Comment from the associate editor, Michael Bahn

Dear authors,

both reviewers think that your manuscript has gained substantially and recommend its acceptance after another round of revisions. While reviewer #2 made a number of useful editorial suggestions, reviewer #3 thinks that section 5 and your conclusions require further focus. I agree with the reviewer that some streamlining should be useful here, but personally do not mind you keeping some key ideas conveyed in the sections 5.1-5.3 in a strongly condensed form.

Section 5.1 and 5.2 are now merged together and were significantly condensed. Section 5.3 was entirely removed from the manuscript.

In an effort to streamline the paper even more, a novel figure (now Fig. 3) was added to illustrate the main findings of the literature review, thereby giving more weight to Section 3.

Accordingly, I would be ok if you were to remove just the first point (i) of the last sentence in your conclusion.

We now only refer to new part 5.2 ("Call for a coupled experiments-modelling approach for determination of plant water sources on the basis of isotopic data") in the introduction (now P1 L19-20). Done

Reviewer #3 also had some problems concerning your use of the model by Couvreur et al. 2012. Note that some further clarification to this end will make your paper also more accessible to its readers at large.

We hope that the use of the model of Couvreur et al. (2012) is now clearer to the associate editor and reviewer #3.

Comment from Anonymous referee #2,

General comments:

The authors did a great job in editing the manuscript. The structure of the paper is much better now and easier to follow. However, the authors should check the tenses they use and be more concise. After considering my following suggestions, I would consider the manuscript ready for publication.

Dear referee, we *greatly* appreciate the tremendous effort in detecting the remaining typos in the document! The authors.

Specific comments:

p. 1 l. 20ff: This sentence is rather confusing. Consider editing the sentence structure.

p. 2 l. 8: "…hormonal stress signals…"

Done

l. 17ff: "…the root's ability to extract water…"; "…to fulfill the plant's water demand…"; "…between soil and roots."

Done

l. 21: "…, and exudation."

Done

p. 6 l. 4 ff: add the study by Martín-Gómez (2016) about evaporative enrichment of xylem water in woody stems to this paragraph

This (very nice) study does not study fractionation *during* RWU, only *after* RWU has taken place.

l. 15: "…fall on an "evaporative line…"; consider defining "evaporative line"

Done

l. 17: Chose a more descriptive rather than a too general section title here.

We would like to keep the title "LITERATURE REVIEW" as it echoes the manuscript first part of the title, i.e., "Isotopic approaches to quantify root water uptake: a *review* and comparison of methods". Similarly, the title of part 4 "INTER-COMPARISON OF METHODS" refers to the second part of the title.

p. 7 l. 10: "In a third class (…)**,** …"

Done

l. 14: "…in section 3.2 of this paper."

Done

l. 18: wording

Done

l. 31: "…in section 4 of this paper."

Done

l. 32: wording

Done

p. 8 l. 13: "In the example presented in Fig. 2b…"

Done

l. 19: "…when RLD is constant over depth…"

Done

l. 20: "The graphical inference method may not…"

Done

p. 9 l. 2: Two end-member mixing models

We would like to keep the acronym in the title as we think it will be convenient for the readers, right?

l. 23-24: sentence structure: "…or by taking additional errors…and vacuum distillation into account."

Done

l. 26: "…should have greatest possible isotopic dissimilarities with a low standard error of x."

Done. Thanks!

p. 10 l. 13: "Figure 3 also illustrates…"

Done

l. 19: between 0.3 and 0.4 meter depths

Done. Thanks

l. 21: "…in dual isotope space."

Done

l. 20 ff: Several studies observed differences in terms of uptake depth when considering either the one or the other isotope. This is worth mentioning.

Yes, but, to our knowledge (see supplementary materials), differences where observed when considering either δ^2H or δ^{18}O measurements by authors who used other methods (i.e., not the two end-member mixing model). This is mentioned early in the text (Section 3 introduction, now P7 L30-33):

> **"In the remaining studies, both isotopic compositions were measured and used to provide two separate estimates of relative contribution distributions even though δ^2H or δ^{18}O distributions were strongly linked (see section 2). This last approach is in the present study referred as "double single" (see supplementary materials)."**

p. 11 l. 4: "…not likely or possibly…"

Done

l.7: "…depends on the value of the contributing increment…"

Done

l. 20: delete "by"…IsoSource

Done

l. 23: "…and to (ii) provide a

Done

l. 24: "For this study**,** they used…"

Done

p. 12 l. 22: "The reader is referred to…"; "…to Appendix B2 on how it was implemented for our intercomparison."

Done

p. 13 l. 3: "They"; who is "they"?

Done ("All eight scenarios relied on …", now P13 L22)

l. 4: Why was this plant chosen explicitly?

This plant was chosen because we had access to information on K_{plant} of use for modeling purposes.

l. 19: "…were fixed to 10 and 0.25%,…"; also no space character between numbers and %; applies to the whole manuscript

Done

l. 22: "Finally**,**…"

Done

l. 24: "…methodology, the reader is referred to…"

Done

l. 26: “simulated” -> repetition

Thanks ! Done

l. 27: Couvreur et al. (2012)

Done

p. 14 l. 2-3: “…term of Eq. (1) was proportionally larger (i.e., Scomp….).”; sentence structure

Done. Sentence was split in two (now P14 L22-25).

l. 6: “were” instead of “ could be”

Done

l. 8: “uppermost” layer (0–0.225m)

Done

l. 21 ff: Wording/punctuation

Done

p. 15 l. 10: “…via the analytical model”

We would prefer to keep the conjunction “by”

l. 12: punctuation

Done. Sentence was rearranged.

l. 13: “However**,**…”; this applies to the whole manuscript

Done

l. 29: “…should therefore be…”

Done

p. 16 l. 1-2: “…for theoretically improving the different methods outputs…”

The theoretical basis underlying the different methods is not impacted by the quality of the data, only their precision.

l. 3: “However**,** this was never the case when considering results of…”

Done

l. 3 ff: wording; edit this sentence

Done

l. 8-9: “…with an auger from few centimeters down to meters, ...”

Done

l. 13: You want to increase sampling intervals close to the soil surface: “minimal” is confusing here. Rewrite this and the previous sentence.

