<u>Revised manuscript and author's replies to reviewers</u>

We thank the anonymous referee #1 ("AR1") for his/her review, the intensive examination of our manuscript and the interactive discussion. In particular we want to thank AR1 for his/her repeatedly substantial and useful comments. They helped us a great deal to identify shortcomings in our manuscript and greatly contributed to improving it. As proposed earlier, we will give a point by point response to AR1s referee comments in the following.

<u>Anonymous Referee #1, Interactive Comment 1, General Comments</u>

> *"This paper raises interesting questions, and figures and tables are mostly clear. The authors present a version of Doussan et al. (1998) model of the root hydraulic architecture, for which each root segment is associated to a soil element non-interacting with other soil elements, in order to emphasize the effect of simple combinations of root types (young and mature) and topologies on the dynamism of root water uptake. Then the impact of these combinations on two efficiency indices is illustrated. The first index is called effort and corresponds to the time averaged plant collar water potential before reaching water stress. The second one is called water yield and corresponds to the cumulated transpiration until water stress is reached, divided by the total root length. Both indices are shown to be sensitive to combinations of root types and topology. Then the authors carry out a similar sensitivity analysis using a more complex model accounting for soil water flow with a single complex root system architecture, but different degrees of root maturity (e. g., 60% young root segments and 40% mature root segments). A perspective would be to use these two indices to parameterize root hydraulic properties distributions."*

The main purpose of this study was to principally investigate, to what extent different parameterizations of root hydraulic properties in entire root systems influence basic efficiency criteria in terms of "benefits" and "costs" as well as spatiotemporal root water uptake dynamics. Although we believe our results may be useful identifying likely parameterizations, it was not our primary goal to model root water uptake of a specific plant. Within our abstract, P759 one finds in lines 5-6: "In this paper we explore the role that arrangement of root hydraulic properties and root system topology play for modelled uptake dynamics.".

AR1 follows up with some concerns regarding the manuscript in discussion:

> *"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."*

We understand that our background section needed improvement. We revised it substantially, also to prevent it from being misleading. We now explain that our thought experiment is a simplification of a heterogeneous uptake process. We also better link the background section to the paper to show that axial and radial limitation (which we derive using the simple model of the background section) do also exist in more complicated and heterogeneous systems. Our results and conclusions are still valid independently of the changes in the background section, because they are obtained with more complex and realistic models. We made an effort to make this more obvious in the revision. Please see also our response to RC 7 for more detailed information on the alleged artifact.

> *"Many statements are also not well motivated, and some of the concepts defined in this paper are misused."*

We believe AR1 refers to the concepts mentioned in his/her specific comments, which are (a) the "plants overall resistance to root water uptake", (b) "axial limitation" and (c) "redistribution of root water uptake".

(a) In the revision, we have made sure to more properly distinguish between the "overall resistance to root water uptake" and "effort" ("energy necessary for root water uptake") throughout the manuscript. We also took into account the reviewers related comments during the interactive discussion, an intensive discussion on the connection between "overall resistance to root water uptake" and "effort" can be found on pages C553-C559 as well as Figs. SC2.3 and 2.4 of our second short comment to AR1. We revised the manuscript accordingly.

(b) We understand that denoting two effects with the same name easily causes misunderstandings, regardless if they are interrelated. We introduced two terms to avoid any possibility of confusion in the revision: After having shown that optimal root lengths exist and that they depend on root hydraulic parameterization, we denote with "axial limitation" the prolongation of roots beyond their optimal length in the revised manuscript. Following Zwieniecki et al. (2003), a decay of root water uptake rates in roots will be denoted by the term "hydraulic isolation" (see also our replies to RC10 and RC36 below).

(c) In the revision, we changed the wording in order to indicate that we do not explicitly quantify compensation of local water stress, but that we however suspect that increased efficiency is caused by the before mentioned redistribution of root water uptake (see also our response to RC37 below).

> *"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 understand that we needed to improve the motivation and introduction of our indices, and we did so in the revision. In the specific comments (RC26, RC27) the reviewer specifies that other metrics, like the overall root resistance, are better suited than the ones proposed (“effort” and “water yield”) to evaluate parameterizations, because they are not as much subject to the chosen scenario. However, we aim at comparing different root hydraulic paramterizations in terms of energy necessary for water uptake. During the interactive discussion, we have shown that in conditions of heterogeneous soil water potential, an overall root resistance according to Couvreur et al. (2012) does not reflect entire energy. More details and reference to the previous discussion are given in the response to comments RC26 and RC27.

