Revision of “Estimates of tree root water uptake from soil moisture profile dynamics” by Conrad Jackisch et al.

We again sincerely thank Jesse Nippert, Jia Hu, Leander Anderegg and Chris Still for their constructive comments to our manuscript. We have revised it to convey our findings more clearly.

The revisions are aligned with the main suggestions of the reviewers
i) to simplify the presentation,
ii) to make the lines of arguments more coherent and
iii) to disentangle some of the complicated plots.

Following the suggestion of Leander Anderegg, we have omitted the aspect of sourcing of RWU with reference to matric potential inferred from measured soil moisture and water retention functions. The obvious disagreement of an apparent high tension with high root water uptake (RWU) is an issue to look into. However, it does not contribute to the focus of this study. We have moved the respective information into the Appendix.

Especially Jesse Nippert pointed to the dense information in our figures (and writing). We have revised the complex figures and recompiled new versions, which may still not appear completely intuitive at first sight. With more detailed figure captions and clearer alignment with the methods and results, we hope they are now easier to understand and digest. Specifically, we have now condensed the different steps of calculating RWU and sap flow (SF) in one figure each (Fig. 4 and Fig. 5), in line with the description in the text. The revised Fig. 6 still presents the time series of daily SF and RWU of the two sites. With clear reference of the notations to Fig. 4 C and Fig 5 C, we hope the information is easier to grasp. We also included extra panels for the NSE evaluation and a reference to plant available water content which should help to understand these results.

Because the different methodological steps to distil a comparable flux rate of RWU and SF from respective dynamics of soil moisture and sap velocity caused some confusion, we took special care to lay out these steps more clearly. We explain the methods step by step and describe the corresponding results in more detail.

Specific revisions in reply to the referees:

The referees’ comments are given in *italics* with our original replies in in regular font style. For the most part we followed our initial replies to the comments. In the following we only describe our final changes to the manuscript. Please consider the original replies of the discussion phase if you would like to compare the two. Only comments which required revisions are listed.

Short comment by Jesse Nippert

I have few major concerns or suggestion revisions for the authors to address. My most noteworthy suggestion for the authors is to simply / clarify this manuscript whenever possible. This is an extraordinarily detailed and jargon-rich manuscript that needs to be simplified. I’m a scientist that studies plant-water use (so in theory, this manuscript is directly within my field of study) and yet I found myself reading and re-reading sections to try to understand what was done, what the data means, and how the authors derived their conclusions. For many of the figures, I was never able to gain a full appreciation of what was conveyed (what exactly am I seeing in Figures 11 and 12?) and the legends were often non-descriptive (see Fig. 4 for an example). Thus, I encourage the authors to reduce the jargon, better explain the development of the RWU calculation, and simplify the figures whenever possible. The novelty and creativity of this manuscript is in the top 95%, but the clarity and delivery of the information is in the 50-60th percentile. I’m fully confident the authors can address this issue.

We have worked through our manuscript and simplified the general structure by moving the section about soil moisture dynamics to the site description and by omitting the aspects of soil water retention. By doing so, we hope to reduce much of the cluttered arguments. Moreover, we have extended the descriptions in the figure captions, removed jargon where possible or explained more clearly elsewhere.

Other comments: The Introduction is generally sound, but there are a few items of concern. On page 1 line 17, the authors need to remove ’even over grasslands’. Grasslands are not definitely simpler ecosystems that forests, so please do not refer to them as such.

We agree to the point that grasslands are not simpler ecosystems than forests and that this wording was not well chosen. We have removed the statement.

On line 18, please address the 'optimise their water transport to respiration'. The optimality theory has been challenged many times since 2009, and in fact doesn't appear to be valid. In addition, why would water transport be optimized for respiration? I believe you meant assimilation. Regardless, please update.

You are right, we refer to assimilation here. To make that clear we omit the debate about optimality in the revised manuscript and rephrased the respective passage.

Examples of RWU assessments in the literature are provided on page 2. While I have never read an approach as detailed as the one presented here, transpiration dynamics have been assessed by comparing sap flux with changes in soil moisture dynamics previously. Please check out Holdo and Nippert 2015 Ecology (https://doi.org/10.1890/14-1986.1) for a study comparing transpiration dynamics using sap flux, soil moisture, isotopes, and changes in canopy temperature among coexisting trees and grasses.

Thank you for pointing to this study. After considering it, we do not think it reflects what we want to say here. In the revised manuscript we have inserted statements clarifying the novelty of the approach to reside in the automated derivation of RWU from soil moisture declines in a continuous depth profile – but not the relation of transpiration and soil water status in general. We point to some of the studies which use, for example, isotope methods to learn more about the detailed path of water from different soil depths into trees.

On page 5/line 7, the authors note that sap flux was monitored in 4 trees near the TDR probes at each site. Do subsequent sap flux data (Fig. 3, 5, 6, etc) represent a single tree, or an interpolation across all 4 trees per site?

Yes, the respective data represents a single tree. Originally, we intended to use the tree where we directly measure soil moisture in the rhizosphere. At the slate site we had to change this because of a sensor failure. We justify switching to a different tree with the high correlation of sap velocities among the trees (as shown in Appendix A). We describe the selection of the tree in more detail now in section 2.3 and Appendix A.

Section 3 describes Fig. 3, and the derivation of RWU based on soil moisture step change. How was this 3 day period selected? Can I assume it was the best 3-day period where a step change was observed during this summer? Does the lower correlation in RWU time series (and during drier times) reflect derivation of the metric during an ideal period, which then loses predictive power during mean summer soil moisture periods?

This exemplary period in Fig. 3 has been chosen arbitrarily as it combines clear sky conditions (day 1), clear sky with an intermediate shading (day 2) and a fair weather with radiation noise by smaller cumulus clouds (day 3). The step changes have been observed at many more days. We have introduced a set of simple criteria to define a general step.

Afterwards, we evaluate if the soil moisture declines follow an idealised step shape (not an ideal time period) which we would attribute to mainly root water uptake, as opposed to strong deviations from the step pointing towards an interplay of various processes. To this end we calculate the NSE between the data and an idealised step for each day. The number of days meeting our simple criteria for a general step are summarised in Fig. 6 and 7, along with the additional overlay of the NSE classes from the evaluation step.

Our proposed RWU calculation approach indeed loses predictive power when the changes in soil moisture become relatively small and hence our assumption of the diurnal steps is no longer met. This changes with time and depth layer. Roughly summarised: We find steps in the data with an NSE persistently >0.5 between May and July at the sand site. Also the slate site reports higher NSE values in this period. However, there the level of determination is generally lower. These temporal dynamics are now given as separate panels in Fig. 6.

The NSE evaluation we undertake here is a fundamentally different step from the correlation analysis between estimates of RWU and SF based on KGE (Fig. 9). We have reworked the presentation of methods and results and hope to convey this information now.

When linking RWU from TDR data to transpiration dynamics from an individual tree, how did you account for water use by the understory vegetative community? Unless there were no grasses, forbs, saplings, etc. – wouldn't these species be using water from the same soil depths which would then complicate predictions of individual tree water-use using changes in soil moisture? The methods section does not describe the understory.

We added a sentence in the discussion stating that there was barely any understory vegetation so this effect should be negligible.
With respect to evaporation we expect an effect on the top 0.2 m. However, since the signal from this layer is only rarely evaluated as RWU we are quite confident to be correct here. From a discussion point for the proposed approach, we agree that in many applications with understory vegetation the soil moisture dynamics cannot differentiate between different plants.

On the sandy site, how did you account for capillary action within the soil profile and subsequent evaporation? Or do you have some information (which I may have missed) on evaporation rates, and the depths of the evaporative fronts from these soils?

We do not have any reliable evaporation reference. There is likely some evaporation from the top soil layer which we do not assess but might see in our graphs. We have added a paragraph about this in the discussion section 5.1

Fig. 6 is an impressive behemoth. One item of interest to me is that the rainfall history does not appear to have any temporal synchrony with RWU or sap flux. Is this true? And if so, why not?

We have reformatted the former Fig. 6 and removed the shading of the columns. We now present the NSE values of the step shape as separate panels. Moreover, we greatly extended the description in the caption and in the results section 4.1 and hope the figure is understandable now.

With regard to precipitation, we mainly see its effect on the radiation input and a resulting decreased SF. We also see some increase of SF after rainfall in autumn, which might have been more available water after a dry summer. We added an indicator for available water to the graph and describe the possible influence of precipitation in the results section 4.1 now.

In Fig. 7, how does these predictions of water use in mm/day compare to estimates of Beech from similar locations within the literature. It would be nice to know if these predictions fall in the range reported elsewhere.

We have added literature values for general reference. However, the spectrum of plausible flux rates is rather broad. Given the dependency on site and tree characteristics, we still are confident that our estimates are realistic but cannot provide any more detailed reference.

Page 14, line 9 – I don't think 'ambivalent' is the correct term. An ambivalent picture suggests this was inconclusive research. You concluded many things, and illustrate a path forward for using soil moisture to infer plant water use.

Thank you for pointing to this improper wording. We have now termed it 'nuanced'.

Page 17, line 5. How do you know it's a minor effect? HR can be quite substantial in many ecosystems.

We agree that hydraulic redistribution in the rhizosphere can be substantial and that especially at the sandy site we might miss important factors by neglecting it. We rephrased this and now discuss the general possibility of HR in section 5.3.

Page 17, line 14 – How would cosmic ray measurements be appropriate here? I was under the impression that cosmic ray data pertains to the top 10 cm of the soil only.

We refer to attempts of combining cosmic ray measurements with in-situ soil moisture measurements to overcome the point information towards a better spatial representation like the authors in Nguyen et al. (2019) propose. However, we agree that the link might be rather far-fetched. We removed it and adjusted the outlook accodingly.

In the Discussion section, the authors note that RWU and sap flux were not inter- changeable, but were complementary. The language infers that RWU may be more de- sirable than sap flux for estimating transpiration under certain conditions. This seems a bit misleading to me. Sap flux directly measures a physiological process that relates to canopy transpiration, while RWU is an inferred metric. Under what conditions would the data from RWU be preferred over sap flux? Under what conditions does RWU outperform sap flux for predictions of transpiration?

We do not think that RWU is more informative than sap flow. Certainly both have their merits and drawbacks. We aim to suggest to refer to both means as complementary gauges of a highly interlinked process. Unfortunately, SF does not directly measure the physiological process but a flow velocity over a more or less difficult to guess cross-section. Similarly, RWU is likely rather heterogeneous when considering the moisture changes in the rhizosphere as a 3D space. Hence an estimate based on one profile has clear limitations, too. We can follow the argumentation that the tree trunk is at least some sort of gauge where all water must pass. However, the SF processing from the initial interpretation of the heat pulse advection to flow velocity and subsequent attribution of an estimated cross sectional area of active sap wood involves a series of calculations and assumptions, and the resulting fluxes can vary considerably. We revised the discussion to clarify that we consider both RWU and SF measurements equally justified, as complementary measures.

Referee comment by Jia Hu

One of the main ways in which this manuscript can improve is to clearly discuss the reasons for comparing RWU and SF. The authors state that the aim of the study "is to evaluate the potential and limitations of the diurnal decrease of rhizosphere soil moisture measurements as an estimate for RWU in ecohydrological field studies." They make the point that RWU is an under measured observation, and that other proxies, such as changes in soil water content, are used to infer RWU. Meanwhile, sap flow sensors measure transpiration rates in trees, but because of stored water within trees, sap flow does not measure RWU uptake either. So linking RWU and SF (as mentioned in hypothesis 2) seems to be an important link. However, what wasn't clear for me is that if ET is an important metric to quantify for ecohydrological studies, what does RWU measurements provide that SF measurements don't? In other words, what additional processes related to ET do RWU measurements elucidate? I think this discussion could be enhanced more in the introduction. For example, in lines 28, the authors state, "Furthermore, spatially distributed monitoring of both RWU and soil moisture and SF could help to elucidate differences between the influence of the geological and pedological settings on water supply to transpiration and the influence of the plants themselves and their adaptations in root systems, dynamic sourcing of water and transpiration efficiency." Does this suggest that RWU influences the "geological and pedological settings on water supply to transpiration" while SF measurements assess the "influence of the plants themselves and their adaptation in roots systems...?" But SF also influences RWU, so shouldn't SF and RWU be considered in a framework that acknowledges that they influence each other?

Thank you very much for raising our attention to this point. We see SF and RWU as interrelated elements of the transpiration process, however, with slightly different foci. The method we propose to infer RWU from soil moisture measurements can help to assess the influence of (abiotic) site characteristics on the water availability for the tree. Additionally, assessing the dynamics of RWU from different depths also provides information on the hydrological conditions and processes within the rooting zone. In contrast, SF is mostly used as proxy for actual tree transpiration (with some uncertainty regarding tree water storage and assumptions during the calculations of sap flux), and is also influenced by adaptations of the tree to the local site conditions. We therefore suggest to measure both SF and RWU for a better understanding of the water transport through trees. We have clarified this in the discussion of the revised manuscript.

Figure 3. Why are estimates of Dq positive if the soil moisture decrease throughout the three day period? In page 6, line 22, does "change in soil moisture" refer to Dq? If so, again, why is Dq positive? The positive values of Dq during the

daytime is confusing because in Figure 4B, Dq during the daytime hours is shown as negative. In Equation 1, the authors also state that a check to evaluate the data is that " day slope of soil moisture is negative (decline in soil moisture during the day)…"

We agree that it is confusing that we define the change in soil moisture negatively in Fig. 3 but regularly in Fig. 4 and the calculation. We hope to have resolved this confusion with a respective statement in the caption of Fig. 3.

Page 7, line 1. Do the bolded a) and b) here refer to a subset of "soil moisture (b)" from page 6, line 15? If so, I would change "a) and b)" to "i) and ii)" as to not confuse the reader.

We have changed this as proposed.

Page 7, line 4 and 5. No need to say "no STRONG decline in soil moisture" or "no TOO STRONG increase in soil moisture" since STRONG or TOO STRONG are quite subjective. I think that saying "no decline in soil moisture" or "no increase in soil moisture" followed by the rates of increase or decrease is sufficient.

We have rephrased the paragraph clarifying the idea and avoiding subjective claims.

Page 7, line 30. Why was the assumption made that measured sap flow originates in the soil moisture decrease? Could there be any storage of water in the trunks (i.e. might lags between RWU and SF exist)?

We do expect some lags between RWU and SF due to water storage in the tree, that is why we have highlighted this (rather blunt) assumption. It appears difficult to quantify such a storage effect without further data (i.e. ET and more references of SF). However, with a temporal aggregation to daily values we see a relatively high correlation between RWU and SF (Fig. 7). Thus, we do not expect the lag effect of water storage in the trunk to be very pronounced at the temporal resolution of one day. In other words, the sap flux of several litres per day appears to be a much stronger signal than the water storage dynamics within the tree trunk. We have now clarified the issue of storage in the tree in the introduction and specified our methodological assumption of a closed water balance over the day.

Page 7, line 31. "This is done by linear regression of daily sap flow to the sum of RWU over the soil profile with assumed zero intercept." Is the assumption again here that water from the different soil layers instantaneously feeds into the transpirational stream – in other words, there is no lag in when water is taken up by the roots and then transported to the trunk of the tree?

It is generally correct that we neglect an intercept within the tree by applying a regression. However, since we sample the recorded data to daily aggregates, differences between the fluxes with shorter temporal footprint should cancel out (i.e. the lag between sap flow and RWU in Fig. 3). Hence an "instantaneous" connection is not assumed. Nevertheless, we find strong differences in RWU and SF (Fig. 8), which might hint to water storage dynamics within the tree. However, we cannot assume to have sampled all sources of RWU with the soil moisture profile. Especially at the slate site it is very likely that roots can source water from local subsurface pools or films in the gravelly subsoil. We have largely rephrased the section for more clarity.

Page 8, Line 1. "The resulting factor is the mean reference area required to supply to observed sap flow." Is the 'factor' mentioned here the area or the volume? If RWU is summed across the different soil depths in which soil moisture is measured, how is the resulting factor estimated as area and not volume?