Done. “interval” was replaced with “resolution”, therefore “minimal” is now “maximal”, and vice versa. (now P17 L5-8)

l. 17 ff: "…factor, thus**,** can be sampled multiple times to overcome or characterize…"

Done

l. 22 ff: Confusing sentence structure. Chose a different word for "organ", maybe green plant parts

Done

l. 24-25: What do you mean by "non-conducting" water-bearing?

Sentence was erased from the text for streamlining. (see our answer to referee #3)

p. 17 l. 9: Why do you mention the azeotropic distillation method here? There are multiple other methods available. Which method was commonly used in your reviewed literature?

Sentence was erased from the text for streamlining. (see our answer to referee #3)

l. 20: add "in-situ" and "high-frequency"

Done

l. 31: "…is not limited for isotope analysis."

Done

l. 33: spectroscopes

We would like to stick to "spectrometers" here.

p. 18 l. 1: "greatly sensitive"-> wording

We use now "significantly sensitive". Done

l. 2: "…which was addressed by Pratt et al. (2016) and Orlowski et al. (2016b)." The study by Pratt et al. (2016) only applies to vapor measurements.

Done

l. 6-7: "This should be further tested for other…"

Done

l. 8 ff: Mention the study by Martín-Gómez (2016) here.

The authors could not find this particular study.

l. 20: deep-rooting

We would like to stick to "deep-rooted" here.

p. 19 l. 14: "For example, Rothfuss et al. (2012) ran an…"

Done

l. 17: "…of the transpired water was…"

Done

l. 19 ff: The authors are using "also" way too often. This applies to the entire manuscript.

Done. "also" is now written 13 times (instead of 25 initially).

p. 20 l. 6: "…and, thus,…"

Done

l. 8: "…as they allow for a reduction of…"

Done

l. 11 ff: The authors should not forget about the time and costs of such experiments.

We do not. Done

p. 21 l. 5: "…is a powerful…"

Done and thanks!!

l. 9 "In this review**,**…"

Done

l. 10 ff: The authors should include a few sentences about the methodology before they jump into the description of the results.

Done

l. 14: How was the performance? good/bad/great?; Parnell et al. (2010)

Done

l. 18: "…call for (i) further developments…"

Done

l. 19: replace "organs" by another word

Done

Comment from Anonymous referee #3,

The manuscript has improved tremendously. Well done.

Thanks!

There are basically two items, which I would ask to consider:

1.I would delete sections 5.1-5.3. They are not adding to the manuscript. This would also delete the last paragraph of the conclusions and the last sentence of the abstract.

Section 5.1 and 5.2 are now merged together and were significantly condensed. Section 5.3 was entirely removed from the manuscript. We now only refer to new part 5.2 ("Call for a coupled experiments-modelling approach for determination of plant water sources on the basis of isotopic data") in the introduction.

The last sentence of the abstract was replaced with (now P1 L19-20):

"Finally, the authors call for a development of approaches coupling physically based RWU models with controlled conditions experimental setups."

If experimental precision were an issue than it should be treated in the results section with a virtual experiment, just as the two disjoint soil layers. Otherwise this is just the usual muttering that we need higher resolution observations.

This is why the authors not only mention this problem but emphasize the need to take into account the measurement uncertainty (through the different standard errors coefficients present in Eqs. 8) when using the two-end members mixing model. This is rarely the case from the literature review.

Section 5.4, however, is interesting and not enough elaborated. If a model were inverted, one needs to identify quite a few extra variables such as hydraulic conductivities, etc. The information content in the data is probably not enough to infer all required information.

This is true. Note that the authors mention this problem in the text already (now P19 L9-10):

"We recognize that in comparison with the statistical and conceptual methodologies presented in this review, using a physical (analytical or numerical) model implies the measurements of additional state variables to be fed as input to the model, and of one parameter (Kplant) (when considering the assumption Kplant = Kcomp valid, see Appendix B). Some of these variables are laborious to obtain (e.g., RLD) or not straightforward to measure (HS, HL, and T) – especially in the field – but are mandatory to be able to determine contributions to T across a set of identified water sources."

So the method, which quite a few people would find best, might not be superior to the Bayesian approaches presented here. It is unclear to what extent this plays into the presented methods. For example, the preferred Bayesian inversions depend on strongly on the priors and hence to some assumed soil properties. Did the authors try different priors, e.g. flat priors, Jef freys prior, etc.?

We also argue in the text that the Bayesian method is very efficient in determining relative RWU profiles, while it needs less input data than the, e.g., approach of Couvreur et al. (2012).

Regarding prior information, the authors now mention this in text (now P16 L25-28):

> **"Note that no prior information on the relative contribution to *T* from the different soil layers was used when running the SIAR program, i.e., the authors opted for flat priors. This can be changed by the user, based on additional collected data such as, for instance, information of root architecture and function across the soil profile or information on soil hydraulic properties and water status."**

2. I still do not understand the use of Couvreur et al. (2012). These are virtual experiments so running a full isotope-enabled soil model gives all the information for the virtual experiments.

Paragraph 4.1.1 ("Scenario definition") was substantially rewritten for clarifying the point (P13 L10-27):

> **"We developed eight virtual plausible scenarios of soil-plant systems under different environmental conditions. For each scenario, we set one total soil water potential (H_S) profile and one soil water oxygen isotopic composition (δ_S) profile. These profiles resulted from the combination of a lower boundary condition, i.e., the depth of the groundwater table, and an upper boundary condition, i.e., the soil surface water status. The groundwater table (of water isotopic composition equal to -7‰) was either shallow at -1.25 m depth (prefix "Sh") or deep at -6 m depth (prefix "De"). The soil water potential was considered to be at static equilibrium below the groundwater level. The soil surface was either dry under evaporative conditions (suffix "Dr"), or wet, e.g., shortly after a rain event (suffix "We"). For instance for the scenario "ShDr", we set the δS profile to be maximal at the surface, due to evaporation, and minimal from –0.5 m downward, due to the shallow groundwater table location. For the scenario "DeWe", on the other hand, the increase of δ_S towards the surface was not monotonic due to a recent precipitation event (of water isotopic composition equal to -7‰). Finally, we tested two different values of plant transpiration rate (T) and leaf water potential (H_L) with each of these four combinations (i.e., ShDr, ShWe, DeDr, and DeWe). The transpiration rate was either low (e.g., relevant at night, *T* = 0.01 mm h-1, suffix "_lT") or high (T = 0.30 mm h-1, suffix "_hT"). All eight scenarios relied on a common measured root length density vertical distribution of**

Festuca arundinacea. Table 2 reports the input data. Note that, as hypothetized in Eq. (4b), transpiration and sap flow rates (i.e., per unit of surface area [L T-1]) were considered as equal.