The reviewer further comments that the two metrics are related. We agree this to be the case. We did not use two metrics because we expected different information, but because we wanted to accompany the new one to a more established metric. Water yield refers more generally to the total flux over the boundary, and the latter has been evaluated before to compare model parameterizations (Javaux et al., 2008, Zwieniecki et al. 2003). On the other hand, effort is really a new way for evaluating the plant water status over time, which is based on the work required to uptake water. Both measures evaluate model parameterizations based on what seems physiologically meaningful for the plant. Since, we find that effort is more sensitive than water yield to parameterization, we conclude that it is the measure which conveys more information.

We agree that the sensitivity is not overwhelming (for certain parameterizations) and we included in the revised manuscripts a comment regarding the fact that the measures are related. This may among others depend on the rather short root systems investigated here. However, the fact that the plant function is not strongly affected by arrangement of the roots – as long as some heterogeneity is accounted for – is an important result of our study. Our indices can help identifying parameterizations that are not trivial from a point of view of plant function, for example, because they enhance hydraulic redistribution while at the same time worsening the water status of the plant. Also, both metrics are minimized at the same time with regard to root length, which further supports that our argumentation on axial and radial limitation exist independently for both the more established and the new metric applied to derive it.

> *"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."*

In fact, the indices do not depend on this assumption, our Methods section was probably misleading. We re-organized the Methods section to state this specifically. The corresponding discussion on the applicability of water yield and effort on more realistic scenarios can be found on pages C146-C148 and Fig. 1 of our first short comment to AR1 as well as pages C551-C553 and Figs. SC2.1 and SC2.2 of our second short comment to AR1. Please see also more detailed comments in our response to RC 26.

"Regrettably, many sections of the paper are unclear due to lacking units when defining new symbols, errors in equations, conceptual inaccuracies."

We thoroughly revised the manuscript accordingly.

Anonymous Referee #1, Comment 1, Specific Comments

RC1, P761, L7

"The meaning of the expression "these models resolve the root geometry" is unclear. "Solve water flow equations within soil and root system architecture" might be more adapted."

We changed this accordingly.

RC2, P761, L12

"The meaning of the expression "compensation of local water stress" is unclear. "redistribution of root water uptake due to local limitations of soil water availability" or "due to soil water potential heterogeneity" might be more adapted."

We changed this accordingly.

RC3, P761, L12

"Redistribution of root water uptake is actually reproduced by Feddes et al. (1976) model when coupled to Jarvis (1989) model (see also Simunek and Hopmans (2009)). They are however not based on quantitative hydraulic principles, which is their drawback as compared to Doussan et al. (1998) model. The argument should thus be more balanced."

We changed the wording in order to refer to the empirical model by Feddes et al. (1978) only.

Old: Such processes could not be reproduced with first one-dimensional models, which related uptake directly to rooting density and soil moisture and lead to early water stress when upper densely rooted layers dry out (Feddes et al., 1978).

New: This is a major improvement compared to empirical models (Feddes et al., 1978). The inherent redistribution of root water uptake based on explicit calculations of water flow in roots is also reported to be superior to qualitative approaches (Simunek and Hopmans, 2009).

RC4, P762, L18

> *"The statement "parameterization has to be based on intuition" is a bit strong and sounds like "that's how it should be", which is not true. The point that the hydraulic parameterization is based on scarce quantitative information and is thus generally complemented by qualitative information on roots anatomy might be more appropriate."*

We have changed this section accordingly as follows:

Old: However, as stated earlier, the actual arrangement of hydraulic properties within the root system is most of the time unknown and parameterization has to be based on intuition.

New: However, as stated earlier, the actual arrangement of hydraulic properties within the root system is most of the time unknown and parameterization is based on scarce quantitative information, and researchers are often left to their intuition.

RC5, P762, L29

> *"The point is interesting. Just for the record, Choat et al. (2012) published similar results in Nature a year earlier."*

Thank you, we updated the reference.

RC6, P763, L9-12

> *"This sentence is a conclusion, not an objective or context. It should be removed or reformulated."*

We changed the wording to show what we are aiming at, and leave the result in the discussion.

Old: Within this research we investigate how heterogeneity of root hydraulic properties influences root water uptake dynamics and evolution of xylem water potential. We also investigate the role of branching topology. Our results show that both the heterogeneity of root hydraulic properties and branching strongly influence the modelled evolution of xylem water potential, microscopic and macroscopic location of root water uptake as well as hydraulic lift.