As stated in the mentioned subsection, a proper comparison of SF and RWU requires them to be defined as fluxes. This means that we have to refer to a cross-sectional area of active xylem for SF and a reference rhizosphere volume for the observed change in soil moisture attributed to RWU. Here the height of each volume increment is given by the integration length of the soil moisture profile probe, which is 0.2 m. Without knowledge about the actual root distribution we simply assumed a cylindrical rhizosphere. The "factor" is hence the projected area of this cylinder which can be expressed as radius for a plausibility check (see legend in Fig. 7). Since the RWU is defined in mm/day (a volume normalised by the area) the regression factor has to be the area to derive the volume flux. We have rephrased the methodological description of this regression-based derivation (section 3.4) and also clarified for which further analyses we use these assumed rhizosphere dimensions.

Page 10, Line 2. "In later summer, the RWU signal ceases although the sap flow signal continues at lower rates." In Figure 6, I don't see when this occurs across the entire instrument period.

The visual comparison of sap flow (L/day) and RWU (mm/day) dynamics has its drawbacks. This is why we opted to extend the analysis with the estimate for fluxes instead of the direct signals. However, it is not clear how much the assumptions to derive the volume fluxes will blur the actual signal in the observations. We agree that this statement can be seen as subjective.
Along the revisions and extension of the methods and result description, we have clarified the signal interpretation to avoid subjectivity. Moreover, we revised the respective figures, to make them easier to follow.

Page 10, Line 32. "With a working-hypothesis of a closed water balance...the linear regression also results ....at the sandy site the cylinder would have a radius of 4.2m...slate site one would estimate a radius of 5.5m." I may have missed this, but how did you reach these readius values? Where is the linear regression model reported? I see that there are radius values reported in Figure 7, but how were these calculated?

We have revised the presentation of the regression in the methods section 3.4.

Page 12, Line 2. "However, the high initial correlation drops in July. At the sand site, this marks the shift to RWU ranging below SF. At the slate site, no such transition is apparent." In Figure 8, when the spearman correlation drops, the precedes when RWU drops below sap flow. There are also instances later in July when RWU is consistently below SF but the spearman correlation ratio does not change. What does this mean?

The Spearman rank correlation "punishes" the change in ranks. Frequent changes result in low correlation values (e.g. August at the slate site). When RWU is consistently below OR above SF the correlation can become rather high. Since this is not giving the full picture, we report the KGE as alternative measure of correlation which "punishes" both the deviation of the dynamics and the absolute values. We extended the description of the results with special focus on the correlation measures and hope to be clearer now.

Page 14. Line 9. I would recommend changing the work "ambivalent" to "mixed."

Thank you. We changed the wording to 'nuanced'.

Page 16, line 9. "What is the optimization function of the plant's RWU sourcing and SF variability?" What do the authors mean by this? Please explain.

Gao et al. (2014) show that climate leads to an adaptation of the rhizosphere storage capacity. Saveyn et al. (2008) show how different SF can take place in the xylem under different weather conditions. We agree to your argument that RWU and SF have to be considered as interactive processes. Hence we expect the plants to adapt to climatic and site conditions. We expect that this adaptation is not a random process but some sort of optimisation.
Based on the comments by Jesse Nippert on the issue of the concept of optimality, we have now avoided the optimality term in the document except for two specific citations. Here we rephrased the sentence to discern the plant's adaptation from the search for some "optimisation function", which describes this adaptation.

Page 16, line 12. Yes, wounding from sap flow sensors can indeed underestimate sap flux velocity, and non-homogenous xylem depths can influence estimates of total transpiration rates, but it seems unlikely that these effects would be most noticeable during periods when both sap flux and RWU begin to decline. The authors allude to other factors in the previous paragraph (e.g. stem storage, leaf level transpiration) that offer more likely explanations for why correlations between RWU and sap flux correlations decrease as the soils dry out.

Thank you for your evaluation of these influencing factors. We have revised the paragraph to now refer to the linear regression analysis and to propose the effect of wounding to be minor since the observed regression has a seasonal pattern but not a noticeable deviation from the regression. We removed the repeated mentioning from the discussion.

Referee comment by Leander Anderegg

In this manuscript, the authors pair soil moisture measurements that have high spatial and temporal resolution with tree sapflow measurements at two different sites to test whether such soil moisture measurements can be used to estimate daily transpiration and identify depths of root water uptake (RWU). They find promising similarities between sap flow and estimated RWU during a fairly wet period at their site with sandy soil, but worse correlations at a site with more heterogeneous soil characteristics and a time series that extended into a drier period. They also found interesting evidence for differences in the depth of RWU at the two study sites, though this is somewhat deemphasized in the text. While the estimated daily RWU uptake appears promising in some regards, they also found a confusing lack of relationship between RWU and soil matric potential calculated from soil moisture release curves and soil water content. All told, these results suggest that the method is promising but still has some kinks to be worked out, some of the largest probably relate to spatial heterogeneity at large scales (lateral variation over meters) and fine scales (inability to infer matric potential from soil moisture release curves on nearby soil samples.

This is an interesting manuscript that presents a promising approach to estimating transpiration and RWU at high temporal scale. However, my three main concerns are:
1) The writing and figures are extremely dense and sometimes confusing/contradictory. I had to read the Results at least two times, and often had to parse out individual sentences multiple times before I could begin to follow their meaning. Some of this could be due to a difference in fields (hydrology vs the plant ecophysiology terminology that I am more familiar with), but I would recommend a considerable expansion of the Results to explain the more complicated an nuanced findings and make this interpretable by a broad audience. I have given multiple suggestions below in the 'Specific Comments' section, but would general recommend a careful edit and clarification of the most complicated sentences in the Results. I also would recommend simplifying some of the figures by breaking out aspects into multiple panels rather than layering on 4-5 different sources of information that I found almost impossible to interpret simultaneously. In particular, Fig 6 and 12 are nearly impenetrable (and Fig 11 is also quite dense).

Thank you for your intense study of our manuscript and taking the challenge to dig out our messages so well. We gratefully received your suggestions and have now clarified and simplified the manuscript including some of the figures for better understanding.

2) The introduction oversells the novelty of monitoring soil moisture to estimate RWU dynamics and transpiration. True, the ability to monitor soil moisture with high enough precision to assess daily RWU is fairly novel and new, but people have been measuring soil moisture to estimate depths of RWU and understand transpiration budgets for decades! In fact, I would argue that gravimetric or volumentric soil moisture measurements are the original method for estimating transpiration (e.g. just to name a couple that come up with a quick google search: Denmead & Shaw (1962) "Availability of soil water to plants as affected by soil moisture content and meteorological conditions" Agronomy Journal; Novak (1987) "Estimation of soil-water extraction patterns by roots" Agricultural Water Management). Thus, I think it is important in the Introduction to stress that it is the precision of these measurements (allowing high temporal and spatial estimation of RWU) that is interesting, not the method and theory itself.

We generally agree to this point. We have revised the introduction and hope to be more concise about the goal of our study now: Although the connection of transpiration to soil moisture changes are well-known, we want to highlight the capability of our easily available technique for such analyses - given the level of precision and spatial coherence of the available soil moisture data.

3) I think the authors do a good job honestly discussing where their approach did not perform well, but I would both urge them to focus and structure the discussion around a coherent argument for what the key processes and attributes *are that screw up these measurements (e.g. what are the 4 biggest problems, list them out, and show us how you concluded that these are what is causing the method to fail at the Slate site and in dry soils).*

Thank you for acknowledging our efforts. From our measurements we cannot distill a list of biggest problems. We revised the manuscript to make clear that we consider both RWU and SF as useful complementary measures to understand the transpiration process. As for our RWU algorithm we hope to now discuss better what its capabilities but also its limitations are.

I would also urge the authors to reconsider the framing and discussion around their 'Hypothesis 3'. It is currently framed as an open question whether tension gradients drive variation in root water uptake. And then Figure 11 is presented as evidence that this may not be the case. I think this is a misrepresentation of both where the field is at and what the confusing findings of Figure 11 represent. Plants can alter RWU via changes to root properties (changing aquaporin expression to alter root permeability) and root distribuitons, but they cannot physically fight potential gradients as the authors seem to suggest with Fig 11 and in the Discussion. Plants can ONLY extract and move water by moving it down a potential gradient, and there is no physical way the plant can be extracting and transpiring water from soils with a matric potential 10s-100s of MPa below 'permanent wilting point' (~1.5 MPa, or 4.2 (log10(hPa)). The general dogma (assuming +/- equivalent root resistances throughout the soil profile) that water uptake by roots should be proportional to the pressure difference and the root surface area/biomass should be used as a final test for the reliability of this method to estimate RWU, rather than using the data to test the dogma. In this case, I think it is painfully obvious that we have essentially no reliable way to convert water content to matric potential at the spatial and temporal scales that are relevant to these transpiration estimates. In fact, we're SO BAD at it, that it would appear that the Slate trees are extracting water from soil with a matric potential of « -10 MPa (when leaf water potential, the ultimate pressure differential driving water movement, is almost certinaly > -2 MPa). That tells me that there's a problem with the method, not the theory. However, recognizing this allows you to say something interesting about why we can't back calculate matric potential from these measurements (spatial heterogeneity in soil properties? Problems with rock fractions? Rock fractures that don't behave like soil samples used for dehydration curves?).

We completely dropped this aspect from the main part of the study because the methodology is problematic (as we explained in our initial replies), and it also does not contribute to the focus of our study. We left some of the details in Appendix B.

Specific comments: Pg 6 L11-14: Please explain a little more what you mean by 'NSE is a measure which is very sensitive to deviations from shape features" (perhaps you could add a day that does not pass this cuttof to Fig 4 to illustrate?), what cutoff of NSE you used, and how you arrived at that cutoff.

We rephrased the NSE description to make clear that we do not use the NSE as a cutoff for RWU calculations but rather as an additional evaluation how the identified soil moisture declines correspond to a mainly RWU-driven step shape. We added additional examples for such declines and the respective NSE values to Fig. 4.

Pg 7 L8-12 and pg10 L30 and Fig 7: I am very confused about what 'corrected' means. In the Methods, I interpreted 'Corrected' to mean RWU extrapolated from the linear regression through the nightly data (magenta line in Fig 4a). But in Fig 7 the 'not corrected' values (blue points) are higher than the 'corrected' values (colored points), which tells me I'm getting confused somewhere. Please clarify this in Fig 4, and Fig 7 and the associated Results text (pg 10 L30).

Thank you for pointing this out. We took care to clarify this in the revision. We now call the approach without the regression through the nightly data the "simplified" approach and then introduce our extended approach with the regression step by step in the methods section 3.1. As we continue the analyses with the extended approach, we now also mention explicitly when we do the comparison of both approaches (section 4.4).

Pg 7 L20-29: This paragraph about turning sap velocity into sap flux is very confusing. I did not understand it until I scrutinized Fig 5. Please rewrite/clarify. Also, in the Fig 5 legend/caption it is worth noting that the "5mm, 18mm, and 30mm" are depths from the outside of the tree (or inside of inner bark? Not sure which).

We have completely revised this section (3.3) to guide the reader though the calculations step by step, alongside Fig. 5. We hope the procedure can be understood more easily now.

Figure 6: I had a very difficult time extracting the desired inferences from this figure. The shading (which varies per site, over time, and in different soil layers) is almost impossible to see and interpret (not to mention some of the colors become colors used for other soil depths when shaded) yet are referenced multiple times in the text. Also, the stacked bar plots make it almost impossible for me to interpret which depths are providing RWU, mostly I just take away total bar height. I would recommend 1) breaking out the information about how well the RWU estimation likely worked into another panel or method other than shading (filled versus unfilled bars/symbols, perhaps?). and 2) either finding a more holistic way of showing depth information (e.g. coloring whole bars by the weighted average depth of RWU) or just making a different panel that showed line graphs of uptake by depth through time. In fact, I would potentially advocate for breaking out the depth of extraction information into a new figure altogether.

We have revised the figure and removed the shading. Using a line plot did not turn out to be helpful. Instead we have also clarified the processing of the data to derive the plot more clearly in the new Fig. 3. We hope that these revisions have led to a much easier comprehension of our approach and data. As a summarising information about the soil water availability, we added this data to the figure.

Pg 12 L14-15: I don't quite understand what data are being compared in this sentence "Comparing RWU correlation between the two sites, applying the nocturnal correction improves Spearman rho form 0.42 to 0.52. KGE remains almost the same with 0.27 increasing to 0.3." All data from both sites (if so, why is this a useful comparison)? Or somehow site-level averages?

We clarified the difference between our approach including the nightly recharge and the simplified approach of simply assessing the soil moisture reduction between two days in the methods section. We moved the topic to a separate discussion section (4.4) to clarify what we compare and conclude. Basically, we repeat the correlation calculations between RWU and SF and between the two sites with the simplified approach and compare the resulting measures.

Section 4.3 – I think this section is very cool, but I understood very little of the text. What does "a diffuse redistribution into the surrounding soil aggregates" mean and why can it be "seen as parallel declines. . .in the different depth layers"? Please explain more what "flashy transport through the macroporous soils and fill-and-spill mechanisms of subsurface pools" means, and much more importantly how this analysis influences our interpretation of the method for assessing RWU in this site. Clearly you learned something interesting and highly relevant (possibly that helps us interpret Fig 11?), but I do not understand what it is based on the current text. For instance, I have no idea what these sentences mean and how they relate to Fig 10b "Here, roots are likely to grow along joints and fractures, where event-water can be stored with little effect on the bulk soil moisture. As such, the measurements might miss parts of the active rhizosphere."

We moved this part to the site description (section 2.2) as it gives some background to the contrasting pedological conditions of the sites, which are likely to affect water availability to the tree. We have revised the paragraph and hope it is easier to understand now. However, some of the jargon persisted as standing terminology.

Section 4.4 – See above comments about interpretation and framing of these results. Also, the current Figure 11 is nearly impossible for me to interpret. I would recommend displaying SOME aspect of this information in multiple panels. (e.g. maybe splitting the soil columns up into three depths and displaying them as separate panels so you can color by SF). Also, the units/label on the x axis of this figure is confusing to me. And honestly, after reading the text of this section 4 times, I still don't have any idea what it means. I can't even decipher it enough to make suggestions on how to clarify it. I don't know what the referenced 'reactions' are and how I'm supposed to assess them in the figure. Moreover, I do not at all see the 'correlation of matric potential and depth' that supposedly exists in slate site.

We will re-evaluate Fig. 11. As you point out, we also need to rework the whole argument showing that it is not the plants sourcing at high flux rates against physiologically impossible tensions but the conversion of soil moisture into matric potentials, which does not represent the state around the roots. We will take care of this in the revision.

We have moved this to the appendix and rephrased most of it.

Pg 14 L14: This sentence "At the same time, we pointed out considerable limitations to the approach with respect to soil water state (no detectable signal during low moisture periods) and soil properties (high variability in heterogeneous soil profiles)" is the most interesting sentence of the discussion to me, but comes out of no where and needs much more explanation. In order for me to follow your train of thought, I require much more explanation. . .

Thank you for highlighting this lack of reference. We have revised Fig. 6 to include plant available soil water and an evaluation of the detected steps with NSE>0.5. Going into more detail about the determination of our approach reveals that it cannot be explained with soil water availability alone but that the seasonal state of the tree has also a strong effect. We have revised the presentation of the results and the discussion accordingly.

