. (2006)]. We will cite this paper alongside with the other papers based on a static root distribution cited in the introduction.

- Notation table with model parameters and their values. The revised manuscript will contain a notation table with all the variables, their units and values used where applicable.

References

[Amenu and Kumar (2007)] Amenu, G. G. and Kumar, P.: A model for hydraulic redistribution, Hydrology and Earth System Sciences Discussions, 4, 3719–3769, 2007.

[Eissenstat (1991)] Eissenstat, D. M.: On the Relationship between Specific Root Length and the Rate of Root Proliferation - a Field-Study Using Citrus Rootstocks, New Phytologist, 118, 63–68, 1991.

[Goldstein et al. (1998)] Goldstein, G., Andrade, J. L., Meinzer, F. C., Holbrook, N. M., Cavelier, J., Jackson, P., and Celis, A.: Stem water storage and diurnal patterns of

water use in tropical forest canopy trees, Plant Cell & Environment, 21, 397–406, 1998.

[Jackson et al. (1997)] Jackson, R. B., Mooney, H. A., and Schulze, E. D.: A global budget for fine root biomass, surface area, and nutrient contents, Proceedings of the National Academy of Sciences of the United States of America, 94, 7362–7366, 1997.

[Janos et al. (2008)] Janos, D. P., Scott, J., and Bowman, D. M. J. S.: Temporal and spatial variation of fine roots in a northern Australian *Eucalyptus tetrodonta* savanna, Journal of Tropical Ecology, 24, 177–188, doi:10.1017/S0266467408004860, 2008.

[Kelley (2002)] G. Kelley: Tree water use and soil water dynamics in savannas of northern Australia, PhD thesis, Northern Territory University, Darwin, Australia, 2002.

[Laio et al. (2006)] Laio, F., D'Odorico, P., and Ridolfi, L.: An analytical model to relate the vertical root distribution to climate and soil properties, Geophysical Research Letters, 33, doi:ARTNL18401, 2006.

[Meinzer et al. (2003)] Meinzer, F. C., James, S. A., Goldstein, G., and Woodruff, D.: Whole-tree water transport scales with sapwood capacitance in tropical forest canopy trees, Plant Cell & Environment, 26, 1147–1155, 2003.

[Reggiani et al. (2000)] Reggiani, P., Sivapalan, M., and Hassanizadeh, S. M.: Conservation equations governing hillslope responses: Exploring the physical basis of water balance, Water Resources Research, 36, 1845–1863, 2000.

[Schenk and Jackson (2005)] Schenk, H. J. and Jackson, R. B.: Mapping the global distribution of deep roots in relation to climate and soil characteristics, Geoderma, 126, 129–140, 2005.

[Schymanski (2007)] Schymanski, S. J.: Transpiration as the Leak in the Carbon Factory: A Model of Self-Optimising Vegetation, Ph.D. thesis, University of Western Australia, Perth, Australia, 2007.

[Schymanski et al. (2008)] Schymanski, S. J., Roderick, M. L., Sivapalan, M., Hutley, L. B., and Beringer, J.: A canopy scale test of the optimal water use hypothesis, Plant Cell & Environment, 31, 97–111, 2008a.

[Schymanski et al .(2008)] Schymanski, S. J., Sivapalan, M., Roderick, M. L., Hutley, L. B., and Beringer, J.: An Optimality-Based Model of the Dynamic Feedbacks between Natural Vegetaton and the Water Balance, Water Resources Research, (submitted), 2008b.

[Silberstein et al. (2001)] Silberstein, R., Held, A., Hatton, T., Viney, N., and Sivapalan, M.: Energy balance of a natural jarrah (*Eucalyptus marginata*) forest in Western Australia: measurements during the spring and summer, Agricultural and Forest Meteorology, 109, 79–104, 2001.

[Unsworth et al. (2004)] Unsworth, M. H., Phillips, N., Link, T., Bond, B. J., Falk, M., Harmon, M. E., Hinckley, T. M., Marks, D., and U, K. T. P.: Components and controls of water flux in an old-growth Douglas-fir-western hemlock ecosystem, Ecosystems, 7, 468–481, 2004.

[Zweifel and Häsler (2001)] Zweifel, R. and Häsler, R.: Dynamics of water storage in mature subalpine *Picea abies*: temporal and spatial patterns of change in stem radius, Tree Physiology, 21, 561–569, 2001.

[Zweifel et al. (2001)] Zweifel, R., Item, H., and Häsler, R.: Link between diurnal stem radius changes and tree water relations, Tree Physiology, 21, 869–877, 2001.