New: This modeling study aims at describing and assessing the combined role of heterogeneity of root hydraulic properties and branching topology on root water uptake dynamics. We also investigate their relation to the spatiotemporal evolution of xylem water potential, the overall efficiency of root water uptake and microscopic and macroscopic water relations including hydraulic lift.

RC7, P763, L16 – P764, L12

> *"Even in the uniform unbranched root used in the example, there are actually an infinite number of parallel radial pathways (of the same radial resistivity), each corresponding to a different relative position to the top of the root. The consecutive axial pathways are more or less resistive depending on the position of the radial pathway (less resistive if closer to the top). For simplification purpose, the authors postulate that these pathways can be summarised as two single pathways in series (one radial and one axial). Consequently, they find out that the total resistance of the uniform unbranched root is a function of its length. This function is first decreasing and then increasing for long root lengths. 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."*

We substantially revised the background section, in particular to accommodate this comment by the reviewer (see also our reply to RC12). Our original idea in writing this section was to guide the reader and improve understanding, by introducing the concept of axial and radial limitation upfront. We therefore appreciate the comment that it has been misleading.

If we understand the reviewer correctly, his/her argumentation consists of two assumptions: (a) the simple model proposed only shows minimum effort, because it has been modeled with a single segment and therefore was not properly discretized. (b) Because we motivate our definition of radial and axial limitation from this simple model also the concepts of radial and axial limitation should not exist. The latter would have implications on the rest of the paper, since we often refer to the concept of axial limitation.

This very important point has been part of the interactive discussion. We are aware that a discretization of a root needs a sufficiently large number of segments to avoid artifacts. For that reason we performed the simulations presented in the discussion paper with discretizations of 100 segments for unbranched single roots, 192 segments for branched single roots and more than 1000 segments for the entire root system. In order to point this out more clearly, we added the number of segments to the model parameters (Table 1).

In the interactive discussion, we repeated our simulations with respect to the number of segments. Our results illustrate that effort indeed has an optimum at a given root length, independently of discretization and that the number of segments used are sufficient (see Fig. 2 of our first short comment to AR1). Therefore the concepts of axial and radial limitation are valid and not an artifact of discretization. Within the discussion we also explained, why we did not calculate the “real” resistance for a discretized model: in realistic situation, where the water around the root is depleted and soil water potential is heterogeneous, the root resistance does not reflect the overall energy necessary for root water uptake we are interested in (see also our reply to AR1s second interactive comment, pages C553-C559, paragraphs 10-25, as well as our response to RC26 and RC27 below).

In our paper, axial and radial limitation indicate from a functional point of view, whether it is efficient to invest in prolonging an existing root, or alternatively investing on a new parallel root. This has implications for efficient root branching, which is what we investigate later in the paper. We motivate this early in the background section using a different but familiar concept, namely root resistance on a single element, and we extend this towards efficiency (in terms of energy) of a discretized root branch later in the paper after the efficiency metrics are introduced.

We intended the thought experiment of our background section to be related to the time integral of the water uptake processes, spanning from standard moist conditions up to water limitation, and encompass water uptake moving along the root. In our background section, we force water to be taken up equally along the root, by considering only one segment. This is a simplification of the real process, where water uptake moves away from the collar and when integrated over time it is (almost) equal along the root. The moving uptake also sequentially increases the active root length, which we incorporate by increasing the length of the single segment. In other words, omitting discretization is not an artefact, but done on purpose to represent the uptake process in a limited reservoir. We have changed the background section to make this more clear and avoid misunderstanding (see also our reply to RC12).

RC8, P763, L21 – P764, L14

> *"None of the variables in this section is presented to have units. For the sake of clarity, when new variables or parameters are defined, in any section of the paper, their units should also be given."*

We added missing units throughout the entire manuscript.

RC9, P764, L14

> *“The expression is reported to have “m” units, which is wrong. That expression has “m^(3/2)” units.”*

We thank AR1 for this comment. Indeed, the radius was missing in the derivation, which brings the units back to m. We changed equations (2) – (7) in the revised manuscript accordingly.

RC10, P764, L15-19

> *"Following RC7, “axial limitation” as defined by the authors does not exist. It would however be interesting to discuss the sensitivity of the total root resistance to axial and radial resistances, according to root topology and to the distribution of hydraulic properties."*

As discussed in our answer to RC7, we changed the background section, to avoid misunderstandings. However, this does not change the message of the background section, that under these specific conditions an optimal root length for water uptake and thus axial limitation both exist. Later in the paper, this line of thoughts is further extended and supported by the observation that the energy necessary for root water uptake is minimized for a specific root length (see Fig. 3 of the manuscript).