Figure 12 and associated text of Section 5.1: I had an extremely hard time interpreting this figure. Please 1) remove the red bars for total extraction to new panels (two axes y- axes with different interpretations is much more than my brain can handle). 2) Explain what the NSC cutoffs indicate, and what the larger blue bar for 'all detected' is and why the inset bars for different detection thresholds do not sum to it 3) Put panel A and B on the same axis (e.g. 0%-90%) and switch the big numbers to be % of days and little numbers to be # of days. Also, how does Fig 12 show "The RWU derivation function appears to perform very well in general and can be used to evaluate a broad range of diurnal changes in soil moisture (Fig. 12)." (L1-2). Moreover, this sentence doesn't really make sense to me "Unlike the first impression in Fig. 6, the proportion of steps with higher uncertainty about the actual fit of the shape with the assumptions is higher in the slate site data, which is in line with the lower overall RWU detection there." Could you explain what you mean by "higher uncertainty about the actual fit"? Also, how "uncertainty" and rate of "overall detection" differ? Throughout this section, please be much more explicit about the site, times, and layers you are referring to when, for example, you write "Under somewhat ideal conditions with soil moisture sensors and roots in good contact with a rather homogeneous soil matrix and sufficient soil water availability, the diurnal steps are identified and evaluated with great confidence." Finally, this feels like it should be in the Results, perhaps even near Figure 1, rather than in the Discussion.Pg 15- L5: I think it's worth explicityly mentioning the take-away from Figure C1: that flux amount is unrelated to how well the step function fits the daily soil moisture pattern.

Thank you for pointing out the difficulty of this figure. We have opted to leave the figure as it is because we considered it important to have the red bars directly in the figure to correctly interpret the significance (or lack thereof) of the blue bars. However, we have greatly extended the figure caption, guiding the reader through the figure in hopefully enough steps now. We also added more explanation to the respective text paragraph. With respect to the proposed equal scaling of the y-axes to the respective proportions, we have left the figure with reference to separate counts. By doing so we hope to avoid misleading interpretations of the comparison of the different observation periods. The sand site does not include the later phase of the season.

Pg 16-L25-35: See my comments about Hypothesis 3 and Figure 11. Also, the sentences at L28 ("At the sandy site. . .") seem confusing and almost self contradictory to me.

We revised hypothesis 3 to simply highlight the site influence on RWU and SF (as a research question) without any further assumptions. Consequently, we removed the whole consideration of matric potential from the main manuscript to the appendix following your suggestions. We refer to some of it in the discussion but point to the uncertainty in these calculations and refrain from any interpretation.

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Estimates of tree root water uptake from soil moisture profile dynamics

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Abstract. Root water uptake (RWU) as ~~one~~ an important process in the terrestrial water cycle can help to better understand the interactions in the ~~soil-water-plant system~~soil-plant-atmosphere continuum. We conducted a field study monitoring soil moisture profiles in the rhizosphere of beech trees at two sites with different soil conditions. We present an algorithm to infer RWU from step-shaped, diurnal changes in soil moisture.

While this approach is a feasible, easily implemented method ~~during wet and moderate~~ for moderately moist and homogeneously textured soil conditions, limitations were identified during drier states and for more heterogeneous soil settings. A comparison with time series of xylem sap velocity ~~reveals~~ underlines that RWU and sap flow (SF) are complementary measures of the transpiration process. The high correlation between the ~~sap flow~~ SF time series of the two sites, but lower correlation between the RWU time series, suggests that ~~the trees adapt RWU to soil heterogeneity and site differences~~soil characteristics affect RWU of the trees but not SF.

1 Introduction

Evapotranspiration (ET) is a key water and energy flux in ecosystems. Although ET amounts globally to 60% of total precipitation in terrestrial systems (Oki and Kanae, 2006) and transpiration is claimed to dominate the terrestrial water cycle (Jasechko et al., 2013), it remains one of the most challenging fluxes to observe and understand ~~(Wulfmeyer et al., 2018)~~(Wulfmeyer et al., 2018; Renne
ET describes the ~~transport of water from the soil towards the atmosphere,~~ release of water vapour into the atmosphere, driven by the saturation deficit of the atmosphere and influenced by soil ~~characteristics determining water supply, atmospheric conditions acting as driving gradient and land use and vegetation characteristicscontrolling the transport. While evaporation is addressed in~~ and vegetation characteristics, which control soil water uptake and transport. It can be either limited by the radiative energy supply or by the terrestrial water supply.

Evaporation is studied using experiments and models ~~(Shuttleworth, 2007; Or et al., 2013) and can be modelled reasonably well, ET dynamics at sub-daily resolution is still challenging (Renner et al., 2019) – even over grasslands.~~

~~Transpiration of vascular plants, which optimise their water transport to respiration (Schymanski et al., 2009), adds complexity in the ecohydrological and thermodynamical system. Moreover,~~ (e.g. Shuttleworth, 2007; Or et al., 2013). Transpiration is a more complex interplay of different fluxes including root water uptake (RWU) and sap flow (SF). It is well known that the controls of transpiration are not static ~~in a forest stand (Renner et al., 2016; Dubbert and Werner, 2019).~~ (Renner et al., 2016; Dubbert and Werne Plants can adapt their water uptake and transport to their assimilation under different stressors (Schymanski et al., 2009; Lu et al., 2020). Additionally, plants can store water to buffer intermediate stresses ~~(Gao et al., 2014)~~(Cermak et al., 2007; Gao et al., 2014), resulting in deviations between RWU and SF. Studies on plant transpiration frequently focus on stomatal control (Schymanski and Or, 2017) and theories on leaf-related dynamics and the transpiration loss function (Sperry and Love, 2015). To estimate transpiration of individual trees, ~~sap flow (SF)~~ SF measurements are widely used (e.g. Nadezhdina et al., 2010; Poyatos et al., 2016). However, a series of approximations and assumptions is needed to convert the sap velocity ~~values in the xylem to the water transport of a whole tree or even to stands~~to the volumetric water flux in a tree or stand.

~~For root water uptake (RWU) as an indicator of water supply for the plant and possibly an estimate of transpiration~~RWU is a missing link to understand water limitation, as it taps the soil water store and is most difficult to observe. Accordingly, comparably few studies and measurement standards exist. For small plants, lysimeters are ~~a means to infer the overall effect of plants on~~ one means to quantify how plants control ET (e.g. Gebler et al., 2015). ~~More~~ Moreover, details about the shape of the rhizosphere can be revealed with tomographic analyses (e.g. Kuhlmann et al., 2012; Pohlmeier et al., 2017), but not necessarily about the dynamic RWU process in the rhizosphere. At larger scale and for larger plants, changes of groundwater levels (e.g. Maxwell and Condon, 2016; Blume et al., 2018), isotope signatures of water (e.g. Dubbert and Werner, 2019) and carbon (e.g. Vidal et al., 2018), and ~~sap flow~~ SF measurements in the roots have been employed (e.g. Burgess et al., 2000). To understand RWU, a series of approaches to measure (e.g. Mary et al., 2016) and simulate (e.g. Pagès et al., 2004; Javaux et al., 2008) the root architecture and its interaction with soil hydrology have been developed. Among these ~~representation through~~ are representations based on resistance terms (e.g. Couvreur et al., 2012) or ~~thermodynamic optimisation based on the assumption that the plant minimises~~ based on thermodynamic optimality through a minimisation of physical work during root water uptake (Hildebrandt et al., 2016)~~have been proposed~~. It is known that RWU responds to soil water conditions (Cai et al., 2018) and thus soil structure. Additionally, studies found that roots and soil structure co-evolve (Carminati et al., 2012) and that roots can actively modify the soil properties by mucilage (Carminati et al., 2016; Kroener et al., 2018).

So far, only few examples for ~~in situ~~ quantitative in-situ observations of tree RWU dynamics exist (e.g. Rodríguez-Robles et al., 2017; Leuschner et al., 2004). Approaches based on an analysis of stable isotopes in the rhizosphere and the plant xylem can identify the path of the water from different soil depths into different parts of the tree in great detail (Dubbert and Werner, 2019; Zarebanad From a soil perspective, the complex effect of RWU can be observed as a decrease of soil water content during active water transport through plants ~~(Feddes and van Dam, 2005; Guderle and Hildebrandt, 2015), but spatially distributed measurements~~ (Novák, 1987; Feddes and van Dam, 2005; Guderle and Hildebrandt, 2015), but technologies for spatially distributed measurement of soil moisture dynamics at relevant scales are just emerging ~~(Klenk et al., 2015; Allroggen et al., 2017; Boaga et al., 2013)~~(Klenk et al., 201 However, there has not been much research on how well this diurnal decrease reflects the water transport into and within trees.

A change of soil moisture is not necessarily RWU, SF and eventually transpiration. It can also be caused by hydraulic redistribution ~~(Burgess et al., 1998). Hence, following the notion of spatially distributed monitoring of soil water dynamics to reveal function (Jackisch et al., 2017),~~ within the soil (Burgess et al., 1998). Similarly, temporary water storage in the tree's hydraulic system can lead to SF and transpiration without the corresponding RWU (Cermak et al., 2007; Matheny et al., 2015). Hence, studying the spatio-temporal dynamics of soil-moisture-derived RWU and its correlation to SF might be key to ~~develop means to~~ more holistic observations ~~(York et al., 2016)~~ (Jackisch et al., 2017; York et al., 2016) of forest water dynamics ~~and its spatial patterns. Furthermore~~including the main actors (the trees, Ellison et al., 2017). In that sense, spatially distributed monitoring of both RWU from soil moisture and SF could help to elucidate differences between the influence of the geological and pedological settings on water supply ~~to transpiration~~ and the influence of the plants themselves~~and~~, i.e. their adaptations in root systems, dynamic sourcing of water (Nadezhdina et al., 2010) and transpiration ~~efficiency~~regulation (Lu et al., 2020).

The aim of this study is to evaluate the potential and limitations of estimating RWU from the diurnal decrease of rhizosphere soil moisture ~~measurements as an estimate for RWU (Guderle and Hildebrandt, 2015; Guderle et al., 2018) in ecohydrological field studies, focusing on~~ (Guderle and Hildebrandt, 2015; Guderle et al., 2018) in forest systems. ~~We test the following hypotheses~~We structure our analysis along the following research questions:

1. ~~Daily RWU can~~ Can daily RWU be robustly derived from records of ~~diurnal~~ soil moisture dynamics~~.~~?

2. ~~The~~ Are the dynamics in derived RWU ~~is~~ consistently related to dynamics in SF~~.~~?

3. ~~The effect of~~ How do soil and site characteristics ~~on RWU is mainly driven by the tension gradient between ET demand and soil matric potential.~~ affect RWU and SF?

For this analysis we develop and assess an automated approach to derive RWU estimates from soil moisture profile measurements. ~~Moreover, we~~ We compare the RWU dynamics to ~~sap flow measurements. In order to compare volumetric fluxes, we apply an estimate for the active sapwood cross-section. We examine the relation of RWU and SF~~ SF measurements in two beech stands of different geological and pedological setting but with very similar weather, climate and topography~~in a catchment in western Luxembourg.~~. The developed calculation algorithm is published as python package *rootwater* under MIT license (Jackisch, 2019).

2 Field sites and monitoring~~methods~~

In the vegetation period of 2017, we selected and instrumented two sites in mixed beech stands (*Fagus sylvatica*) in contrasting geological settings, one on loamy sand in a sandstone basin (~~sandy~~ sand site) and another on loamy regosol on periglacial coverbeds of the slate Ardenne Massif (slate site, Fig. 1). Both sites are located in the Attert experimental watershed ~~(Hassler et al., 2018)~~in western Luxembourg and are part of the monitoring setup within the CAOS research unit

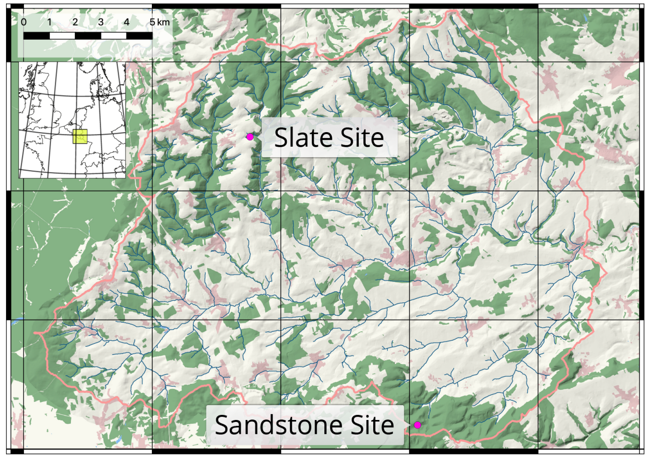

Figure 1. Attert experimental basin, Western Luxembourg. Locations of the two reference sites. Basemap: Landcover from OpenStreetMap contributors. Shading and river network calculated with a combined DEM of the administrations of Luxembourg and Wallonie.

(Zehe et al., 2014). The climate is temperate semi-oceanic, mean annual rainfall is 845 mm (Pfister et al., 2014) and mean monthly temperatures range between 0°C in January and 17°C in July (Wrede et al., 2015).

2.1 ~~Soil hydraulic characteristics of the sites~~

~~The sandy site is located in the Huewelerbach subbasin which is characterised by deep, homogeneous sandy soils and deep groundwater-driven hydrology. The second site on regosol of the slate Ardenne Massif is located in the northern part of the Colpach subbasin. There, the hydrological regime is dominated by flashy reaction through macroporous soils and fill-and-spill mechanisms of subsurface pools on the jointed bedrock (Jackisch, 2015; Loritz et al., 2017).~~

~~Soil water retention properties of these soils were assessed in a previous study using the free evaporation method of the HYPROP apparatus and the chilled mirror method in the WP4C (both Meter AG) with 250 ml undisturbed soil samples from the sites (Jackisch, 2015). Following this method, the matric potential is divided into bins (0.05 pF). All retention data of the reference soil samples is bin-wise averaged to form the basis for the fitting of a retention curve (Figure C1, parameters in table C1). We have aggregated the results of 44 and 41 soil samples in the subbasins of the sand and slate site for a more robust representation (as discussed by Loritz et al., 2017).~~

~~Soil water retention curves for two soil layers at both experimental sites. To derive the retention curves, the matric potential is divided into bins of 0.05 pF. Measured soil moisture values of all samples and at tensions that fall into each bin are averaged and displayed as dots. The retention curve is fitted to these points. The resulting van Genuchten parameters are given in table C1. The number of soil samples that form the basis for the retention curves is given as n. The shaded areas mark the range of soil moisture values we observed with the TDR probes in this study.~~

2.1 ~~Monitoring techniques~~Soil moisture monitoring

Soil moisture was monitored using a sequence of TDR tube probes (Pico Profile T3PN, Imko GmbH), which allow for installation with minimal disturbance using an acrylic glass access liner (diameter $48\,\mathrm{mm}$). The liner tube was installed in the rhizosphere of the trees without any excavation using a percussion drill (about $0.5\,\mathrm{m}$ from the stem). For optimal contact of the liner with the surrounding soil, the drill diameter was $40\,\mathrm{mm}$ and the tube was installed more than one year prior to the recorded data set. Each TDR probe segment integrates the soil moisture measurement over its length of $0.2\,\mathrm{m}$. The signal penetrates the soil about $0.05\,\mathrm{m}$ which results in an integral volume of approx. ~~$0.001\,\mathrm{m}^3$~~1 L. The probes are stacked directly on top of each other, permitting spatially continuous monitoring over the soil moisture profile.

At the ~~sandy~~ sand site, we were able to install a profile with a sequence of 12 probes reaching a depth of $2.4\,\mathrm{m}$. At the slate site, percussion drilling was inhibited by the weathered bedrock. There ~~, we installed~~ we could only install a profile with a sequence of 9 probes reaching a depth of $1.8\,\mathrm{m}$.

~~Sap velocities were monitored in four beech trees in the direct vicinity of the soil moisture profile (as part of the CAOS research unit) . At the sandy~~

2.2 Soil hydraulic characteristics of the sites

The sand site is located in the Huewelerbach subbasin which is characterised by deep, homogeneous sandy soils and deep groundwater-driven hydrology. The second site on regosol of the slate Ardenne Massif is located in the northern part of the Colpach subbasin (Fig. 1). It is characterised by high gravel content and inter-aggregate voids (Jackisch et al., 2017). In this area the hydrological regime is dominated by a flashy response to rainfall through macroporous soils (Glaser et al., 2019).

The two sites show contrasting hydrological characteristics. An exemplary event water balance, based on above-canopy precipitation and the change in soil moisture in the different depth layers, is given in Figure 2. While both sites show about 30% of the event water being stored in the soil after five days, the response of the soil profiles to the water input is very different between the sites.