The objective was not to use an advanced numerical model such as, e.g., SiSPAT-Isotope or Soil-litter-iso, to produce these scenarios, but rather use synthetic information based on (i) experimental data and (ii) expert-knowledge which would ideally illustrate the performances or limitations of the different methods."

Plus, the idea was to encourage the readers to use much simpler, however still complex RWU models, such as this of Couvreur et al. (2012).

Here, I have to believe that Couvreur et al. (2012) gives the right answer. Is this so?

The model of Couvreur et al. (2012) gives a physically-sound answer. We assume that it gives the right answer, indeed.

The following clarification was added to the text (Introduction of section 4, now P12-13 L29-4):

"It has been proved (Couvreur et al., 2012) that this model gives similar results than a 3D physically based model with detailed descriptions of the root architecture and of the water flow in soil and roots. In that sense, this is the best current model existing nowadays to simulate water fluxes in a soil-plant system (based on biophysical considerations). Other current models make assumptions or use empirical relations to predict RWU, which are not based on bio-physical considerations only (Jarvis, 2011; Simunek and Hopmans, 2009). Obviously, we do not mean that the model of Couvreur et al. (2012) gives the reality but rather the best estimate of the water flow based on our physical knowledge."

Or I do not understand the method. It is NOT well described: "Mean RWU depths (provided by the GI method) and xj distribution (provided by the two end-member and multi-source mixing models) were determined from soil and xylem water oxygen isotopic composition distributions. While the former information was prescribed to the different methods, the latter was
calculated with the physically based analytical RWU model (referred to as "Couv") of Couvreur et al. (2012)."

How is GI entering in this? Where are the "soil and xylem water oxygen isotopic composition distributions" coming from? What is "the former" and what "the latter"? What are you referring to?

This sentence was reformulated (indeed, this was clear enough!) as such (now P12 L25-28):

"Mean RWU depths (provided by the GI method) and xj distribution (provided by the two end-member and multi-source mixing models) were determined from the δ_S profile and the δ_{Ti} value. For

each virtual experiment the δ_S profile was prescribed to the different methods while δ_{Ti} was calculated with the physically based analytical RWU model (referred to as "Couv") of Couvreur et al. (2012).".

We hope it is now clearer.

How I understood virtual experiments: you run the most advanced physical model and add some noise on the output. Then you use this noisy output to infer properties, states or fluxes, which were calculated in the physical model. It seems to be different here.

This is not what we have been doing because the objective was not to find the best method but rather to compare outputs of methods. Therefore we did not need to have a "real" or "simulated" case with the "most advanced physical model". Please see for this our answer above. Doing the virtual experiment you propose is a good objective for a next study, when a novel 3D physical model for root water uptake, soil water flow and stable water isotope fate will exist (what you call "most advanced physical model").

Minor comments:

a) page 1, lines 17-20: I cannot understand the sentence. Please reformulate.

The sentence now reads (now P1 L16-17):

"The benchmarking of these methods illustrates the limitations of the graphical and statistical methods while it underlines the performance of one Bayesian mixing model."

b) page 4, 20-23: theory says something different and Rothfuss et al. (2015) only proposed that it might be the point of the steepest gradient. Please reformulate.

Text now reads (P4 L20-23):

"Finally, note that Rothfuss et al. (2015) argued that, at transient state ($\delta_E \neq \delta_{source}$), the maximal isotopic enrichment in the soil profile might not point to the location of the evaporation front. Instead, they proposed that the depth where the steepest gradient in the isotopic profile is observed corresponds to the evaporation front."

Done

c) page 9, 8: i should be superscript and A, B subscript.

Thanks! Done

d) page 14, 31: you call Figure 6 still Figure 5 from this point on.

Thanks! Done

e) page 15, 32: 8 layers were not shown but only mentioned. If you claim that it might be a good way forward then it might warrant a figure or including it in Fig. 6.

The results of the Bayesian and analytical modelling methods are shown for eight soil layers in Table 3. Nevertheless, it is true that the methods of Phillips and Gregg (2003) and this of Parnell et al. (2013) are not compared in the text for eight soil layers. The text was therefore modified accordingly (now P16 L22-25):

> **"As highlighted in this series of virtual experiments, the Bayesian method showed for the case of two and three soil layers much more convincing results than the method of Phillips and Gregg (2003). The Bayesian method was particularly efficient in the case of eight soil layers, illustrating the interest of reaching the best vertical resolution and maximizing the number of identified potential sources (Table 3)."**

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Isotopic approaches to quantify root water uptake: a review and comparison of methods

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Abstract. Plant root water uptake (RWU) has been documented for the past five decades from water stable isotopic analysis. By comparing the (hydrogen or oxygen) stable isotopic composition of plant xylem water to those of potential contributive water sources (e.g., water from different soil layers, groundwater, water from recent precipitation or from a nearby stream) studies could determine the relative contributions of these water sources to RWU.

In this paper, the different methods used for locating / quantifying relative contributions of water sources to RWU (i.e., graphical inference, statistical (e.g., Bayesian) multi-source linear mixing models) are reviewed with emphasis on their respective advantages and drawbacks. The graphical and statistical methods are tested against a physically based analytical RWU model during a series of virtual experiments differing in the depth of the groundwater table, the soil surface water status, and the plant transpiration rate value. The benchmarking of these methods illustrates the limitations of the graphical and statistical methods while it underlines the performance of one Bayesian mixing model. The simplest two end-member mixing model is also successfully tested when all possible sources in the soil can be identified to define the two end-members and compute their isotopic compositions. Finally, the authors call for a development of approaches coupling physically based RWU models with controlled conditions experimental setups.

Keywords

Root water uptake; hydraulic redistribution; hydraulic lift; water stable isotopologues; isotope mixing model; physically based root water uptake model

1 INTRODUCTION

Understanding how the distribution of soil water and root hydraulic architecture impact root water uptake (RWU) location and magnitude is important for better managing plant irrigation, developing new plant genotypes more tolerant to drought or

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Deleted: , but only when the number of considered water sources in the soil is the highest to closely reflect the vertical distribution of the soil water isotopic composition.

Deleted: future challenges in studying RWU with stable isotopic analysis are evocated with focus on new isotopic monitoring methods and sampling strategies, and on the implementation of isotope transport in physically based RWU models.