In order to sharpen our argumentation we introduced the terms “axial limitation” and “hydraulic isolation” to discriminate between the non-optimal length of a root with given hydraulic properties, and the decay in local RWU rates along a root strand.

As stated above we did not aim to calculate root resistance as we are interested in energy necessary for root water uptake (see also our responses to RC7, RC26 and RC 27 as well as our reply to AR1 second interactive comment, pages C553-C559, paragraphs 10-25). However, the measure "effort" integrates over an entire transpiration period, which allows us to answer a question similar to the one the reviewer raises in the second part of this comment.

RC11, P765, L1-2

> *"The fact that the root water uptake dynamics is sensitive to the ratio of radial to axial hydraulic conductances was already reported in the introduction with different references (see P762, L2-5). These should be grouped."*

We mention these two specific references here to point out the difference to previous work. However, we added the missing reference earlier in the manuscript accordingly.

RC12, P765, L4-5

> *"Following RC7, this statement is wrong. It would however be interesting to balance interests and drawbacks of extending roots in the introduction. The access to water and nutrients, as well as the carbon cost to build roots, should be mentioned. Lynch (2013) wrote an interesting paper on the topic."*

The first part of the comment is addressed in our response to comment RC7: Within a finite soil reservoir, there exists axial limitation to root water uptake, and it is independent of the discretization. We included a comment on nutrient and carbon costs as follows:

Old: When root length is shorter than its optimum, an increase in root length decreases total resistance by increasing the uptake area. We will refer to this case as “radial limitation”. On the other hand an increase of l beyond its optimal value increases total resistance, because in this case the axial resistance term dominates. This situation will be referred to as “axial limitation” in this paper.

New: When root length is shorter than its optimum, an increase in root length decreases overall resistance to root water uptake by increasing the effectively utilizable uptake area. We will refer to this case as “radial limitation”. On the other hand an increase of *l* beyond its optimal value increases overall resistance, because water has to travel longer distances through the root and in this case the axial resistance term dominates. We will refer to such situations as “axial limitation” in the rest of this paper.
Although we are aware that the above-mentioned example is clearly a simplification, it nevertheless captures a more complex representation of roots in limited water reservoirs. The real uptake process is heterogeneous and transient along the root length, as described above. It is still possible to calculate a pure effective root resistance. Couvreur et al. (2012) nicely accounted for the heterogeneity of the soil water potential by identifying an equivalent soil water potential felt by the root. However, our approach is different as we do not aim to separate the effects of the root from those of the soil. We aimed to understand the combined effects of the root hydraulic architecture and the soil on the collar water potential for different root hydraulic architectures. We will show later in this paper that a similar optimum corresponding the effective resistance of the root-soil continuum can be observed when considering an average work per unit water taken up by the root. Please note also, that we put our focus on root water uptake only, combined effects of nutrient uptake or carbon costs (Lynch et al., 2013) are neglected.

RC13, P765, L23

> *"The sentence is unclear. The word “altered” seems misused."*

We changed the wording as follows:

Old: Second, we explain how heterogeneity of root hydraulic properties was systematically altered along the different root systems.

New: Second, we explain how root hydraulic properties were systematically varied within the different root systems.

RC14, P766, L6-7; RC15, P766, L7-8 and RC16, P766, L8-9

> *"It is not clear whether the authors mean "water content" or "water potential" was uniform."*
>
> *"I guess that the authors mean that there was no soil water flow between soil layers. Water redistribution might also be due to root hydraulic redistribution. This point should be clarified."*
>
> *"It is not clear whether the authors mean that the soil "hydraulic properties" are uniform or that the soil "hydric state" was permanently uniform (bulk approach). Also, in case of a bulk approach, is the soil hydric state uniform around each individual root or on the whole soil profile? This should be clarified. Also, the volume of the soil buckets should be given."*

In all of our simulations, the soil hydraulic parameters were uniform within the entire soil domain. The soil water content changes in response to root water uptake and with it soil water potential. We put emphasis on enhancing this throughout the revised manuscript and added the size of the soil cylinders in the table of simulation parameters (Table 1). In particular, we reorganized and changed the specific paragraph as follows:

Old: Water is taken up from a soil cylinder with radius rsoil surrounding the root. We assumed that water was distributed initially uniformly along the soil profile. Furthermore water redistribution between the soil layers was neglected. Since the soil is also considered to be homogeneous, changes in soil matric potential reflect changes in soil water content.