At the sand site (Fig. 2A), the fraction of the precipitation which is not intercepted in the canopy and litter layer enters the top soil horizon and successively percolates through the soil profile. This can be seen as diagonal patterns. The overall event water balance remains roughly constant. These dynamics are coherent with an expected event reaction of an ideal porous medium. Here, we can reasonably assume to represent the rhizosphere soil water dynamics in our profile measurements.

At the slate site (Fig. 2B), the same event causes a fast response in deeper soil layers with an initial overshoot of the water balance and a quick recession. This suggests a non-uniform infiltration process, followed by diffusive lateral redistribution into the surrounding soil. The latter can be seen as simultaneous declines of soil moisture in the different depth layers. The hydrological regime at this site is dominated by flashy transport through the macroporous soils and fill-and-spill mechanisms of subsurface pools on the fissured bedrock (Jackisch, 2015; Loritz et al., 2017).

Since soil moisture is measured as dielectric permittivity of the bulk soil, the measurement principle integrates over the entire soil volume, irrespective of stone content, voids or wetted contact surfaces. The joints and fractures of the weathered

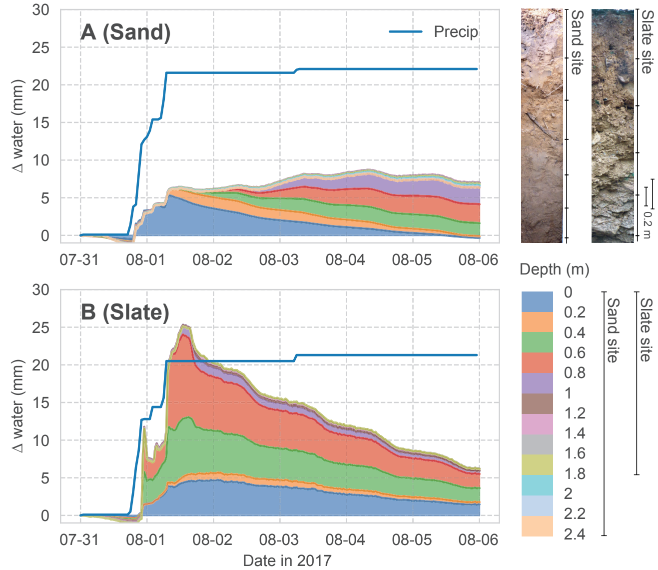

Figure 2. Event water balance observed at both sites. Shown is the stacked change of soil water content in each monitored soil depth. Cumulated above-canopy precipitation input is given as the blue line. The other colours correspond to the different depths in the soil profiles as shown in the figure legend. Two profile images give an impression of the soil conditions at the two sites.

bedrock at the slate site add two restrictions to representative soil moisture measurements: i) Roots are likely to grow along these fractures where event water will be stored with little effect on the bulk soil moisture. ii) Rocks inhibiting the drilling prevented us from sampling the entire rooting depth. Hence, the soil moisture measurements are prone to miss parts of the active rhizosphere at this site.

2.3 Sap velocity and meteorological data

SF sensors were installed in several trees at breast height before leaf out of the vegetation period in 2017. At the sand site, the reference sap velocity time series for this study could be obtained from the ~~exact tree~~ beech tree closest to where the TDR sensors were installed. It had a diameter at breast height (DBH) of 64 cm and was approximately 0.5 m away from the TDR tube. At the slate site, the sap velocity sensor of the intended tree failed 3 weeks after leaf out. There, we refer to a neighbouring beech tree with a DBH of 48 cm about 9 m from the TDR measurements (see Appendix A for details). The ~~sap flow sensors~~ SF sensors we used (East30 Sensors) are based on the heat ratio method and measure simultaneously at 5, 18 and 30 mm depth within the sapwood. Installation and calculation of sap velocities followed the description in Hassler et al. (2018). ~~The sensors were installed before leaf out of the vegetation period.~~

As further reference for the drivers of temporal dynamics in soil moisture and sap velocity we use solar radiation records (Apogee Pyranometer SP110) and corrected radar stand precipitation at canopy level ~~(data from DWD (Deutscher Wetterdienst, Germany), A~~

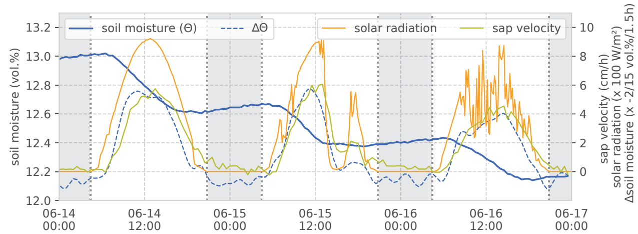

Figure 3. Example of observed ~~solar radiation~~soil moisture, sap velocity and ~~soil moisture~~ solar radiation during three days ~~of~~ in the vegetation period. The example is from the ~~sandy~~ sand site dataset, soil moisture values are in 0.7 m depth. ~~The~~ June, 14 is a sunny day with clear sky conditions, June 15 has clear sky intermitted by one shading spell in the afternoon and June 16 is a day with fair weather and radiation noise by scattered cumulus clouds. Shaded areas refer to astronomical night time. Notice that the change in soil moisture ~~compares with~~ is inverted in the plot for easier comparison to sap velocity ~~with $r_s = 0.87$~~ and ~~when linearly sealed with KGE=0.64~~radiation.

(data from DWD (Deutscher Wetterdienst, Germany), ASTA (Administration des Services techniques de l'agriculture, Luxembourg) and KN
The interception in the canopy and litter layer is not addressed. There is no understory vegetation at both sites.

3 ~~Inferring daily RWU from change in soil moisture~~Methods

~~On days with very little vertical soil water movement~~Estimating RWU from changes in soil water is not a novel idea in general (Novák, 1987; Feddes and van Dam, 2005). With precise and distributed measurements, step-like dynamics of soil moisture are observed on days with negligible vertical soil water movement (Guderle and Hildebrandt, 2015). These steps coincide ~~and highly correlate~~ – and the respective soil moisture changes highly correlate – with the observed sap ~~flow dynamics. In~~ velocity dynamics. For illustration, we selected an exemplary three-day ~~time series in~~ interval in the vegetation period. This interval contains a sunny day with clear sky conditions, a day with clear sky intermitted by one shading spell and a day with fair weather and radiation noise by scattered cumulus clouds (Fig. 3~~the~~). The correlation between changes in soil moisture and sap velocity give a Spearman rank correlation (r_s) of 0.87~~and when linearly sealed to the same mean a Kling-Gupta-Efficency (KGE, which is sensitive to curve fitting~~. Applying the Kling-Gupta-Efficiency (KGE) which considers the contributions of mean, variance and correlation when calculating time series deviations (and is thus sensitive to both the curve shape and its absolute values) yields a value of 0.64 (after linear scaling of the value ranges). Especially on June 15 the coherence between solar radiation, sap velocity and change in soil moisture becomes very obvious, when intermittent cloudiness lets radiation and sap velocity drop in the afternoon. During the same period the decline of soil moisture is halted, too. Furthermore, one can see that the signal of sap velocity follows the solar radiation with a slight time lag. Change in soil moisture follows the same pattern. When we can exclude percolation and pedophysical soil water redistribution as main drivers of soil moisture change, we may attribute these observed steps in the rhizosphere soil water content to RWU. The remainder of this methods section explains the steps to estimate daily RWU and SF (as illustrated in Fig. 4 and Fig. 5) and our approach of a comparison of both fluxes.

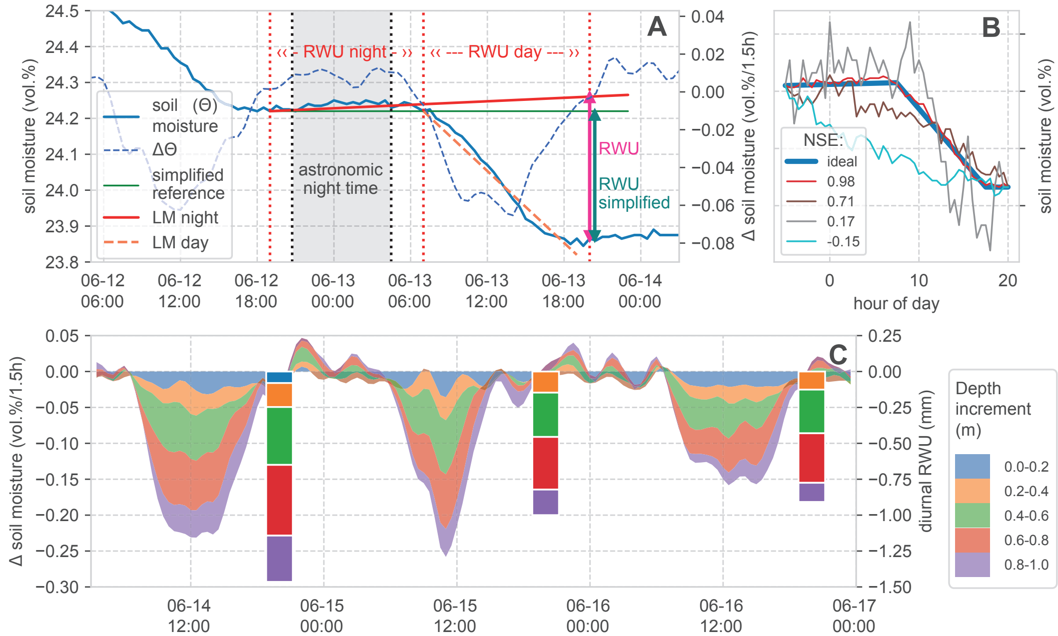

Figure 4. Calculation of root water uptake from soil moisture change. **A:** Time series of soil moisture and change of soil moisture during one day in one soil layer and indication of calculated RWU, showing the effect of including a linear regression model for nightly water redistribution (LM night) compared to the simplified calculation. **B:** Comparison of several exemplary (scaled) soil moisture declines to an artificial reference step ("ideal") and calculation of the Nash-Sutcliffe-Efficiency (NSE) for evaluation. **C:** Stacked change in soil moisture in the top soil layers and calculated daily root water uptake (bars) with the top measured soil layers also at the top of stack. No RWU is calculated if the time series does not meet the required basic criteria of the step shape (presented in section 3.1). This was not the case for the 0–0.2 m layer on June 15 and 16, hence the blue color at the top of the stack is missing for these days. The stacked bars form the basis for the comparison in Fig. 6.

3.1 RWU calculation

Based on the idea of Guderle and Hildebrandt (2015) and Blume et al. (2016), we developed an ~~evaluation algorithm for the observed soil moisture dynamics within the tree rhizosphere~~ algorithm to identify the characteristic declines and to extract daily RWU from the ~~measured soil water changes~~ observed differences of soil water between two sunsets (Fig. ~~??~~4 A).

~~First,~~

First, we identify the inflection points of the time series ~~are identified~~ (Fig. ~~??A~~4 A, vertical dashed red lines). These points are i) the beginning of a decline of soil moisture after sunrise and ii) the end of this decline near sunset. The astronomic reference times have been calculated with the *Astral* package (Kennedy, Simon, 2019) using the geographic positions of the sites. Our algorithm scans for the first soil moisture change of $\geq 0\,\mathrm{vol\,\%\,h^{-1}}$ in a window starting five hours before sunset and identifies this as the beginning of the night. The next decrease below $-0.02\,\mathrm{vol\,\%\,h^{-1}}$ is marked as beginning of diurnal RWU.

The beginning of the next night is used as final evaluation reference. ~~Because the~~ This approach is sensitive to noise in the data. Due to the high quality of the employed TDR sensors ~~show very little noise,~~ we could avoid strong smoothing~~of the time series of soil moisture changes between three time steps. However~~. To make the procedure more robust, we applied a 1D Gaussian filter with one standard deviation to the resulting time series ~~before evaluation to make the procedure more robust.~~ of changes in soil moisture before evaluation.

~~A) Calculation of root water uptake from soil moisture change of one day in one soil layer. B) Comparison to artificial reference step.~~

~~Compliance of the day-to-day soil moisture signal with the hypothesised step shape is evaluated with two control measures: First, we construct a synthetic step interpolating between the observed soil moisture values at two successive sunsets and an artificially increased (by 0.01 vol%) moisture at 3 h past sunrise in between (Fig. **??**B). This synthetic reference is compared to the observed time series by calculating the Nash-Sutcliffe-Efficiency (NSE). The NSE is a measure which is very sensitive to deviations from shape features. As second set of criterions, we fit two linear regression models to the night and day phases of the observed time series~~ Generally, the estimate of the diurnal RWU is simply the reduction in soil moisture between two days (Fig. 4 A, green line). We extend this simplified approach, to account for hydraulic redistribution of soil water in the rhizosphere. We assume that such redistribution fluxes manifest as changes in soil moisture during the night but remain active during the day. To calculate these changes we fit a linear regression model (LM) to the observed soil moisture time series during the night and extend it to the reference time at the end of the day (Fig. ~~**??**A). With the following consistency checks we can evaluate the~~ 4 A, slightly increasing red line). Now, the calculated difference in soil moisture compensates for hydraulic redistribution. In the time series in our example, soil moisture is increasing during the night. There are also cases with slightly decreasing nocturnal soil moisture. We stick to the approach correcting for hydraulic redistribution in the following analyses and later evaluate its benefits compared to the simplified version.

Because diurnal change in soil moisture is not necessarily RWU, we assess a) the general step shape of the observed ~~curves (a) and the absence of strong external fluxes dominating changes~~ daily declines and b) the occurrence of external fluxes which could dominate soil moisture changes before estimating RWU. To this end, we calculate the slope of linear models (LM) fitted to both night- and day-time changes in soil moisture ~~(b):~~ respectively (Fig. 4 A). We define the following criteria to characterise the expected step-shape:

a) ~~day~~ The day-time slope of soil moisture ~~(a_{day})~~ is negative (decline in soil moisture during the day) and three times smaller than ~~night~~ the night-time slope (general step shape of the curve).

$$min(0, 3a_{\text{night}}) > a_{\text{day}}$$

b) ~~night~~ The night-time slope of soil moisture ~~(a_{night}) is ≥ -0.01 vol% /12 h(no strong~~ remains at moderate levels of diffusive flux rates between -0.01 vol% and 0.02 vol% in 12 h. A stronger decline in soil moisture during the night ~~, which~~ would indicate percolation or external withdrawal as ~~dominating process) and < 0.02 vol% /12 h (no too strong increase in soil moisture during the night, which~~ a dominating process, whereas a larger increase would indicate an ~~externally driven~~

external input of soil water~~).~~

$$\frac{0.02\,\mathrm{vol\%}}{12\,\mathrm{h}} > a_{\mathrm{night}} \geq \frac{-0.01\,\mathrm{vol\%}}{12\,\mathrm{h}}$$

.

~~Moreover, the nocturnal regression model is used for extrapolation of any externally driven changes of soil moisture. This change is hypothesised to be soil water exchange or recharge with areas surrounding the rhizosphere layer, as "corrected" reference for the difference calculation (Fig. ?? red line).~~ In the identified steps which meet the given criteria, the change in soil water content over the day is calculated ~~with and without a "correction" term~~ at the beginning of the next night period (Fig. ~~??~~ 4 A, magenta and green vertical arrows).

~~The developed calculation algorithm is published as python package rootwater under MIT license (Jackisch, 2019)~~Fig. 4 C gives an example of the resulting daily RWU estimate for the first metre of the soil profile, alongside the corresponding changes in soil moisture. There, one can also see that on June 15 and 16 the soil moisture dynamics in 0–0.2 m depth did not meet the criteria for the step shape. Hence there is no RWU estimate in this layer.

3.2 ~~Conversion~~ Evaluation of the estimated RWU~~and sap velocity to flux ratesIn order to rigorously compare the detected RWU(given in change in soil moisture per time)to the observed sap velocity (given in length per time) , we have to derive a sap flow integral from~~

In addition to the ~~sap velocity dynamics measured at three points of the sap flow sensor~~ general check of the step shape of soil moisture dynamics during the calculation of RWU, we add an evaluation measure of how well the observed diurnal step agrees with a synthetic reference.