Deleted: Root water uptake (RWU) is defined as the amount of water abstracted by a root system from soil over a certain period of time.

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tackling ecological questions in water-limited ecosystems, such as the competition for soil water by different plants (Javaux et al., 2013).

RWU - defined as the amount of water abstracted by a root system from soil over a certain period of time - is principally driven by transpiration flux taking place in the leaves. Its magnitude depends on the atmospheric evaporative demand and stomatal opening. The latter depends amongst others on leaf water status and stress hormonal signals from the roots transported to the leaves (e.g., Huber et al., 2015; Tardieu and Davies, 1993). Leaf water status and stress hormonal signals are related to the soil water potential distribution and to the plant hydraulic architecture (Huber et al., 2015). The distribution of RWU is very variable in time and space, depends on the presence of roots and their ability to extract water. This ability is a function of radial conductivity but axial conductance may also limit water flow in younger roots or when cavitation occurs. The flux of water depends also on soil water availability, i.e., the ability of the soil to provide water at the plant imposed rate (Couvreur et al., 2014): a highly conductive root segment will not be able to extract water from a dry soil. Locally, this is the difference of water potential between the root and the soil which drives RWU, and its magnitude is controlled by the radial hydraulic resistances in the rhizosphere, at the soil root interface and in the root system (Steudle and Peterson, 1998). The actual RWU profile is thus a combination of different aspects: the root's ability to extract water (characterized by the amount of roots and their hydraulic properties), the ability of the soil to fulfill the plant water demand, and the water potential difference between soil and root (Couvreur et al., 2014).

Plants have numerous mechanisms to cope with heterogeneous soil water distribution, e.g., adaptive root growth, adaptive root conductivity or exudation (Carminati et al., 2016). A particular process, which has attracted the attention of plant breeders and ecologists is the ability of plants to extract water from non or less water limited soil areas with potentially low root lengths densities (RLD [L L^{-3}], usually expressed in cm root per cm^3 soil), known as root water uptake compensation (Heinen, 2014). To describe the RWU rate in soils, we will use the root water uptake flow per volume of soil, defined as S [L^3 T^{-1} L^{-3}] described as a sink term in the Richards equation. According to Couvreur et al. (2012), root compensation is defined as the process that decreases or increases RWU at a certain location compared to the water uptake from that location when the soil water potential would be uniform in the root zone. Thus, the distribution of the $S(x,y,z)$ is a sum of two spatially distributed components:

$$S(x,y,z) = S_{uniH}(x,y,z) + S_{comp}(x,y,z) \quad (1)$$

where x, y and z are the 3D spatial coordinates, S_{uniH} is a term proportional to the root distribution and S_{comp} the compensatory part of the RWU distribution. The first term on the right-hand side of Eq. (1) is always positive while the second one can be either positive or negative. Figure 1 illustrates how this equation affects S distribution in a one-dimensional (1D) space. When there is no compensation ($S_{comp}(x,y,z) = 0$), the RWU distribution follows the root distribution (i.e., highest at the surface and lowest in the deepest layer, Fig. 1a). When $S_{comp}(x,y,z) < 0$ but its absolute value is lower than $S_{uniH}(x,y,z)$, then $S(x,y,z)$ is positive and different from the root vertical distribution. In case $S_{uniH}(x,y,z)$ is small, as in Fig. 1c, $S_{comp}(x,y,z)$ can locally be higher in absolute value and $S(x,y,z)$ can be locally negative which implies that there is a water

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efflux out of the root (called "Hydraulic redistribution" or "Hydraulic lift" in this particular case, Caldwell and Richards, 1989; Dawson, 1993; Kurz-Besson et al., 2006).

Despite its importance, datasets with measurements of RWU are lacking. This is related to the difficulty of measuring root and soil water fluxes. Often soil water content change is used as a proxy for RWU. Yet, as change of soil water content with time is not due to root extraction only (i.e., soil water redistribution can also occur), the assessment of RWU based on water content distribution alone is not possible in conductive soils (Musters and Bouten, 2000). Rather, the full soil water flow equation accounting for root uptake and soil water redistribution must be solved in an inverse mode, and, with an accurate knowledge of soil and root properties RWU distribution can be inferred (Guderle and Hildebrandt, 2015; Hupet et al., 2002; Musters and Bouten, 1999; Vandoorne et al., 2012). Nuclear magnetic resonance (NMR) imaging has been suggested as an adequate technique to measure water flow velocity in xylem vessels but no application exists yet on living roots in soils (Scheenen et al., 2000). More recently, Zarebanadkouki et al. (2012) could measure for the first time RWU in porous media by combining a tracer experiment (i.e., deuterated water) monitored by neutron tomography with inverse modelling of a transport equation. Yet, this was performed under controlled conditions while there is no standard method to monitor three dimensional water uptake distribution of growing roots *in situ*. In woody plants, in which roots are thick enough, Nadezhdina et al. (2010; 2012; 2015) used sap flow measurements in roots to quantify hydraulic redistribution.

Since the seminal work of Zimmermann et al. (1967) which reported that RWU of *Tradescantia fluminensis* occurred in the absence of fractionation against water oxygen stable isotope, water stable isotopologues ($^{1}H^{2}H^{16}O$ and $^{1}H_{2}^{18}O$) have been frequently used to identify and quantify RWU in soils through the measurements of their natural (and artificial) isotopic abundances. Methods include simple graphical inference to more sophisticated statistical methods, i.e., two-end members and multi-source linear mixing models. While the former attempts to locate the "mean root water uptake" in the soil, the latter category of methods provides profiles of relative contributions to transpiration flux across a number of defined soil layers.

This present paper has three objectives: (i) performing a literature review on the use of water stable isotopes to assess RWU; (ii) presenting the methods for translating the isotopic information into RWU profiles (i.e., graphical inference and statistical multi-source linear mixing models); and (iii) comparing these methods with a series of virtual experiments differing in the water and isotopic statuses in the soil and the plant. Prior to the review and inter-comparison, the paper reports on the mechanisms at the origin of the spatiotemporal dynamics of natural isotopic abundances in soil and on the background knowledge of isotopic transfer of soil water to and from roots. Finally, we evoke opportunities offered by novel isotopic monitoring tools which provide unpreceded high frequency isotopic measurements, and call for a development of approaches making use of physically based models for RWU determination.