New: Each root segment is provided with a limited soil water reservoir. Water is taken up from closed soil cylinders with radius r_{soil} = 1.2cm surrounding the root segments. The water content within each of those soil cylinders is assumed to be spatially constant, but may be different between soil segments. Soil water flow between the soil cylinders was neglected. All soil cylinders share the same hydraulic properties. The soil water potential $\psi_{Soil}^{(i)}$ (m) within each soil cylinder i is derived from volumetric soil water content $\theta_{Soil}^{(i)}$ (m^3/m^3) with a van Genuchten parameterization of the soil $\theta_{Soil}^{(i)} = f(\psi_{Soil}^{(i)})$. Parameters are taken from Schneider et al. (2010) and were originally obtained for a sandy soil (see Table 1 for details). Thus, the change in soil water status within the soil cylinders is related entirely to root water uptake or release. Simulations are started with initially uniform water content throughout the entire soil domain.

RC17, P766, L15

> *"Resistance units are missing. According to other units, they should both be "s m^-2"*

We changed this accordingly.

RC18, P767, L2

> *"Units for the radial resistivity are thus wrong. They should be "s"."*

They are seconds; see original discussion paper, P767, L2. However we slightly changed the wording:

Old: The factors $\zeta_{Ax}^{(i)}$ and $\rho_{Rad}^{(i)}$ are the axial and radial resistivity, given in s m-3and s respectively

New: The factors $\zeta_{Ax}^{(i)}$ (s/m^3) and $\rho_{Rad}^{(i)}$ (s) are the axial and radial root hydraulic resistivity of root segment i.

RC19, P767, L14

> *"Equation 3 does not cover the case of root branching. This should also be accounted for."*

We changed the equation to make it more general and include convergence of water flow from branching (see equations (8)-(10) in the revised manuscript).

RC20, P767, L24-26

> *"This type of water stress boundary condition is typically referred to as "isohydricity". It would be good to mention it."*

We changed the wording accordingly.

Old: All simulations are started with a flux boundary condition until collar potential drops to a critical threshold…

New: All simulations are started with a flux boundary condition until collar potential drops to a critical threshold (here taken as a typical value of the permanent wilting point $\psi_{Crit} = -150m$ (-1.5 MPa) upon which the boundary condition switches to the potential boundary condition $\psi_x^{(0)} = \psi_{Crit} = -150m$, thus mimicing "isohydric plants".

RC21, P768, L7-8 and RC22, P768, L8-10

> *"I understand that this assumption was made for reasons of simplicity. I would add that it was made to explain in simple terms the impact of soil water potential distribution on root water uptake distribution for different root hydraulic types. It totally makes sense. However, when stating that this assumption is "suitable when root water uptake velocity dominates soil water dynamics", the authors should define the concepts involved (i.e. domination; comparing distributed velocities to dynamics) and referring to literature detailing in which conditions this statement would possibly be true. I would actually remove the second part of the sentence of the paper."*

> *"Unless I missed a point in the recommendations of HESS, I think that results of the current paper are not supposed to appear in the methodology section. The methodology should have its independent justifications. Furthermore, stating that "results of the simple model are in good agreement with those of the complex one" does not make sense per se, especially since they represent different types of root systems and are used to simulate different scenarios. The authors probably meant that they expected redistribution of root water uptake to occur in both models results since they are both based on root hydraulic principles."*

We have changed the paragraph following the reviewers suggestion as follows:

Old: This assumption is made for reasons of simplicity and is suitable, while root water uptake velocity dominates soil water dynamics. Furthermore the results are in good agreement with the ones obtained with the complex root water uptake model which explicitly accounts for soil water redistribution (see Sect. 3).

New: These assumptions are made for reasons of simplicity, and in order to investigate in simple terms the impact of soil water potential distribution on root water uptake distribution for different root hydraulic architectures. The complex root water uptake model explicitly accounts for soil water flow (see Sect. 2.2).

RC23, P768, L22-24

> *"Same comment as RC22."*

Although this comment prematurely refers to the results, we believe it helps the reader to place the models in context. In this particular case we kept the statement but changed the wording to account for the early reference to a result.

Old: Indeed, our assumptions are justified subsequently as the qualitative results are reproduced within the complex root water uptake model at a full level of complexity (see Sect. 3)

New: In order to test whether they are reproduced in more realistic conditions, we apply the complex root water uptake model described in the next section.

RC24, P769, L6

> *"The reference seems inappropriate. Richards (1931) or a reference to a 3-D solver of Richards equation (such as SWMS-3D or Wave) would probably fit better. "*

We have included the method of the solver for the soil water model and the reference.