For this, we construct a synthetic, "ideal" step based on the observed soil moisture values at two successive sunsets and our criteria for the expected step shape (see Sec. 3.1). Between the observed values at sunset, we insert an increased moisture value (by 0.01 vol%) at 3 h past astronomic sunrise and let the value at sunset be reached 3 h early. The intermediate values are linearly interpolated (Fig. 4 B, blue line). This synthetic reference is compared to the observed time series by calculating the Nash-Sutcliffe-Efficiency (NSE). The NSE is a measure which is very sensitive to deviations from shape features.

Fig. 4 B contains several observed soil moisture steps and their respective NSE values. For all steps, the general criteria are met but the deviations from the idealised step can be quite substantial. This can be due to signal noise or due to other reasons causing a reduction in soil moisture. We expect an NSE ≥ 0.5 to be a fair reference for good agreement of the observed dynamics with mainly RWU-driven soil moisture decline.

As a qualitative evaluation, we compare the number of detected steps in each soil layer with the total number of days with SF $> 0.1\,\mathrm{L\,d^{-1}}$.

3.3 Conversion of sap velocity to volumetric flux rates

After processing the original heat pulse measurements (Hassler et al., 2018), we obtain sap velocity observations at three positions (5 mm, 18 mm and 30 mm) within the tree xylem, measured from the cambium (Fig. ~~??~~5 A). ~~This owes to the~~

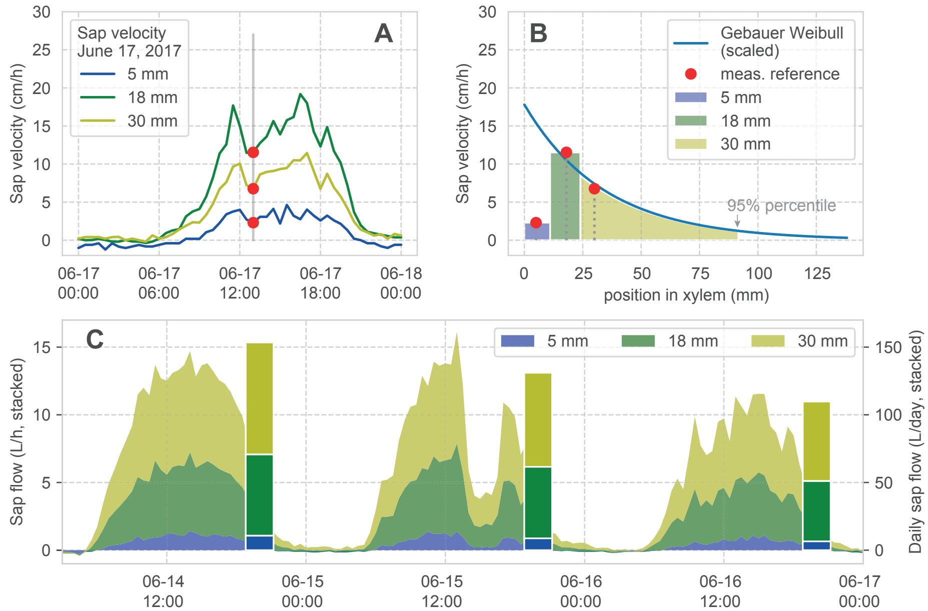

Figure 5. Calculation of sap flow. **A:** Measured sap velocity dynamics on June 14, 2017 for the three measurement points of one sensor, **B:** Fit of a Weibull distribution after Gebauer to the measured reference sap velocities in A. This is required to estimate the radial velocity distribution and especially the border to the inactive xylem (95% percentile of the distribution) for the calculation of sap flow. The width of the coloured bars and shaded area under the curve show the three respective increments which are used for the calculation of the sapwood area corresponding to each velocity measurement. **C:** Stacked time series of calculated sap flow and its daily aggregate (bars) for a hypothetical tree with a DBH of 64 cm for three consecutive days. The stacked bars form the basis for the comparison in Fig. 6.

~~facts~~ Calculating sap flow from the individual velocities requires multiplication with the corresponding sapwood area for each measurement point. Moreover, one needs to consider that i) the ~~sapwood cross-section is radial symmetrically larger with larger reference radius, and~~ areas of the respective sapwood increments corresponding to each velocity measurement are dependent on the tree DBH, and that ii) the sap velocity in the xylem is unevenly distributed over the sapwood area (Gebauer et al., 2008). Ignoring this can lead to strongly erroneous estimates (Čermák et al., 2004).

~~We assume the two outer measurement points in the sapwood to be~~

We calculate the three sapwood area increments corresponding to our measurements, based on the measured DBH and the position of the sensors. Since our sensors are positioned directly in the xylem but DBH includes bark, we removed the bark thickness from our xylem area for further calculations, after Rössler (2008). The two outer sap velocity measurement points are considered representative for the radial area between ~~0 – 11 mm and 11 mm~~ 0–11 mm and 11–24 mm~~. Both~~ , respectively. These depths are the mid points between the sensor positions ~~. The inner sensor is representing a flow field, which has~~ within the xylem measured from the cambium (Fig. 5 B). For the inner part of the active xylem radial sap velocity profiles have been shown to follow a Weibull distribution (Gebauer et al., 2008)~~in the active sapwood. To estimate the sap velocity distribution~~

~~at each time step, we fit the Weibull function with the beech-parameters of Gebauer et al. (2008)~~. We fit this distribution with the parameters for beech (Gebauer et al., 2008) to the observed measurements at ~~the mid and inner point~~ 18 mm and 30 mm for each time step, via a scaling factor (Fig. ~~??~~5 B). ~~For a correct position reference, the bark thickness is removed after Rössler (2008). Since Gebauer et al. (2008) reported parameters for the Weibull distribution for different tree species, one should note that the effect of these on the estimate for the flow velocity distribution over the sapwood radius is minor (Fig. ??B, purple dashed line for alternative parameters). As inner end, the~~ The transition from active to inactive sapwood is determined with the 95~~% percentile is used to mark the transition to the inactive sapwood (Gebauer et al., 2008).~~ % percentile of the Weibull distribution (Gebauer et al., 2008), which finally defines the required integral for the third sapwood area increment. The resulting time series is now reporting ~~sap flow~~ SF in $\mathrm{L\,h^{-1}}$ and is aggregated to daily values. Fig. 5 C shows the stacked time series for our example period and the daily aggregated stacked bars, which we use in the forthcoming analyses.

~~Example for sap flow volume calculation. A) Measured sap velocity on June 14, 2017 with one exemplary sample. B) Application of Weibull distribution of sap velocity in sapwood for the sampled set to derive radial distribution. C) Resulting time series of sap flow and its daily aggregate (bars) after applying the radial sap velocity distribution to a tree with a DBH of 64 cm for the same days as in Fig. 3.~~

~~Assuming the measured sap flow fully originates in the soil moisture decrease, we can convert the calculated RWU from~~

3.4 Estimation of RWU as volumetric flux

In order to rigorously compare the signals of RWU in the rhizosphere and sap velocity in the tree stem, we refer to the respective volumetric fluxes. We have already converted the observed sap velocity (given in length per time) to SF (given in volume per time). RWU (given in change in soil moisture per time~~to a volumetric flux, too. This is done by~~) then needs to be converted into a volumetric integral as well. We evaluate the validity of our RWU approach based on a closed diurnal water balance assuming that water storage in the tree stem has a minor effect.

With RWU as withdrawn soil moisture in increments of $0.2\,\mathrm{m}$ over a continuous profile, we are basically left with a guess about the lateral dimensions of the rhizosphere to derive a flux. This lateral extent can be estimated as a specific area, which is the scaling factor of a linear regression of ~~daily sap flow to the sum of RWU over the soil profile with assumed~~ sap flux ($\mathrm{L\,d^{-1}}$) and RWU ($\mathrm{mm\,d^{-1}}$) with zero intercept. ~~The resulting factor is the mean reference area required to supply the observed sap flow. Assuming a circular shape , this yields the~~

As most simple assumption, we consider the rhizosphere to be cylindrical – although it is known that the shape is highly species and site specific (Kutschera and Lichtenegger, 2002). This allows us to convert the lateral reference area into the mean rhizosphere radius as further evaluation reference for the proposed approach. ~~We acknowledge that the assumption of a closed water balance is probably overly simplified, hence we only consider this approach a rough check-up on general dimensions of the rhizosphere, but we do not interpret the results any further.~~

3.5 ~~Evaluation~~ Comparison of ~~estimated~~ RWU and ~~sap flow~~SF

The quantitative comparison of derived RWU and SF is ~~done as direct time series analysis and its overall correlation measures. To evaluate the general correlation between the fluxes and sites, we calculate~~ based on the calculated volumetric fluxes. As validation of our RWU calculation and with respect to our second research question, we evaluate the correlation between RWU and SF at the two sites. For this we use the Spearman rank correlation ~~. As measure being more sensitive to~~ and the Kling-Gupta-Efficency (KGE). KGE is sensitive to both the curve shape and ~~absolute volume fluxes, we moreover employ the Kling-Gupta-Efficency (KGE). To account for the non-uniformity of the processes over the vegetation period, the correlation measures are also calculated~~ its absolute values by considering mean, variance and correlation of two time series. In addition to evaluations of the full time series, we apply the measures in a moving window of 21 days~~. These measures are applied to RWU and SF at each site and for an inter-site comparison~~, to account for the non-uniformity of the processes over the vegetation period.

~~As reference for the soil hydrological site characteristics , we explore the event water balances of both sites in reaction to a 20 mm precipitation event in August 2017.~~ For an analysis of the effect of soil and site characteristics on RWU and SF (third research question), we compare SF and RWU between the two sites using the same methods.

~~With respect to our third hypothesis, we investigate influences on the observed RWU and sap flow dynamics over the vegetation period on the basis of the soil water state. For this, measured soil moisture is converted into matric potential by applying the measured soil water retention characteristics (Figure C1).~~ Finally, we calculate all correlation measures also for the simplified RWU method as final check-up if including hydraulic redistribution in our method holds any merit.

4 Results

4.1 RWU calculation

~~Fig. ??~~ Building on the pre-processing leading to the stacked bars in Fig. 4 C and 5 C, Fig. 6 presents time series of ~~sap flow~~ daily SF and estimated RWU for both sites. ~~In the~~ The top half of each panel ~~stacked daily sap flow and precipitationis given. In the lower half of both panels~~ shows stacked daily SF and precipitation, whereas in the respective lower halves the stacked RWU estimate from the different soil layers is displayed. ~~At the sandy~~ As an indicator for plant available soil water, we accumulated the soil moisture above the permanent wilting point over the soil profile. At the sand site, two summer thunderstorms damaged the loggers in the middle of the vegetation period, which caused an early end of the time series.

~~Sap flow (upper part) and RWU estimate (lower part) at two sites. The colour coding of the different depth sources of RWU is complemented with its color strength taken from the NSE evaluation of the step shape evaluation (opaque is high compliance/high NSE).~~

Water transport activity in the SF time series is linked to radiative forcing: during days with observed precipitation, a respective drop in SF can be seen. The general decline in tree water fluxes over the summer appears to be halted with a rain spell in mid September and higher activity in a subsequent sunny spell.

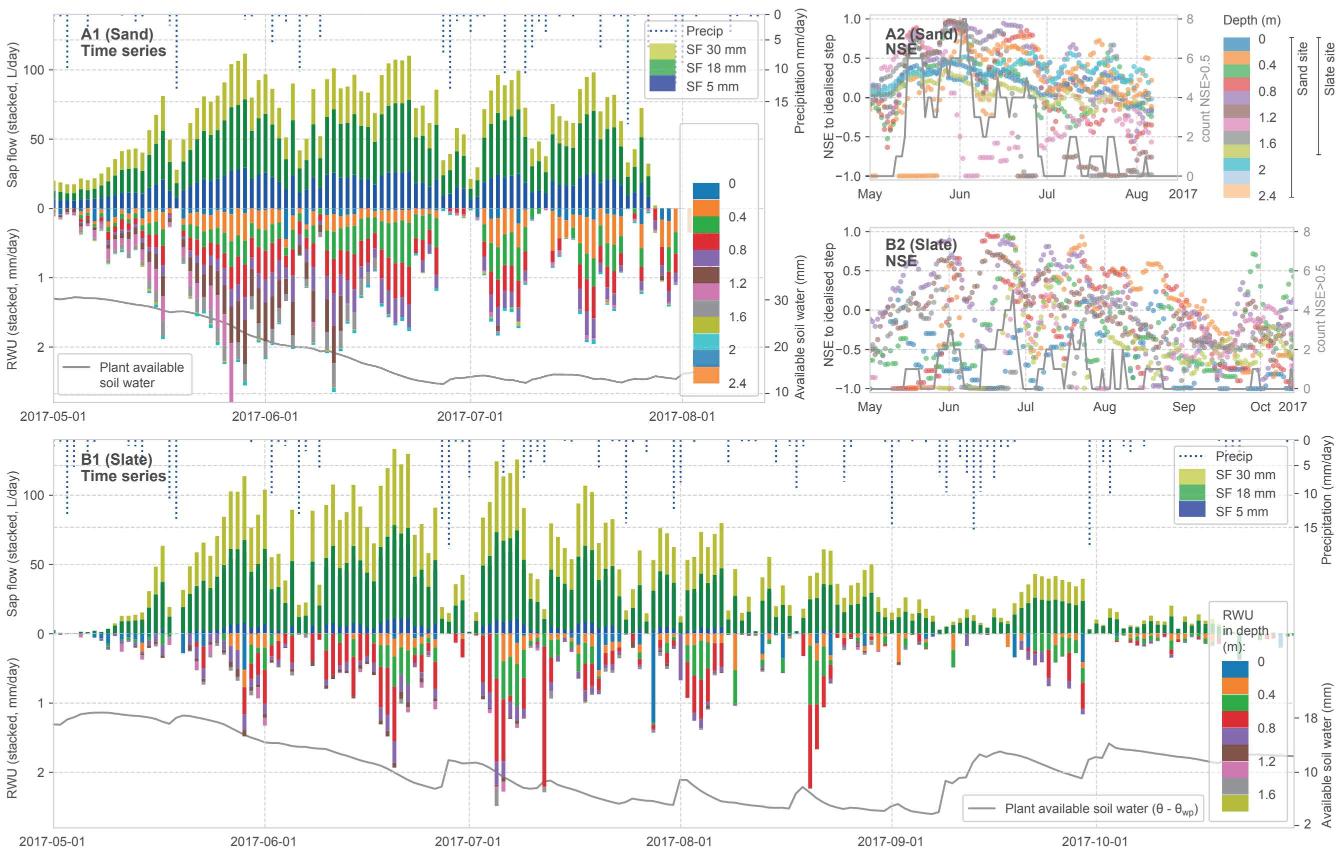

Figure 6. Summary of calculated time series for SF and RWU estimates as stacked daily values (see Fig 4 and 5 for methods). SF (upper half) is given as volume flux, while RWU (lower half) is given as flow of withdrawn water (without an assumption of the lateral dimension of each soil layer tapped by roots). As an indicator for soil moisture state, we report the plant available soil water in the soil column as the difference between the measured water content minus the water content at the permanent wilting point (grey line a the bottom of the panels A1 and B1). In panels A2 and B2 the evaluation of the observed diurnal soil moisture time series to the idealised step is reported for each soil layer at the two sites (rolling 7-day mean of NSE to avoid scatter) alongside the daily counts of detected steps with NSE > 0.5 across all layers. High NSE values point to high determination of the RWU estimates in the stacked bars in A1 and B1.