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2 FLOW OF ISOTOPOLOGUES IN THE SOIL-PLANT SYSTEM

In a study that laid the basis for future work in isotopic ecohydrology, Zimmermann et al. (1967) provided a steady-state analytical solution for soil water isotopic composition (δ_S, expressed in ‰ relative to the Vienna Standard Median Ocean Water international (VSMOW) isotope reference scale, Gonfiantini, 1978) in a water-saturated isothermal bare sand profile from which water evaporated at a constant rate. Under these steady-state and isothermal conditions, the upward (convective) liquid flux of isotopologues, triggered by evaporation (E) and rising from deeper layers equals the downward (diffusive) isotopic flux from the evaporating surface which is enriched in the heavy stable isotopologues due to evaporation. Furthermore, by conservation of mass, the isotopic composition of evaporation equals that of its source (e.g., groundwater), i.e., $\delta_E = \delta_{source}$. A profile is obtained (Fig. 2a, dark blue line) whose exponential shape depends on boundary conditions, i.e., the source water and surface water isotopic compositions (δ_{source} and δ_{surf}), the diffusion coefficient of the isotopologues in water, and of a soil "tortuosity factor", conceptually defined as the ratio of the geometrical to actual water transport distance. Barnes and Allison (1983) extended this formulation to a non-saturated sand column evaporating at isotopic steady state. In this case, the evaporating surface (i.e., the liquid-vapor interface) can be located below the soil surface and splits the profile into two regions where isotopic transport predominantly occurs either in the vapor phase above or in the liquid phase below it. In the "vapor region", relative humidity generally is still close to unity for sand total water potential below 15 bars. At isotopic steady state, the maximal isotopic enrichment is at the evaporation front (δ_{EF} at soil depth z_{EF}) and can be simulated with the Craig and Gordon (1965) model. The isotopic composition of the soil residual adsorbed water in the "vapor region" above the evaporation front can be obtained by assuming thermodynamic equilibrium conditions and by applying Fick's law, and is shown to decrease linearly towards the value of the liquid water at the soil surface which is at thermodynamic equilibrium with the ambient atmospheric water vapor (Fig. 2a, light blue line). Finally, note that Rothfuss et al. (2015) argued that, at transient state ($\delta_E \neq \delta_{source}$), the maximal isotopic enrichment in the soil profile might not point to the location of the evaporation front. Instead, they proposed that the depth where the steepest gradient in the isotopic profile is observed corresponds to the evaporation front.

In a two-dimensional ($\delta^{18}O$, $\delta^{2}H$) space, liquid soil water sampled below the evaporation front will plot on an "evaporation line" with a slope typically lower than six and greater than two, depending on atmospheric and isotopic forcing, as a result of kinetic processes during evaporation. Above the evaporation front and at isotopic steady-state, soil liquid water is in equilibrium with a mixture of atmospheric water vapor ($\delta^{18}O$-$\delta^{2}H$ slope ~8) and evaporated soil water vapor rising from the evaporation front ($2 < \delta^{18}O$-$\delta^{2}H$ slope < 6) (Sprenger et al., 2016). As a result, an intermediate value for the slope is expected, depending on the mixing ratio of atmospheric water vapor to evaporated soil vapor at a given soil depth. Finally, under natural conditions, the δ_S profile is not solely a result of isotopic fractionation but is as well highly impacted both spatially and temporally by input precipitation isotopic composition through modification of the upper boundary condition (δ_{surf}).

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As opposed to the removal of water vapor by evaporation, RWU has been described in a number of studies and over a wide variety of plant species not to be associated with (kinetic) isotopic fractionation (Bariac et al., 1994; Dawson and Ehleringer, 1993; Thorburn et al., 1993; Walker and Richardson, 1991; Washburn and Smith, 1934; White et al., 1985; Zimmermann et al., 1967). Consequently, for plants growing in homogeneous external conditions, e.g., in hydroponic solution, root xylem sap water and external water have the same isotopic compositions. In natural soils where the liquid phase is not homogeneous and a vertical gradient of isotopic composition due to evaporation exists, the root system takes up water at different depths having thus different isotopic compositions.

Assuming that water transport time in roots is negligible, the isotopic concentration of the xylem sap water at the root tiller (C_{Ti} [M L^{-3}]) can be modeled as the weighted average of the product of the soil water isotopic concentration (C_S [M L^{-3}]) and $S(x,y,z)$:

$$C_{Ti} = \frac{\int_{x,y,z} C_S(x,y,z)\cdot S(x,y,z)\cdot dx\cdot dy\cdot dz}{\int_{x,y,z} S(x,y,z)\cdot dx\cdot dy\cdot dz} = \frac{\int_{x,y,z} C_S(x,y,z)\cdot S(x,y,z)\cdot dx\cdot dy\cdot dz}{J_{Ti}} \quad (2)$$

with J_{Ti} [L^3 T^{-1}] the xylem sap flux at the root tiller. Following Braud et al. (2005):

$$C = \rho\cdot R_{ref}\frac{M_i}{M_w}(\delta+1) \quad (3)$$

with ρ [M L^{-3}] the volumetric mass of water, R_{ref} [-] the Vienna-Standard Mean Ocean Water (V-SMOW) hydrogen or oxygen isotopic ratio, M_w and M_i [M L^{-3}] the molar masses of $^1H_2{}^{16}O$ and isotopologue ($^1H^2H^{16}O$ or $^1H_2{}^{18}O$), respectively, the xylem sap water isotopic composition at the root tiller δ_{Ti} [-, expressed in ‰] can be expressed as:

$$\delta_{Ti} = \frac{\int_{x,y,z} \delta_S(x,y,z)\cdot S(x,y,z).dx\cdot dy\cdot dz}{J_{Ti}} \quad (4a)$$

with $\delta_S(x,y,z)$ [-, expressed in ‰] the isotopic compositions of soil water at coordinates (x,y,z). Mostly, a one dimensional description of RWU is used assuming that δ_S and RWU do not vary in the horizontal direction and δ_S is obtained for discrete soil layers of depths z_j ($j \in [1,n]$) and thickness $\Delta z_j = z_{j+1} - z_j$. It is usually further hypothesized that J_{Ti} equals the transpiration flux T [L^3 T^{-1}] (low to no plant capacitance or phloem-xylem contact):

$$\delta_{Ti} = \frac{\sum_{j=1,n}\delta_S(z_j)\cdot S(z_j)\cdot\Delta z_j}{\sum_{j=1,n} S(z_j)\cdot\Delta z_j} = \frac{\sum_{j=1,n}\delta_S(z_j)\cdot S(z_j)\cdot\Delta z_j}{q_{Ti}} \quad (4b)$$

where $q_{Ti} = J_{Ti}/(\Delta x\cdot\Delta y) = T/(\Delta x\cdot\Delta y)$ represents the sap flow rate in the root tiller per unit surface area [L T^{-1}].