Old: (…), water redistribution is gradient driven and calculated by explicitly solving the 3D Richards equation (Kolditz et al., 2012).

New: Within this block, soil water flow is gradient driven and numerically calculated with a finite element method solving the three-dimensional Richards equation (Kalbacher et al., 2011; Kolditz et al., 2012)

RC25, P770, L20-25

> *"The authors explain criterions defining whether root segments are young or mature. As far as I understood, the given criterions are not sufficient to isolate one possible distribution of root properties for each percentage of maturity. Did the authors use a threshold root age as additional criterion to discriminate between young and mature root segments? This part should be clarified."*

It is true that our statement was incomplete. Please note that the manipulation of the root hydraulic properties was not performed in the first place to re-produce a natural plant, but to discover shortcomings in root parameterization. We have revised the entire Sect. 2.3 and included more information on how the distribution of root hydraulic properties was varied between modeling scenarios.

RC26, P771, L23-24 and RC27, P771, L24

"Effort was first presented as an "index for overall plant resistance", or an "index used to quantify the overall resistance to root water uptake", but surprisingly, it turns out that it is an average collar potential. When reading these lines, I first questioned myself about why making this index so vague and mysterious, why not directly saying that your first index is the average plant potential before stress, symbolized as "Psy~", which you expect to be sensitive to overall plant hydraulic resistance?

My second reaction was to think that "Psy~" is also very sensitive to the chosen scenario (i.e. to the transpiration rate, to the initial soil water potential, to the critical leaf water potential,…), but you essentially want the index to inform you on the plant property (overall plant resistance), not to inform you on the chosen scenario. Then why not making it simple and straightforward by using the plant overall resistance as index? This index would also have the advantage to be measurable on real plants, in opposition to effort, which would require a real plant to transpire at constant rate to be estimated."

"As presented, it is not clear what kind of average the authors used when defining w(t). The term "ratio of cumulated work to cumulated water uptake" might make it clearer. I actually found it misleading to use the symbol "w" for an average work which actually does not have units of work (same remark for "V~", which doesn't have volume units). And again units are not defined with the new symbol, which makes it even harder to catch the exact signification of the variable."

We agree that the introduction, definition, motivation and discussion of both "water yield" and "effort" needed improvement, and we have made an effort to do so. We have changed the methods section to make it obvious that the index "effort" is the flux weighted average work invested per unit water uptake by the plant, which is evaluated over a given time. This index "effort" reduces to the time average xylem potential, only in the special case that the water uptake rate is constant with time, which is the scenario applied throughout the manuscript for matters of simplicity.

The reason why we did not calculate the plant resistance itself like proposed in Couvreur et al. (2012) is that our approach is different. We did not aim to separate the effects of the root from those of the soil, but to measure energies. We have discussed this in the interactive discussion (see our reply to AR1 interactive comment 2, paragraphs 10-25, and Figs. SC2.3 and SC 2.4). The root conductance (K_{rs}, m/s) can be considered as an effective parameter of the root or root system, such that the transpiration rate (T, m³/s) can be calculated from the gradient of an effective water potential in the soil (ψ_s, m) and at the root collar (ψ_c, m).

$$T = K_{rs} \cdot (\psi_c - \psi_s)$$

We have shown in the interactive discussion, that the spatial distribution of root hydraulic properties does not only determine the overall root resistance, but also influences the temporal evolution of the effective soil water potential ψ_s under heterogeneous soil water status. Hence, not the resistance of the root system but the xylem water potential at the root collar contains the information about the energy necessary for water uptake.

Our introduced index effort integrates this information about the soil water status, root system resistances, and other factors mentioned above. Moreover, effort has the great advantage that it captures in one value a metric which can be used to evaluate efficiency of uptake for a given root parameterization.

We revised the introduction of both indices "effort" and "water yield" in the Methods section (Sect. 2.4). In particular, we replaced equations 5 and 6, give a general definition of both water yield and effort which are valid under arbitrary boundary conditions, before we introduce the special quantities "~w" and "~v", which are only valid under specific boundary conditions (see equations 15-18 in the revised manuscript). Information on results for diurnal transpiration rates and special features of water yield and effort are presented in detail in the interactive discussion (pages C146-C148 and Fig. 1 of our first short comment to AR1 as well as pages C551-C553 and Figs. SC2.1 and SC2.2 of our second short comment to AR1).