The RWU identified from change in soil water content follows the course of ~~sap flow~~ SF over the year~~(Fig. ??~~, which is seen as general symmetry along the time axis in Fig. 6 (panels A1 and B1). It starts with leaf-out and increasing water fluxes through the tree until end of May. In July, both fluxes start to decrease again. In later summer ~~, the RWU signal ceases although the sap flow~~ with less plant available soil water, several days do not show a RWU signal although the SF signal continues at lower rates. Similarly, the evaluation of the coherence of the diurnal soil moisture steps with a synthetic step as NSE follows this seasonal pattern with decreasing compliance later in the year (Fig. 6 panels A2 and B2). A substantial proportion of the identified steps scores below the intended reference NSE value of 0.5.

Fig. ~~?? suggests~~ 6 panels A1 and B1 suggest that the depths of RWU and the magnitude of the sourcing for each depth are not static over the vegetation period. During leaf-out both ~~plots show reactions in~~ sites show RWU from deeper layers. Especially at the ~~sandy~~ sand site, the sourcing from below $1\,\mathrm{m}$ depth can only be found before mid July. But also intermediate soil horizons appear to disconnect over time. It is interesting to note that the two sites differ mainly in the contributions from the shallow and deeper layers. ~~Uncertainty of the identified RWU is given with less opaque colours for~~ The frequent occurrence of low NSE values of the identified step shape ~~. The transparent colours in summer~~ (Fig. 6 panels A2 and B2) suggest that the method reaches its limits not only when RWU ~~becomes insignificantly small~~ is insignificantly small (such as in earlier spring and autumn), but also when soils are dry (most prominently between July and September). However, the count of detected steps with an NSE > 0.5 (Fig. 6 panels A2 and B2, grey lines) is not entirely explained by plant available soil water. It remains difficult to discern the interlaced effects causing the seasonal pattern within the scope of this study. ~~Interestingly, the uncertainty of the RWU derivation function is generally smaller at the slate site.~~

~~Overall, an answer to our first hypothesis is that a derivation of RWU from changes in soil moisture is possible. However, the time series might be influenced by false-negative results, when the detection failed and resulted in no value. This might be the case~~

4.2 Comparison of RWU detection and sourcing to SF

Following our approach to evaluate the RWU detection against the occurrence of SF $> 0.1\,\mathrm{L\,d^{-1}}$, Fig. 7 reports the number of days with successful RWU detection in relation to days with SF. In order to set this binary, qualitative measure into perspective, we included the total sum of detected RWU for each layer in the plot (Fig. 7, red bars).

In the most active part of the rhizosphere (0.2–1 m at both sites), RWU was detected in about 80% of the SF days at the sand site and in about 60% of the SF days at the slate site~~, when days with similar sap velocity lack a signal from a certain layer (mostly 70 cm end of June and beginning of July) . Moreover, some days with reduced sap flow do not show any RWU. Furthermore, quite a number of diurnal RWU sums show~~ . In general, a large proportion of steps could be identified with acceptable certainty (NSE > 0.5) in the most active layers. However, there remains substantial uncertainty about the step shape ~~(low NSE and less opaque colour in the plot). Hence, the robustness of the automated detection of the diurnal soil moisture decrease is limited.~~ at both sites. The overall detection rate and the step compliance are better at the sand site. A further reference about RWU magnitude and step shape NSE is given in the Appendix Fig. B1.

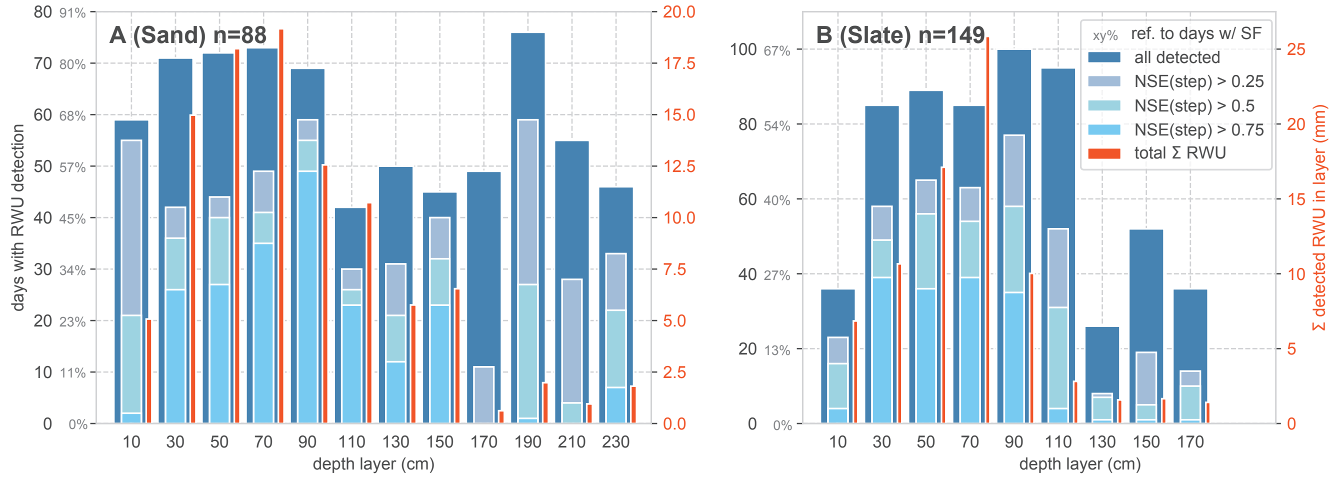

Figure 7. Qualitative evaluation of the RWU derivation algorithm for the sand (A) and the slate site (B). The reference n is the number of days with a SF > $0.1\,\mathrm{L\,d^{-1}}$. The dark blue bars refer to the number of days with a successful RWU detection according to the general step criteria. Their proportion of the reference SF days is given in the grey percentages on the y-axes. The lighter blue colours report the compliance of the detected RWU with the ideal step-shape assessed with the NSE, as respective sub-fraction of the total dark blue bar height. For comparison to the magnitude of the detected RWU in each layer, the total sum of RWU over the entire season is given as red bars.

4.3 ~~Comparison of seasonal RWU and SF dynamics~~

~~With respect to the second hypothesis, despite good general agreement Fig. ?? shows substantial differences of sap flow and the RWU estimate. While we might attribute some of this difference to the limited capabilities of the method, there might also be a difference in RWU and sap flow caused by the different sourcing in the rhizosphere, state of the tree physiology and possible wounding response to the sap flow sensor~~Comparing the depth distribution of total RWU sourcing at both sites (Fig. 7, red bars), the sand site appears to supply the water more evenly distributed over a larger range of the rhizosphere down to $1.5\,\mathrm{m}$. The slate site strongly peaks in $0.7\,\mathrm{m}$ depth and appears to deliver little water supply from below $0.9\,\mathrm{m}$. However given the limits of representative soil moisture measurements in structured soil settings, this might be an artefact of the method.

4.3 Comparison of seasonal RWU and SF dynamics

The sites differ strongly in the dynamic pattern of RWU sourcing (Fig. ~~??~~6 and Appendix Fig. B1). In sand the tree sources ~~RWU~~ water from deeper layers during spring and early summer. This deep RWU ceases over the course of the vegetation period although ~~matric potential increases~~ overall soil moisture decreases only slightly. Such deep sources were not detected at the slate site. However, we cannot exclude that roots may source water from the weathered bedrock ~~, which would not be detected by the~~ below the reach of our soil moisture sensors.

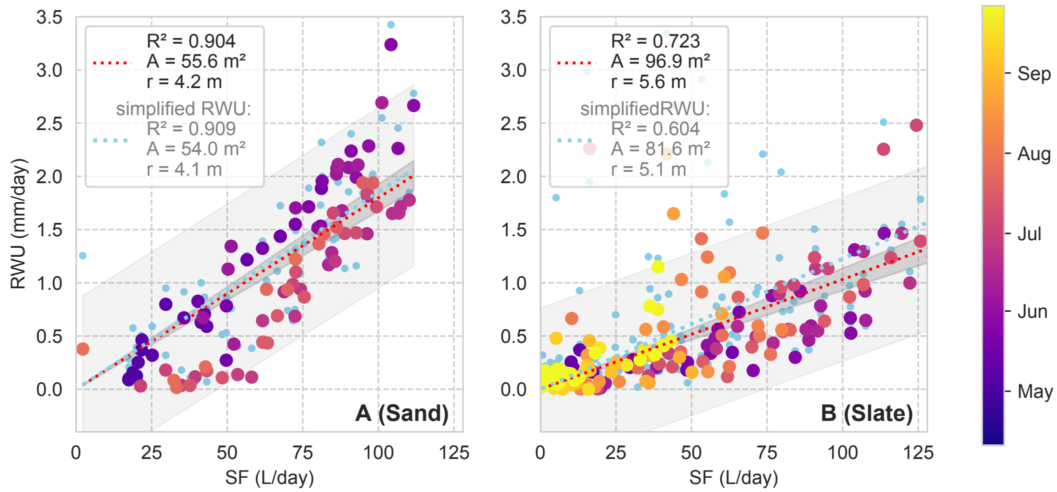

Figure 8. Daily ~~sap flow and cumulated~~ RWU ~~over all soil layers~~in relation to SF for both sites. ~~Colour~~ The colour coding ~~for~~ corresponds to the day of the year. Linear regression models are given as dashed lines. ~~Light blue dots and regressions are RWU estimates without "nocturnal correction". Grey~~ The grey shades ~~give~~ show predicted and observed confidence intervals. The linear regression model is assumed with zero intercept resulting in a scaling factor which is reported as mean area (A) and radius (r) of a cylindrical rhizosphere in the legend (possible storage in the tree is neglected). The light blue dots and regressions refer to RWU estimates with the simplified RWU calculation approach for comparison.

Looking at the correlation of the RWU estimate and ~~sap flow~~ SF (Fig. 8), the ~~sandy~~ sand site presents constantly higher RWU/~~sap flow~~ SF ratios during the onset of the growing period compared to summer. However, with an R^2 of 0.91 the correlation of both signals is quite high. At the slate site, the correlation is less well-determined (R^2 of 0.72). Despite the larger scatter, ~~The~~ the correlation appears to be influenced by the deviating values in the second half of the vegetation period, which are not included in the sand site data. ~~The correction based on nocturnal changes does not show any substantial effect for the sandy site. However, at the slate site, the method appears to improve the estimates more substantially.~~

~~With a working-hypothesis of a closed~~ Based on the assumed closed daily water balance between SF and RWU, ~~the linear regression also results in an estimate for~~ we can calculate an estimate of the mean rhizosphere radius ~~. At the sandy~~ from the linear regression (Fig. 8). At the sand site the cylinder would have a radius of 4.2 m. At the slate site one would estimate a radius of ~~5.5 m. Given the broad assumptions, these values are within a plausible range, corroborating the proposed approach~~5.6 m. We use these values to calculate the fluxes for the following correlations.

The temporal dynamics of the estimate of RWU and observed ~~sap flow~~ SF correlate quite well with an overall Spearman rank correlation coefficient of 0.89 and 0.76 for sand and slate, respectively (Fig. 9). However, the high initial correlation drops in July. At the sand site, this marks the shift to RWU ranging below SF. At the slate site, no such transition is apparent, but correlation decreases with decreasing plant available soil water. The KGE hints to slightly lower correlation of the exact dynamics and flow volumes (0.62 and 0.56 for sand and slate). Both measures corroborate the visual findings in Fig. ~~??~~ 6 that

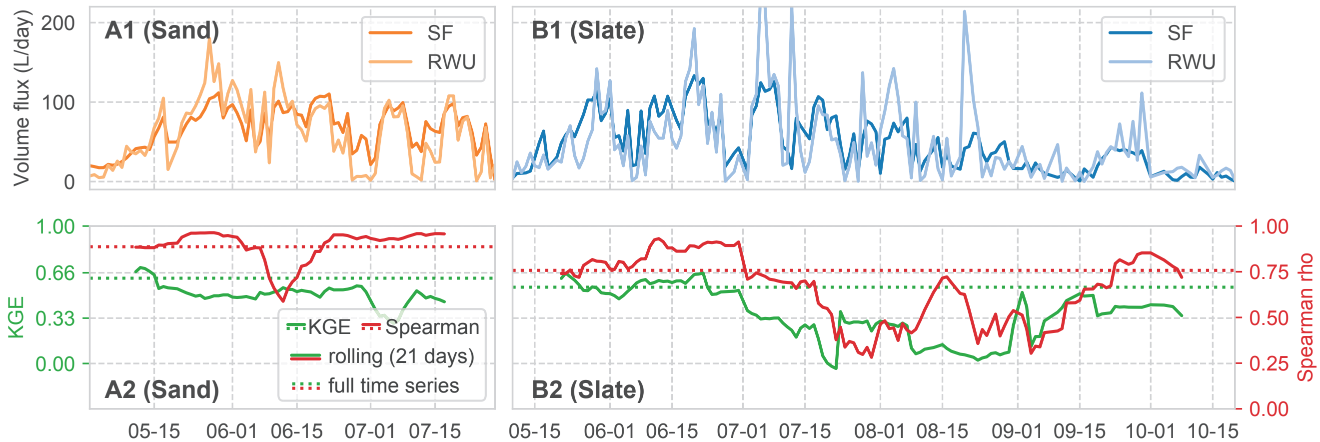

Figure 9. ~~Time~~ Comparison of the time series ~~correlation between~~ of calculated volume fluxes for RWU and ~~sap flow. (A) Sand site~~SF, at both sites (~~B) Slate site,~~ panels A1 ~~,~~ and B1 ~~: Time series plot of calculated daily volume fluxes~~for sand and slate, respectively). Correlations between the RWU and SF time series are shown in panels A2 ~~,~~ and B2~~: Correlation measures~~, both as KGE and Spearman rho. The solid lines for the correlations show a 21-day rolling mean, the dashed lines are the mean correlations for the whole time series.

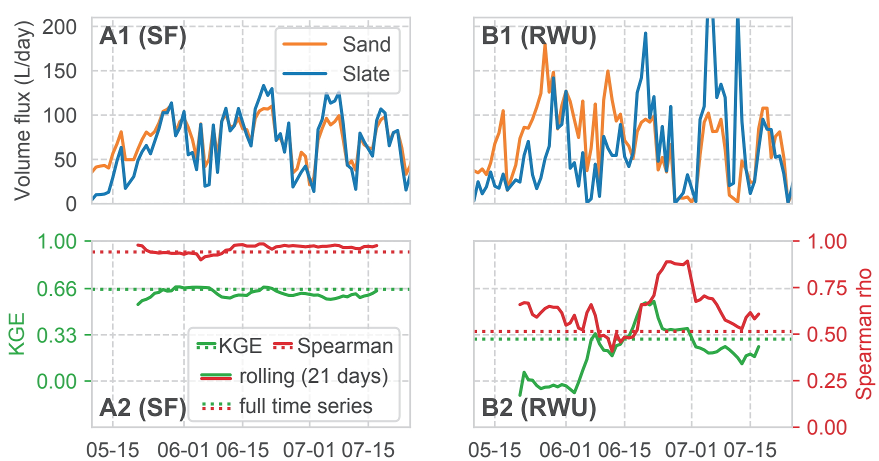

Figure 10. ~~Time~~ Comparison of the time series ~~correlation~~ of the calculated volume fluxes for RWU and SF, between both sites ~~. 1~~(panels A1 and B1 for SF and RWU, ~~3: Time series~~ respectively). Correlation of ~~calculated daily volume~~ the fluxes ~~. 2~~between the sites, ~~4: Correlation measures~~of RWU and SF between both sites, both as KGE and Spearman rho. Signatures are similar to Fig. 9.

the correlation in summer (between July and September) is less convincing. ~~Moreover, these findings point out strong~~ While this might be a limit of our RWU estimate, it can also point to limitations of our ~~working-hypothesis~~ working hypothesis of a closed water balance between RWU and SF.

A comparison between the two sites (Fig. 10) clearly depicts a very high ~~similarity of sap flow~~ correlation of SF (Spearman rho of 0.94 and KGE of 0.64) compared to weaker correlation of RWU (Spearman rho of 0.52 and KGE of 0.3). It is interesting to note that the correlation of SF remains almost constant over the whole period, while the RWU correlation is more dynamic. As we would assume a constant influence if this variability would result from an artefact of our method, the differences point towards contrasts of the RWU process between the sites.