δ_{Ti} can be accessed at different locations in the plant depending on the species, but the sampling location should not be affected by evaporative enrichment in heavier isotopologues or back-diffusion of the isotopic excess accumulated at the sites

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of transpiration (stomatal chambers) in the leaf. For grasses and nonwoody plants, this is done by sampling the root crown (e.g., Leroux et al., 1995), the aerial nodal roots (e.g., Asbjornsen et al., 2007), the meristematic petiole, or else the collars (e.g., tillers) at the base of the plant (e.g., Dawson and Pate, 1996; Sánchez-Perez et al., 2008). In the case of ligneous plants the fully suberized stem (Asbjornsen et al., 2007) or sapwood (e.g., White et al., 1985) is sampled. On the other hand, δ_S is usually measured by sampling soil profiles destructively. Finally, water from plant and soil is predominantly extracted by cryogenic vacuum distillation (Araguás-Araguás et al., 1995; Ingraham and Shadel, 1992; Koeniger et al., 2011; Orlowski et al., 2013; West et al., 2006).

Lin and Sternberg (1992) and Ellsworth and Williams (2007), amongst other authors, reported however that for some xerophyte (plants adapted to arid environments, e.g., *Prosopis velutina* Woot.) and halophytes species (plants adapted to saline environments, e.g., *Conocarpus erecta* L.), and mangrove species (e.g., *Laguncularia racemosa* Gaert.), RWU led to fractionation of water hydrogen isotopologues. For mangrove species, it was hypothesized that the highly developed Casparian strip of the root endodermis would force water moving symplastically (i.e., inside the cells) and therefore crossing cell membranes (Ellsworth and Williams, 2007). Water aggregates are then dissociated into single molecules to move across these membranes. This demands more energy for $^{1}H^{2}H^{16}O$ than for $^{1}H_{2}{}^{16}O$ and $^{1}H_{2}{}^{18}O$, thus preferentially affects $^{1}H^{2}H^{16}O$ tranport and leads to a situation where xylem sap water is depleted in this isotopologue with respect to source water. Meanwhile, this affects to a much lesser extent $^{1}H_{2}{}^{18}O$ transport, so that no detectable isotopic fractionation of water oxygen isotopologues is observed. It can be concluded that, for the majority of the studied plant species, either RWU does not lead to isotopic fractionation or its magnitude is too low to be observable.

Finally, plant water samples will, similarly to soil water samples, fall onto an "evaporation line" of a slope lower than eight in a two-dimensional ($\delta^{18}O$, $\delta^{2}H$) space (Javaux et al., 2016).

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3 LITERATURE REVIEW

By entering the search terms (("root water uptake" or ("water source" and root) or "water uptake") and isotop*) into the ISI Web of Science search engine (webofknowledge.com), 159 studies published in the last 32 years were identified (see a listing of all studies in the supplementary materials). Cumulative number of articles as a function of publication year follows an exponential shape: in average over the period 1985-2014, number of publications per year increased for about 0.3 and reached 8 (2014). In both years 2015 and 2016, the isotopic method for locating or partitioning water sources to RWU gained significantly more attention with 20 publications per year (Fig. 3a).

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When sorting plant species simply by their form and height, it appears that trees are the most studied group of plants (present in about 60% of the studies), followed by annual and perennial grasses (21%) and shrubs (e.g., desert and mangrove species, 21%) (Fig. 3b). Only 15% of the publications study RWU in agricultural systems (e.g., maize, wheat, millet, rice), which is reflected by the small portion of peer-reviewed journals of which the category is listed under "Agronomy and Crop Science"

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(8%) by Scimago Journal & Country Rank (www.scimagojr.com). This is a rather surprising finding given the fact that drought stress is considered as a major threat for crop yields and that RWU is a crucial mechanism to sustain drought periods. "Soil Science" is a relatively underrepresented category with 8% as well. This is corroborated by the fact that 27% of the studies do not report any information about soils (e.g., texture, FAO class, structure, particle size distribution, or physical properties) (Fig. 3c). In comparison, the "Ecology" and "Ecology, Evolution, Behavior and Systematics" categories are significantly more represented with 22% of the studies altogether.

Four classes of methods for RWU analysis on basis of isotopic information emerged from our analysis (Fig. 3d). In a first one, representing 46% of the studies, RWU is either located in a specific soil layer using the method of "direct inference" (Brunel et al., 1995) or in some water pool (or water "source", not to be mistaken with the concept of water source defined in the previous section), e.g., groundwater, soil water, or rainwater (Andrade et al., 2005; Beyer et al., 2016; Roupsard et al., 1999). In a second class (32% of the studies), relative contributions of at least three water sources to RWU are determined using multi-source mixing models (e.g., MixSir and MixSIAR, Moore and Semmens, 2008, representing 2% of the studies; SIAR, Parnell et al., 2013, 5%; IsoSource, Phillips and Gregg, 2003, 21%). In a third class (18% of the studies), relative contributions of two particular water sources (e.g., water in two distinct soil layers, or groundwater versus recent precipitation etc.) to RWU are calculated "by hand" with a two end-member linear mixing model (Araki and Iijima, 2005; Dawson and Pate, 1996; Schwendenmann et al., 2015). Note that classes two and three (representing 50% of the studies) are both based on end-member mixing analysis (EMMA) (Barthold et al., 2011; Christophersen and Hooper, 1992) and will be further pooled into "statistical approach" in section 3.2 of this study.

In a fourth class, only accounting for 4% of the studies, assessments are provided using physically based analytical (Boujamlaoui et al., 2005; Ogle et al., 2014; Ogle et al., 2004) or numerical (i.e., SiSPAT-Isotope, Rothfuss et al., 2012; HYDRUS-1D, Stumpp et al., 2012; Sutanto et al., 2012) models, therefore leading to an estimation of a RWU profile variable in time.