RC28, P785, L17 – P786, L17 and RC29, P772, L1-5

> *"Here I jump to the Appendix A to continue commenting on "w". Again in this section, units would be helpful to the reader. The perspective to quantify water transfer in terms of work is interesting. However, equation A2 contains an error. In the electric analogy, the voltage corresponds to a potential difference between a region of high potential and a region of low potential. Applied to soil-plant water dynamics, the region of low potential is indeed the collar, while the region of high potential is the soil. The soil water potential is thus missing in equations A2, A3 and A4. Under constant transpiration rate, "w" thus equals the difference between time averaged collar and soil water potentials. See Gardner and Ehlig (1963), Lhomme (1998) and Couvreur et al. (2012) for more information on such electric analogy."*

> *"The mathematical definition of effort should be corrected according to RC28. The sign of effort will thus be positive instead of negative."*

We have commented on this concern in the interactive discussion (pages C562-C563, paragraphs 30-35). It is true that we do not consider a potential difference, and we therefore cannot motivate the $w(t)$ from the electric analogue. Moreover, the effort is not a resistance, but a (specific) work. We understand that our naming had to become clearer, and we have looked not only through the Appendix, but also through the entire discussion paper to avoid confusion.

We return to the definition of the water potential as Gibbs free energy. Effort can be calculated under heterogeneous and time dependent soil water status. The above mentioned changes have no influence on the functional form of effort. However, the derivation of effort is now more consistent. We thank the reviewer for catching this.

RC30, P772, L6-7 and RC31, P772, L7-8

> *"Figure 2 should be updated according to RC7 and RC28, except if the authors want to keep the time average collar potential as index. Then only the sensitivity of the results to root discretization should be verified (see RC7). Also graduations of the vertical axis are not always visible."*

> *"The authors state that in figure 2, "it can be seen that in this case water yield is proportional to "t~". The only evidence for that in figure 2 is the equation of water yield, which was already presented (Eq. 5) and told to be proportional to "t~" earlier. This sentence should thus be removed. Also the equation for water yield in figure 2 is wrong; the root length term is missing"*

As stated in our response to RC7, the alleged artifact does not exist. However, together with the revision of sect 2.4, we updated Fig. 2 as follows: According to the changes in the manuscript we changed the variables to ~v and ~w, and included formulas corresponding to the respective equations of water yield and effort.

RC32, P772, L16-17

> *"As discussed in RC26, the effort is not a measure of the total resistance to root water uptake of a root system. Effort is sensitive to the total resistance, and extremely sensitive to plant transpiration rate. If the authors wanted to give a measure of the overall plant hydraulic resistance, they should have given the overall plant hydraulic resistance."*

As stated above, we understand that the terms "total resistance", "effort" and "energy" were not properly used. For heterogenous soil water potential surrounding the root, the root resistance does not contain all the information we are interested in (more details are given in our response to RC26). We changed the wording as follows:

Old: Water yield gives the total volume of water that could be extracted per unit root length before water stress occurred. The effort relates to the time evolution of water potential and gives a measure of the total resistance to root water uptake of a root system, integrating all soil and root hydraulic properties.

New: Water yield gives the normalized total amount of water that could be extracted under unstressed conditions. In more general terms, it is simply the water flow over the boundary of the system, and it has been applied before by other researchers to evaluate root parameterizations (Schneider et al., 2010; Javaux et al., 2008). On the other hand effort relates to the time evolution of xylem water potential at the root collar and the work necessary for root water uptake. It depends among others on the total resistance to root water uptake a root system has to overcome. As far as we are aware of, the index effort is a new way of measuring plant performance, and it carries a physiological meaning.

RC33, P773, L7

> *"Figures 3 and 4 should be updated according to RC7, and possibly to RC26. Same for figure 5 and RC7."*

As stated in our response to RC7, the alleged artifact does not exist. Therefore we only changed the nomenclature of water yield and effort in Figs. 3, 4 and 5 to ~v and ~w.

RC34, P773, L12-14

> *"Here and in several other parts of the paper, optimal lengths given by both indices are very similar. This is not surprising since water yield is proportional to "t~", which is sensitive to the plant overall resistance, to the transpiration rate and to the initial soil water potential (in the same way as effort). Then why making a second index? They are quite correlated; the main difference being that the second index is less sensitive to the properties of interest."*

As stated above, we believe that the correlation between water yield and effort is not a complete surprise, since they are both sensitive to plants overall resistance. However, we believe that they convey different information in terms of "costs" and "benefits", and a strong correlation was not expectable a priori. Moreover, water yield and effort are normalized indices. Roots extend the accessible water reservoir by root growth. Therefore, optimality in terms of volumetric water uptake has to be normalized by the amount of available water. We use root length as a proxy for this amount in the index water yield. Correspondingly effort is measuring the total amount of energy per unit of water uptake. Therefore we consider the similarity between the two indices an important result of our study.