~~So far, the analyses referred to the RWU calculation including the nocturnal correction.~~

4.4 Evaluating the benefit of including nocturnal water redistribution in RWU calculation

We employed the more sophisticated approach of determining RWU including potential nightly recharge via a linear regression (as described in Sec. 3.1 and shown in Fig. 4A). To evaluate whether we gained any improvement in the RWU estimates from this method compared to the simplified approach, we consider the general correlation (Fig. 8, blue signatures) and repeat the previous comparison with the simplified approach.

In Fig. 8 we see that our approach does not show any substantial effect for the sand site, compared to the simplified approach. However, at the slate site, our method appears to improve the estimates more substantially (improved R^2 from 0.60 to 0.72). The effect of ~~this assumption on the temporally explicit measures is~~ using our approach over the simplified one on the correlations between RWU and SF was negligible for the ~~sandy site(Spearman~~ sand site: Spearman r_s improved from 0.85 to 0.89, KGE decreased from 0.66 to 0.62~~)~~. At the slate site, ~~phases of improved and decreased correlation exist. However,~~ the overall improvement of the Spearman ~~coefficient~~ r_s is from 0.67 to 0.76 points, for KGE from 0.38 to 0.56 when applying ~~the nocturnal correction.~~ our approach. In accordance with the observed temporal differences in the correlation (Fig. 9B2), phases of improved and decreased correlation exist using the more sophisticated approach.

Comparing RWU correlation between the two sites ~~, applying the nocturnal correction improves Spearman~~also shows this improvement as an increase in Spearman's rho form 0.42 to 0.52 ~~.~~ when using our approach. However, KGE remains almost the same with 0.27 increasing to ~~0.3.~~ 0.30, which we attribute to the observed differences of the RWU dynamics between the sites in general.

Overall, this points to an improvement of RWU estimates when including nightly recharge especially for sites with more heterogenous soil conditions.

4.5 ~~Event water balance at both sites~~

~~The two sites show contrasting hydrological characteristics. An exemplary event water balance based on the above canopy stand precipitation and the change in soil moisture in the different depth layers is given in Figure 2. While both sites show about 30% of the event water being stored in the soil after five days, the reaction of the soil profiles is very different between the sites. At the sandy site, the fraction of the precipitation which is not intercepted in the canopy and litter layer enters the top soil horizon and successively percolates through the soil profile. The overall event water balance remains constant. At the slate site, the same event causes a fast response in deeper soil layers with an initially quick recession of the free water. This~~

~~is followed by a diffusive redistribution into the surrounding soil aggregates seen as parallel declines of soil moisture in the different depth layers.~~

~~Event water balance observed at both sites. Change of soil water content in each colour-coded reference depth layer. Cumulated above-canopy precipitation input given as blue line.~~

~~In conclusion, the sandy site follows the expected event reaction of an ideal porous medium (Figure 2A). The assumption that the rhizosphere soil water dynamics is represented in our profile appears well-justified, and the roots will most likely source water from the soil matrix.~~

~~At the slate site, the hydrological regime is dominated by flashy transport through the macroporous soils and fill-and-spill mechanisms of subsurface pools on the fissured bedrock (Figure 2B). Since soil moisture is measured as bulk apparent dielectric permittivity, the measurement principle has to integrate over the total sensed volume, irrespectively of stone fraction, voids or wetted contact surfaces. Here, roots are likely to grow along joints and fractures, where event-water can be stored with little effect on the bulk soil moisture. As such, the measurements might miss parts of the active rhizosphere.~~

4.5 ~~Dynamic sourcing of RWU~~

~~The sourcing of RWU from different depths and the respective matric potential allows an alternative view of the data by relating RWU to soil state and depth (Fig. C1). Although no clear correlation of RWU and matric potential can be seen, the depth-related colour coding corroborates the strong differences between the sites . In general, there is more tolerance of RWU to higher matric potential at the sand site. Given the slight tendency to higher maximal rates at lower matric potential above the wilting point (PWP), the high RWU rates at higher tensions might point to limits in the simplistic retention function application. The less bound water in deeper layers appears not to contribute much to RWU. In the slate regosol the pattern is more diverse but also more intuitive. Highest RWU rates occur at relatively low matric potential in moderate depths. However, high observed sap flows (large dots) also coincide with high matric potential and reactions in various depths. At the sand site, a correlation of matric potential and depth appears to exist, which is in line with the observed event reaction (Fig. 2).~~

~~Sourcing of RWU: Daily values of matric potential in each soil layer and RWU. Colour coding with respective depth. Dot size marks the reference sap flow of the day. The marginal histograms and kernel density distributions on top refer to the occurrence of the respective matric potential bin in the observed period. The marginals on the left give the distribution of RWU (blue) and the total RWU of a certain bin (green). PWP marks a matric potential at the wilting point with pF 4.2.~~

5 Discussion

Our results give ~~an ambivalent~~ a nuanced picture: Inferring RWU from changes in soil moisture within the rhizosphere ~~was~~ is possible with our approach and provides interesting insights into the hydrological functioning of the root system for individual sites. The relatively high temporal resolution ~~and spatial distribution~~ of the data~~enabled~~, its continuous spatial distribution and its quality enables a perspective into the rhizosphere water dynamics, which is often conceptualised in models (Kuhlmann et al., 2012) but rarely measured. At the same time, ~~we pointed out considerable limitations to~~ our results point to considerable limitations of the approach with respect ~~to~~ soil water state (~~no detectable signal during low moisture periods)~~ less detectable signals during periods of low plant available soil water), physiological state of the tree (overall seasonal pattern of the signal) and soil properties (~~high variability~~ less determination in heterogeneous soil profiles).

5.1 Performance of the RWU derivation ~~function~~algorithm

The RWU derivation ~~function~~ algorithm appears to perform very well in general (detection of 80% in sand, 60% in salte) and can be used to evaluate a broad range of diurnal changes in soil moisture (Fig. 7). ~~In the most active part of the rhizosphere (between 0.2 m and 1 m~~RWU is prone to be underestimated on days when the detection failed due to incoherence with our criteria. This might be the case during days with active percolation (e.g. sand site end of June, Fig. ~~7)at the sandy site, RWU was detected in about 80% of days with sap flow larger than 100 mL.A large proportion of steps could be identified with acceptable certainty (high NSE of step-shape as~~ 6). We find a failure of RWU detection primarily at the slate site, visible in days with similar sap velocity (e.g. July 5 and 6 compared to July 7 and 8) lacking the RWU signal from a usually active layer (mostly 0.7 m). Furthermore, quite a number of RWU estimates show uncertainty about the step shape (NSE < 0.5 in Fig. ~~??B, see also Fig. B1). At the slate site about 60% of SF days are also found with RWU in the most active part of the rhizosphere. Unlike the first impression in Fig. ??, the proportion of steps with higher uncertainty about the actual fit of the shape with the assumptions is higher in the slate site data, which is in line with the lower overall RWU detection there.~~ 6 panel A2 and B2).

~~Number of detected days with RWU (blue) and the total sum of RWU over the season (red) for each depth layer. The compliance with the hypothesised step shape is days exceeding a given NSE. Reference number (n) refers to days with a total sap flow above 100 mL. To this reference the percentage of days is given.~~

In our analyses, we neglect the contribution from direct soil evaporation or understory transpiration and focus on the tree transpiration. At our sites, understory vegetation is mostly absent and we have a characteristic thick litter layer of beech leaves. We therefore regard the effect of understory transpiration as minor. However, it is noteworthy that the performance of our RWU derivation algorithm is comparably poor in the top layer, which might be exactly due to direct evaporation from the soil.

From a more technical point of view, we had the advantage of very little noise in the measured soil moisture data with precise detection of changes in the range of 0.1 permille volumetric water content. The performance of the approach is likely to decrease quickly, when the step functions are more difficult to analyse in more noisy data in different settings and with different sensors. Moreover, we had the advantage of the (vertical) coverage of the whole rhizosphere with the used tube probes. Using more common, buriable probes at specific sample locations might have more difficulties to cover the vertical distribution of RWU (Fig. 7, red bars).

The analyses of the temporal dynamics and the differences between the two sites (Fig. 9) hint at conceptual limits of our approach and experimental design: Under somewhat ideal conditions with soil moisture sensors and roots in good contact with a rather homogeneous soil matrix and sufficient soil water availability, the diurnal steps are identified and evaluated with great confidence. In the regosol with high gravel content at the slate site, the approach is challenged when roots may source water from local pools, at contact interfaces with rocks, or in the periglacial cover beds. ~~The high sap velocity despite higher matric tension in the soil might be actually supplied from regions outside the monitored soil moisture profile.~~ Although the depth resolution is very insightful, the likely non-homogeneous rhizosphere ~~might~~ will not be fully represented by a single soil moisture profile and neglecting lateral differences. Effects such as highly active fine roots at the newly growing root tips might be overlooked. Additionally, we greatly simplified the complex form and function of the tree root architecture (Pregitzer, 2008) in the assumption of a cylindrical, evenly utilised rhizosphere. ~~However, we~~

We can answer our first research question with the affirmation that our automated approach of deriving RWU from soil moisture declines generally works, but we have also outlined its limitations. We hope to have contributed an utilisable implementation of RWU detection for further applications (Jackisch, 2019), extending the works of Feddes and van Dam (2005); Guderle and Hildebrandt (2015).

5.2 Correlation of RWU and SF

Scaling the sap velocities to sap flow includes many assumptions and uncertainties (Wullschleger and King, 2000; Gebauer et al., 2008). Our estimates for daily SF of the two trees range around $65\,\mathrm{L\,d^{-1}}$ at the sand site (24–99 $\mathrm{L\,d^{-1}}$ as 0.1 and 0.9 percentiles) and around $50\,\mathrm{L\,d^{-1}}$ at the slate site (7–103 $\mathrm{L\,d^{-1}}$ as 0.1 and 0.9 percentiles, days with SF $\leq 0.1\,\mathrm{L\,d^{-1}}$ were omitted). These values are within the range of results from other studies on beech trees, such as the $60\,\mathrm{L\,d^{-1}}$ (3–238 $\mathrm{L\,d^{-1}}$ as 0.1 and 0.9 percentiles) reported from 39 trees in the same area in Luxembourg (Hassler et al., 2018), the 36–370 $\mathrm{L\,d^{-1}}$ reported in a study in Slovakia (Střelcová et al., 2002) and 32–54 $\mathrm{L\,d^{-1}}$ for a study in central Germany (Kocher et al., 2013). Of course these numbers vary with respect to DBH of the trees, measurement and scaling method and the monitoring time of year, but the range of SF we calculated for our trees seems plausible.

For the quantitative comparison, we greatly simplified the rooting system by using a cylindrical shape whereas a decrease in rooting density with depth might be more appropriate (Leuschner et al., 2001; Volkmann et al., 2016). This does not necessarily entail proportional RWU as trees can adapt the uptake and transport velocity, for example to use water from moist layers even when there are less roots than in drier layers (Dubbert and Werner, 2019). However, we refrain from assumptions about the detailed processes and adaptations of the root systems and use the rhizosphere scaling as an approach to roughly estimate the corresponding water flux from RWU. As the lateral dimensions of our assumed rooting zone of 4.5 m and 5.6 m seem reasonable for beech trees (Kutschera and Lichtenegger, 2002; Lang et al., 2010; Kodrík and Kodrík, 2019), we consider this a feasible approach for our purpose.

Advancing means to monitor ~~soil-water-plant dynamics~~ dynamic processes in the soil-plant-atmosphere continuum is one of the overarching aims of this study. ~~Given the generally acceptable degree of correlation between~~ Although soil moisture-derived RWU and ~~sap flow~~ SF generally correlate quite well (Fig. 8), ~~one might be tempted to consider both measurements interchangeable~~ they are not interchangeable measures for estimating transpiration. The analysis of the temporal development of their correlation (Fig. 9) ~~contradicts~~ supports this notion. We thus argue that observing the plant system at different gauges (RWU, SF, stem storage, leaf-level transpiration) provides the chance to actually analyse the underlying processes. This might help to answer the questions: Why is there a shift of the regression between RWU and SF over time? What is the ~~optimisation function~~ "optimisation function" of the plant's RWU sourcing (e.g. Gao et al., 2014) and SF variability (Saveyn et al., 2008)?

Moreover, not only the presented RWU derivation has uncertainty. Measuring ~~sap flow~~ SF is influenced by a response of the plant to ~~wounding by~~ the sensor installation, and by non-homogeneous xylem ~~depths~~ shapes and associated differences in water transport around the stem (e.g. Bieker and Rust, 2010). The regression analysis (Fig.8) shows the seasonal changes in the observed flux rates. In order to further study effects of seasonal storage, different sourcing, adaptation to environmental conditions and methodological concerns, the correlation between RWU inferred from soil moisture dynamics and SF appears to be an interesting means~~for further studies of plant dynamics in adaptation to environmental conditions. Since~~. However, our working-hypothesis of ~~an instantaneously~~ a closed water balance between RWU and SF ~~could not be corroborated, further~~ remains subject to further research. The observed scatter and seasonal changes in Fig. 8 hint to such effects. Further studies could benefit from measuring RWU and SF complementarily in order to gain more knowledge on the various influences and temporal dynamics of this correlation.

With regard to our second research question we do not see a consistent relation between RWU and SF. This might be partly attributed to the algorithm performance, but also indicates that RWU and SF are not interchangeable but complementary measures.

5.3 Effects of the sites and controls for RWU

Despite ~~very similar sap flow signals , the~~ good general agreement of the SF and RWU both signals show substantial differences over the season and between the sites (Fig. 6). We have shown that the two sites have quite different RWU patterns ~~(Fig. 10).~~ of sourcing and temporal dynamics. It is interesting to note that the main differences in RWU occur during the leaf-out phase until end of June. SF at the two sites is highly similar throughout the year. Thus, very different subsurface water states and sources result in similar fluxes in the trees. ~~It is not a new hypothesis that trees optimise their~~

Our study does not allow for a conclusion about adaptation and regulation of the tree water supply in the process of photosynthesis~~(?).~~. We cannot exclude that some of the apparent differences are due to the limited capabilities of the method. Instead we intend to contribute an easily applicable method for further studies of the interplay between RWU, SF and transpiration (Schymanski et al., 2009; Lu et al., 2020). The presented measurements may be a means to complement analyses of the links between subsurface and stand organisation (Metzger et al., 2017) and transpiration of trees (Renner et al., 2016).

~~However, the third hypothesis that the tension gradient controls RWU , cannot be clearly answered in this experiment and demands further research. Generally,~~ With respect to the dynamic sourcing of RWU one might be tempted to relate the observed soil moisture, SF and the calculated RWU to matric potential inferred from the same data through a soil water retention function. We have done so based on measured soil characteristics and fitted van Genuchten parameters, but found physically inconclusive results (see Appendix C). The difficulties of this approach sets us back to the ~~idea that the tree would minimise its cost for water (by sourcing large sap flows through RWU from layers with low matric potential) does not appear to be the full story (this would mean large light coloured dots at low matric potential and high RWU in Fig. C1). At the sandy site, only low RWU rates could be identified in the wet but deep layers. The correlation of matric potential with depth is apparent. However, all depth layers and soil water states almost equally contributed to RWU. At the slate site, there appears a peak in RWU from intermediate depth (around 0.7 m) and low matric potential. Despite the deeper layers clustering at higher~~

~~tensions, lower RWU rates and higher SF, the sourcing of RWU is not easily reducible to a first-order relationship. High SF and moderate RWU against matric potentials higher than the wilting point might be explained with sources not captured by the soil moisture measurements (deeper pools or local stores)~~general concept of soil moisture, retention properties and capillary flow (Or et al., 2015; Lu, 2020). Namely, the measured soil moisture appears to underestimate the water content in the pore space near the roots. This leads to erroneous values of the matric potential. We have seen similar conceptual shortcomings in a soil water sensor comparison (Jackisch et al., 2020).