RC35, P777, L17-18 and RC36, P777, L19-22

> *"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 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."*
>
> *"The effect of axial limitation is said to "become apparent in the overall higher resistances which lead to the increased effort". Again, the overall resistance decreases not due to an increased root length (see definition of axial limitation given in the background), but to an increased axial resistance. For the record the overall resistance always increases with both axial and radial resistances (and is generally more sensitive to the radial resistance)."*

As stated above we disagree with AR1, that the term "axial limitation" has a fixed meaning in the above mentioned sense. However we agree on the point that a decay in water uptake rates along a root and increased effort due to non-optimal root length / parameter combinations need different names. We denote these effects by "hydraulic isolation" (Zwieniecki et al., 2003) and "axial limitation" in the entire revised manuscript to prevent the reader from misunderstandings. In particular we consider this in the revised background section.

RC37, P778, L7-11

> *"The statement on heterogeneous root systems compensating root water uptake more efficiently is not well motivated. For that, compensation should have been quantified and a clear trend presented. A modelling study of Couvreur et al. (2012) recently demonstrated that compensation of root water uptake is proportional to the root system overall hydraulic conductance. The fact that heterogeneous root systems generated by the authors have a higher overall conductance than their homogeneous root systems would explain better why they do more compensation. Also, in order to justify their statement, the authors should verify if heterogeneous root systems with high overall resistance do more compensation of uptake than homogeneous root systems with low overall resistance."*

We changed this accordingly as follows:

Old: Altogether, compensation for local water stress is more efficient in heterogeneous root systems compared to homogeneous root systems, resulting in higher efficiency (Table 4).

New: Altogether, this leads to higher efficiency in heterogeneous root systems compared to homogeneous root systems (see Table 3), which is likely to be due to a more efficient compensation for local water stress.

RC38

> *"Most of the discussion should be adapted according to the comments on the background, methodology, results and appendix A."*

As stated above, in particular in our responses to RC7 and RC26, we demonstrated in the interactive discussion that our results do neither suffer from modeling artifacts nor from misused concepts. Our results and discussion remain valid. However, we considered the fruitful comments by AR1 in the revision of sections 3 and 4.

RC39, P780, L9-11

> *"The simplified model is said to be "sufficient" because its results are similar to those of the complex model. Sufficient for what? To observe redistribution of root water uptake as well, yes. To quantitatively model soil water dynamics accurately as compared to the complex model, no, such quantitative comparison was not carried out. The authors should clarify this point."*

Within the revised manuscript we emphasized that we refer to similarity in root water uptake redistribution patterns as follows:

Old: This rather strong simplification in the simple model proved to be sufficient as similar results were obtained both in the simple and in the complex model.

New: This rather strong simplification in the simple model facilitates understanding the process of root water uptake redistribution. Qualitatively similar effects were obtained with the complex model which explicitly accounts for soil water flow.

RC40

> *"For convenience, I would have expected table 1 to be included in the "Root properties" section of table 2."*

We changed this accordingly.

RC41

> *"For convenience, figure 5 should also present results for n=4 and n=6."*

We included these results into figure 5.

RC42

> *"In figure 8, the units of z50 are missing."*

We added the units of z_{50} in figure 8.

RC43

> *"In figure 9 (right), the label of the y-axis indicates "fraction of bleeding from transpiration", which is misleading since the bleeding flux is not a part of the transpiration flux. "Ratio of bleeding to transpiration" would be more suitable."*

We changed this accordingly.

RC44

> *"The abstract should be adapted according to the comments on the background, the methodology and the results."*

As stated above, in particular in our responses to RC7 and RC26, we demonstrated in the interactive discussion that our results do not contain modeling artifacts nor from misused concepts. However, we considered the comments by AR1 in the revision of the abstract.

RC45

> *"It is also mentioned that the average root water uptake depth is not influenced by parameterization, which is in contradiction with both figures 8 and 6."*

We changed this accordingly.

P770, L8-9:

> ***"****The use of the word "therefore" seems inappropriate to me since the sentence is not a direct consequence of the previous one(s). Probably a few elements are missing."*

We changed this accordingly.

P770, L22

"I would remove the coma."

We changed this accordingly.

P773, L3

"I would add commas before and after the expression "water yield and effort"."

We changed this accordingly.

References:

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