Given this finding, the conceptualisation of plant-soil-water relations as capillary concept (e.g. Janott et al., 2010) might have essential limits with respect to ~~analyses under changing conditions. With respect to~~ state observability in the rhizosphere. Regarding multiple functions and specialisations of different roots in the root system (Kerk and Sussex, 2001), the controls of RWU and resulting transpiration require more specific approaches with higher spatiotemporal resolution. This is also the case for hydraulic redistribution in the rhizosphere (Neumann and Cardon, 2012) ~~, which we neglected as minor effect~~ including modifications due to root exudates (Carminati et al., 2016). At the other end of the spectrum stem flow (Liang et al., 2011) and its root-induced preferential flow extension (Johnson and Lehmann, 2016) can become essential but have been neglected in this study.

Acknowledging the limited specificity of our soil moisture-based approach, we see differences in RWU sourcing, correlation of the fluxes and their temporal dynamics, affirming the assumption of a geological and pedological influence on RWU, which we formulated in our third research question. Including contrasting site conditions in further detailed and integrated studies of ET in forests will help to untangle some of the issues of the RWU contribution.

5.4 Outlook

As we have shown for moderately moist conditions, an estimate of RWU from soil moisture dynamics appears reasonably robust. Applications of RWU studies based on changes in soil moisture might benefit from laterally distributed or spatially continuous monitoring. Adding this to SF measurements gauging different roots (Lott et al., 1996) and analyses of stable isotope concentration in the xylem water (Rothfuss and Javaux, 2017) could avoid overly simplistic assumptions about soil water availability and mixing. Analyses with higher temporal resolution could also elucidate further details about diurnal variations in xylem water isotopic signatures (De Deurwaerder et al., 2019). Moreover, higher spatial coverage and resolution using hydrogeophysical, quantitative measurements like time-lapse ground penetrating radar (Allroggen et al., 2017; Jackisch et al., 2017) would enable further analyses of the active rhizosphere and its geometry. ~~With quantitative data about root zone soil moisture dynamics, cosmic ray measurements could be a means to cover larger spatial scales (?).~~ Eventually, a more realistic implementation of all compartments controlling transpiration into land surface models (e.g. Kennedy et al., 2019) could support analyses of stressors and adaptability under shifting environmental conditions.

6 Conclusions

Inferring ~~RWU~~ root water uptake (RWU) from changes in soil moisture during days without percolation is promising. ~~An~~ We presented an automated evaluation of respective time series of soil water ~~state dynamics over a profile~~ profile dynamics within the rhizosphere~~can be conveniently applied~~. However, the approach is not universally suitable. The more complex the pedological setting, the more uncertain the estimate becomes. High precision and low noise in soil moisture measurements are a prerequisite for the method, especially when using an automated detection of the diurnal soil moisture decline. Furthermore, monitoring the whole rhizosphere profile instead of preselected depths proved important because the sourcing of the transpiration signal changes over the year.

Our study shows that RWU and sap flow (SF) cannot be used interchangeably as estimates for transpiration. In fact they give complementary information to understand the whole process from the soil water sourcing, transport through the tree towards eventual transpiration to the atmosphere. At our sites, we observed very different patterns in RWU despite similar ~~sap flow~~ SF and almost identical atmospheric forcing. ~~However, contrary to the theoretical assumption for many transpiration models, soil matric potential appears not to be the only control.~~

Transpiration in forests is influenced by both, site conditions and plant characteristics ~~and~~ including their site adaptations. Therefore an experimental design of field studies complementarily measuring the different aspects of transpiration ~~complementarily~~ is promising (e.g. RWU from different profiles within the rhizosphere, ~~sap flow~~SF, stem storage and leaf-level transpiration) to gain a holistic understanding of ~~transpiration.~~ (evapo)transpiration.

Code and data availability. The RWU and sap flow calculation toolbox is published as Python package on GitHub (Jackisch, 2019). The data is available via GFZ Data Services (Jackisch and Hassler, 2019).

Appendix A: Slate site sap flow reference

At the slate site, the sap velocity measurement in the intended tree for reference failed three weeks after leaf-out (T3, DBH of $41\,\mathrm{cm}$). Hence we needed to refer to another beech tree at the site (T1, DBH of $48\,\mathrm{cm}$). The correlation of sap flow of all three monitored beech trees at the site (Figure A1) shows convincing overall signal similarity (r_s>0.8) but stronger deviation in absolute sap flow values (low KGE). ~~Please note that~~ The strongest deviation occurred in the three weeks after leaf-out. This time period also showed the strongest deviation ~~between the sap flow of~~ of sap flow values between the two sites (Figure 10~~1 & 2). We selected the~~), due to differences in timing of leaf-out. We selected tree no. 1 (T1) to replace the intended tree no. 3 (T3) as reference based on the best correlation measures.

Appendix B: ~~Soil retention parameters~~Uncertainty of RWU calculation

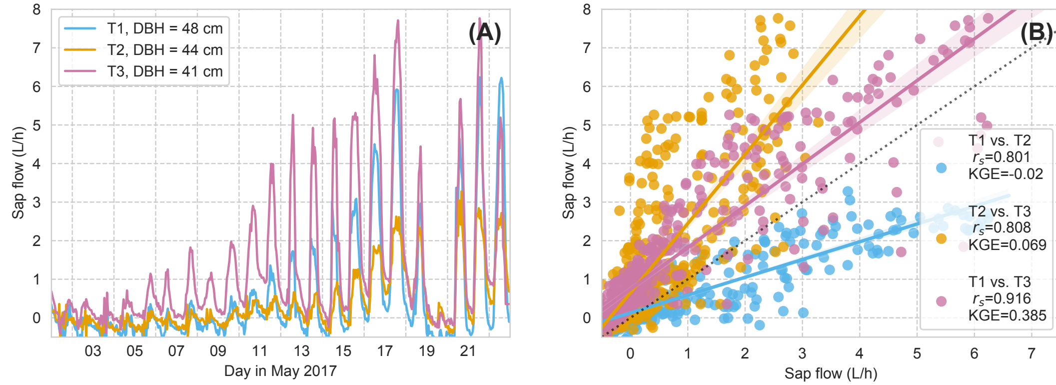

Figure A1. Hourly SF of all three beech trees at the slate site. (A) Time series, (B) Correlation and KGE between time series. T3 is the tree at the soil moisture profile. T1 is the tree used as reference in the study.

~~In the following a table of the site soil properties as~~ We report further details about the identified RWU and the respective NSE of the step-shape (Figure B1). The almost uniform distribution of NSE values across all RWU values at the sand site indicates that there is no detection threshold for RWU. At the slate site, the distribution is skewed towards smaller RWU values. The covered range of values is the same no indication for a detection threshold, too. At the slate site, a larger number of days have a NSE below zero, which might be false-positive results but which might also be another manifestation of the site characteristics discussed in the main part of the manuscript.

Appendix C: Soil water retention and RWU sourcing

Soil water retention properties of the soils at both sites were assessed in a previous study using the free evaporation method of the HYPROP apparatus and the chilled mirror method in the WP4C (both Meter AG) with 250 ml undisturbed soil samples from the sites (Jackisch, 2015). Following this method, the matric potential is divided into bins (0.05 pF). All retention data of the reference soil samples is bin-wise averaged to form the basis for the fitting of a retention curve (Figure C1, parameters in table C1). We have aggregated the results of 44 and 41 soil samples in the subbasins of the sand and slate site for a more robust representation (as discussed by Loritz et al., 2017). The resulting van Genuchten parameters is given ~~(Table C1).~~ in Table C1 and Fig. C1.

Appendix D: ~~Uncertainty of RWU calculation~~

~~We report further details about the identified RWU and the respective NSE of the step-shape (Figure B1). With low correlation at all values for RWU , there is no indication for a detection threshold~~When applying the identified soil water retention curve to the observed soil moisture state values, we can relate the calculated RWU to matric potential in the respective depth layer. This

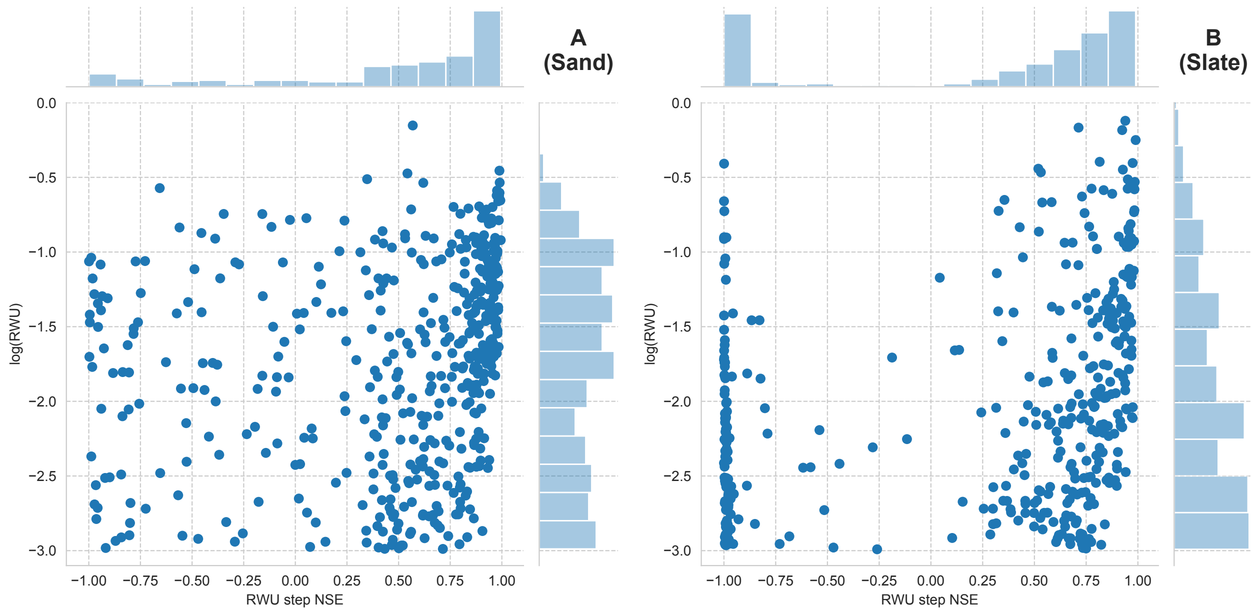

Figure B1. Identified RWU (log10 of RWU in mm/day on y-axes) and corresponding step coherence as NSE to synthetic step (x-axes) for the sand site (A) and slate site (B). Marginals give respective histograms.

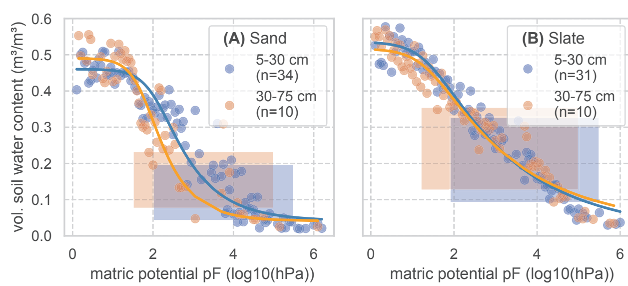

Figure C1. ~~Hourly sap flow of all three beech trees~~ Soil water retention curves for two soil layers at ~~the slate site~~ both experimental sites. ~~(1) Time series~~ To derive the retention curves, ~~(2) Correlation between time series. T3 is~~ the ~~tree at the~~ matric potential is divided into bins of 0.05 pF. Measured soil moisture ~~profile~~ values of all samples and at tensions that fall into each bin are averaged and displayed as dots. ~~T1~~ The retention curve is fitted to these points. The resulting van Genuchten parameters are given in table C1. The number of soil samples that form the ~~tree used~~ basis for the retention curves is given as ~~reference in~~ n. The shaded areas mark the range of soil moisture values we observed with the TDR probes in this study.

	Sand (5-30 cm)	Sand (30-70 cm)	Slate (5-30 cm)	Slate (30-70 cm)
θ_{sat}	0.46	0.49	0.535	0.517
θ_{res}	0.041	0.041	0.011	0.028
α	0.84	1.71	4.13	4.39
n	1.47	1.64	1.21	1.21
m	0.32	0.39	0.17	0.17
k_{sat}	7.4e-5	6.5e-5	1.92e-4	4.13e-4

Table C1. Table of measured soil water retention curve parameters. θ in $\mathrm{m^3\,m^{-3}}$, α in $\mathrm{m^{-1}}$, k_{sat} in $\mathrm{m\,s^{-1}}$

alternative view of the data is given in Fig. C1. Although no clear correlation of RWU and matric potential can be seen, the depth-related colour coding corroborates the strong differences between the sites. In general, there is more tolerance of RWU to higher matric potential at the sand site. At the slate site ~~, a larger number of days have a NSE below zero, which might be false-positive results but which might also be another manifestation of the site characteristics discussed earlier.~~ we recover the peak in RWU from intermediate depth (around $0.7\,\mathrm{m}$), which coincides with low matric potential.

However given high RWU rates at apparently higher tensions than the wilting point (PWP), we cannot trust this relation. Most likely this result corroborates the limits of the concept of soil moisture dynamics in structured soils. The soil water in the layer is not evenly distributed and we underestimate the soil water content in the pore space which is tapped by the roots.

Author contributions. .

CJ and SH developed the study layout, performed the field work, prepared the data and composed the manuscript. SK did the first analyses on this data for his BSc thesis. CJ developed the detection algorithm, compiled most of the data analysis and plots with frequent discussion with SH. TB did preliminary RWU analyses based on soil moisture dynamics within the CAOS research unit. The resulting discussions between TB, EZ, SH and CJ initially triggered the study. EZ and TB supportively accompanied the study and contributed during the manuscript preparation.

Competing interests. The authors declare no competing interests.

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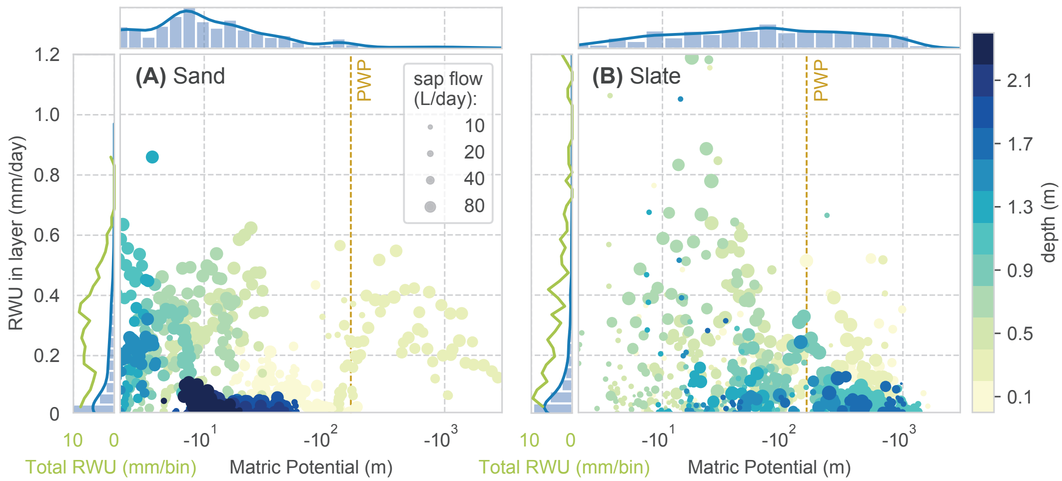

Figure C1. ~~Identified RWU (log10~~ Sourcing of RWU: Daily values of matric potential in ~~mm/~~each soil layer and RWU. Colour coding with respective depth. Dot size marks the reference SF of the day~~on y-axes)~~. The marginal histograms and ~~corresponding step coherence as NSE~~ kernel density distributions on top refer to the occurrence of ~~synthetic step (x-axes) for~~ the ~~sandy site~~ respective matric potential bin in the observed period. The marginals on the left give the distribution of RWU (~~A~~blue) and ~~slate site~~ the total RWU of a certain bin (~~B~~green). ~~Marginals give respective histograms~~PWP marks a matric potential at the wilting point with pF 4.2.

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