Note that all methods have in common to use an inverse modelling approach: the RWU distribution is obtained by optimizing model input parameters until the simulated δ_{Ti} and/or the simulated δ_S profiles fit to the isotopic measurements. One important feature of the three first classes of methods is that they consider soil water isotopic transport flow to be negligible for the duration of the experiment. Numerical models such as HYDRUS-1D and SiSPAT-Isotope on the other hand take this into account in the computation of RWU profiles. The three first methods also differ from the last one by the fact that they only give fractions of RWU instead of absolute RWU rates changing in time and space.

61% of the studies based their estimation of location or quantification of relative contributions on measurement of either δ^2H or $\delta^{18}O$, i.e., in a single isotope framework, while 25% used both δ^2H and $\delta^{18}O$ (i.e., in a dual isotope framework). In the remaining studies, both isotopic compositions were measured and used to provide two separate estimates of relative contribution distributions even though δ^2H or $\delta^{18}O$ distributions were strongly linked (see section 2). This last approach is in the present study referred as "double single" (see supplementary materials). The vast majority of the studies (82%) took

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advantage of natural isotopic abundances while the rest (18%) applied labelling pulses to the soil (either in the profile or at the soil boundaries, e.g., the soil surface and groundwater) to infer RWU from uptake of labeled water.

To summarize, we observe that isotopic analyses have mainly been used up to now to assess water sources under natural ecosystems mainly using statistical approaches. On the opposite, these techniques have not been used much to investigate RWU of crops. It is also observed that the use of water isotope composition datasets combined with explicit physical models is lacking. In the next sections, we analyze the main methods currently use to retrieve RWU with isotopic water composition and compare the different methods. Table 1 summarizes 21 particular isotopic studies that use either one of the first three classes of methods (i.e., accounting for about 96% of the published studies), while class four (physically based RWU models) will be treated separately in section 4 of this study. These 21 studies were chosen according to either the number of citations and contribution importance (for studies published before 2015) or to the novelty of the publications (publication year $\geq$ 2015).

3.1 Graphical inference (GI)

This straightforward approach first proposed by Brunel et al. (1995) and applied by, e.g., Leroux et al. (1995), Weltzin and McPherson (1997) (Table 1) and else by Midwood et al. (1998), Armas et al. (2012), and Isaac et al. (2014) (see supplementary materials) defines the "mean root water uptake depth" $\bar{z}$, as the depth where $\delta_S = \delta_{Ti}$. $\bar{z}$ conceptually indicates to the soil depth where the plant root system, represented as one unique root, would extract water from.

There are cases where $\bar{z}$ cannot be unambiguously identified (e.g., $\bar{z}_1$ and $\bar{z}_2$ of case 2, Fig. 2b) due to the non-monotonic character of the δ_S profile (shown in black dashed line, case 2 of Fig. 2b). In order to define a mean RWU depth for such a case one can derive a monotonously decreasing δ_S profile by smoothing the profile (shown as symbols in Fig. 2b), e.g., by averaging δ_S in a number of layers using the following mass balance:

$$\delta_{S,J} = \frac{\sum_{j \leq J} \delta_S(z_j) \cdot \theta(z_j) \cdot \Delta z_j}{\sum_{j \leq J} \theta(z_j) \cdot \Delta z_j} \quad (5)$$

where J represents the set of depths that belong to the J^{th} soil layer, with θ [L^3 L^{-3}] and Δz_j [L] the soil volumetric water content and thickness of the soil layer centered around depth z_j. Due to this smoothing, the vertical resolution may be drastically reduced. In the example presented in Fig. 2b where a uniform θ profile is assumed, the $\delta_{S,J}$ profile intersects with the vertical line of value δ_{Ti} deeper than for the initially non-monotonic δ_S profile, i.e., $\bar{z}$ (case 2, integrated δ_S profile) < $\bar{z}_2 < \bar{z}_1$. Some authors rule out solutions in case of multiple mean RWU depths, e.g., by excluding the $\bar{z}$ solutions where soil water content was low and/or soil water potential was high in absolute value (e.g., Li et al., 2007; see Table 1).

Note that while Eq. (5) provides a representative value for the isotopic composition that would be measured in soil layer J as a function of those of the water in the set of depths, $\delta_{S,J}$ is however equivalent to the isotopic composition "sensed by the plant" only if the root profile is homogeneous, i.e., when *RLD* is constant over depth in that particular soil layer J.

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The graphical inference method may not only provide $\bar{z}$ but also its uncertainty caused by the uncertainty in measuring δ_{Ti} (e.g., based on the precision of the isotopic analysis and/or sampling natural variability, shown as gray stripe in Fig. 2b). The steeper the soil water isotopic profile, the larger the uncertainty in determining $\bar{z}$ is. Figure 2b illustrates this with estimated minimum and maximum $\bar{z}$ for the monotonic δ_S profile and for the vertically averaged profile. In the latter case, the possible range of $\bar{z}$ is the largest. These ranges give first quantitative indication of variance around $\bar{z}$. Finally, for a complete "graphical assessment" of the variance of $\bar{z}$, one should consider the uncertainty associated with measurements of the δ_S profile (not shown here; for a complete assessment of errors associated with determination of δ_S, see Sprenger et al., 2015) as well.

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3.2 Statistical approaches

3.2.1 Two end-member (TM) mixing model

The TM method is a particular case of end-member mixing analysis (EMMA) and is based on the concept that (i) a plant extracts water from two predominant water sources A and B (e.g., water in distinct upper and lower soil layers, or groundwater and recent precipitation water etc.) in given proportions, (ii) there is no isotopic fractionation during water uptake, and (iii) there is a complete mixing inside the plant of the contributing water sources A and B to RWU. The mass conservation for isotopologues gives:

$$J_{Ti}^{i} = J_{A}^{i} + J_{B}^{i} \tag{6a}$$

$$C_{Ti} \cdot J_{Ti} = C_{A} \cdot J_{A} + C_{B} \cdot J_{B} \tag{6b}$$

with J_A, J_B, and J_{Ti} [$L^3\ T^{-1}$] (respectively J_A^i, J_B^i, and J_{Ti}^i [$M\ T^{-1}$]) the fluxes of water (respectively isotopologues) originating from water sources A and B, and at the plant tiller. C_A, C_B, and C_{Ti} [$M\ L^{-3}$] are the water sources A and B, and xylem sap water measured isotopic concentrations. By introducing $x = J_A / J_{Ti}$ and following Eq. (3), Eq. (6b) becomes:

$$\delta_{Ti} = x \cdot \delta_{A} + (1 - x) \cdot \delta_{B} \tag{7}$$

In this approach, δ_{Ti} is therefore defined as the mean value of the isotopic compositions of water sources A and B (δ_A and δ_B) weighted by the proportions to J_{Ti} of water volume extracted by the plant from water sources A and B, i.e., x and $(1 - x)$, respectively. The error associated with the estimation of x (σ_x [-, expressed in ‰]) can be calculated following Phillips and Gregg (2001):

$$\sigma_x^2 = \left(\frac{\partial x}{\partial(\delta_A)}\right)^2 \cdot \sigma_{\delta_A}^2 + \left(\frac{\partial x}{\partial(\delta_B)}\right)^2 \cdot \sigma_{\delta_B}^2 + \left(\frac{\partial x}{\partial(\delta_{xyl})}\right)^2 \cdot \sigma_{\delta_{Ti}}^2 \tag{8a}$$

$$\sigma_x = \sqrt{\sigma_x^2} = \frac{1}{(\delta_A - \delta_B)} \sqrt{\left(\sigma_{\delta_{Ti}}^2 + x^2 \cdot \sigma_{\delta_A}^2 + (1-x)^2 \cdot \sigma_{\delta_B}^2\right)} \tag{8b}$$

with σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}}$ the standard errors associated with the measurements of δ_A, δ_B, and δ_{Ti}, respectively. The sensitivity of Eq. (8b) to different values of σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}}$ can be tested by considering either minimal possible errors, i.e., the analytical precision of the isotopic analyser (e.g., isotope ratio mass spectrometer, laser-based spectrometer), or by taking additional errors involved with sampling procedure and vacuum distillation technique (see e.g., Rothfuss et al., 2010) into account. Equation (8b) also shows that, independently of the values considered for σ_{δ_A}, σ_{δ_B}, or $\sigma_{\delta_{Ti}}$, σ_x is inversely proportional to $1/(\delta_A - \delta_B)$, indicating that the two end-members should have greatest possible isotopic dissimilarities for a low standard error of x. Therefore, it is especially important, e.g., for partitioning between water from an upper and lower portion of the soil profile, to properly define the thickness of these layers, so that they have distinct isotopic compositions, and that the difference is considerably larger than the precision of the isotopic measurements. Figure 4 shows for example that when (i) x is evaluated at 10 % and (ii) σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}}$ are estimated being equal to 0.02 ‰ (dark blue solid line), $(\delta_A - \delta_B)$ should be greater than 0.75 ‰ (in absolute term) in order to reach a σ_x value lower than 5 %, i.e., more than 37 times the error made on δ_A, δ_B, and δ_{Ti}. To obtain the same standard error for x in case of a higher standard error on the estimation of δ_A, δ_B, and δ_{Ti} (e.g., σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}} = 0.1‰$), $(\delta_A - \delta_B)$ should be greater than 3.00 ‰ (in absolute term). This difference becomes much greater for σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}} = 1.00‰$ and reaches 42 ‰ (not shown in Fig. 4). This certainly highlights the advantage of artificially labelling soil water with water enriched (or depleted) in heavy isotopologues for a more precise assessment of the relative contribution of soil water sources to RWU, as mentioned by Moreira et al. (2000). In another study, Bachmann et al. (2015) labelled the upper and lower portion of the soil profile in a natural temperate grassland with ^{18}O-enriched and ^{2}H-enriched water, respectively. They defined two distinct (upper and lower) soil water sources, for which they calculated the corresponding δ^2H or $\delta^{18}O$ on the basis of measured soil water isotopic profiles and using Eq. (5). They could find evidence against the so-called hypothesis of "niche complementarity" regarding plant water use, which states that RWU of competitive plant species is spatially and temporally distinct, and that this distinction is stronger at high species richness. Figure 4 also illustrates that for given $(\delta_A - \delta_B)$, σ_{δ_A}, σ_{δ_B}, and $\sigma_{\delta_{Ti}}$ values, the "optimal x value" for a low σ_x is 50% (showed by the orange lines).

Table 1 displays a sample of studies that used the two end-member mixing approach. Authors could distinguish between uptake of irrigation and precipitation water (Goebel et al., 2015), precipitation and groundwater (White et al., 1985), soil water and groundwater (McCole and Stern, 2007), or else between stream water and soil water (Dawson and Ehleringer, 1991; McDonnell, 2014). Thorburn and Ehleringer (1995) could for instance locate the dominant source for RWU, i.e., groundwater for their mountain and floodplain test-site and water from the soil between 0.3 and 0.4 meter depths for their cold desert test-site. Other Authors (e.g., Brunel et al., 1995) combined two mixing equations, i.e., one for each isotopologue, into a single one or else, calculated the ratio of geometrical distances between δ_{Ti} and δ_A and between δ_{Ti} and δ_B in dual isotope ($\delta^{18}O$ and δ^2H) space (Bijoor et al., 2012; Feikema et al., 2010; Gaines et al., 2016). As infrared laser-

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based spectrometry now enables simultaneous measurements of $\delta^{18}O$ and $\delta^{2}H$ at lower cost, we believe that this dual-isotope approach (referred as "D" in Table 1) will or should gain in importance in isotopic studies. This is especially useful when (i) under natural conditions the $\delta^{18}O$-$\delta^{2}H$ slope is not constant over depth (Sprenger et al., 2016) or (ii) in the context of pulse labelling experiments, which can artificially change the value of the $\delta^{18}O$-$\delta^{2}H$ slope at given locations in the soil profile. In these cases, two independent mixing equations are obtained, one for each isotopologue.

3.2.2 Multi-source (MS) mixing models

When there are more than two identified plant water sources contributing to RWU, e.g., water from different layers j (j ∈ [1, N]) in soil the profile, Eq. (7) becomes:

$$\delta_{Ti} = \sum_{j=1}^{N} x_j \cdot \delta_{S,j} \quad (9)$$

with N the number of plant water sources (e.g., soil layers) and $\sum_{j=1}^{N} x_j = 1$. As there are more water sources than (number of mixing equations + 1), there is not a unique solution but an infinite range of possible solutions. However, based on background information or knowledge, some of these solutions are not likely or possible. A range of solutions that is most likely based on prior information can be obtained using Bayesian methods. In the method proposed by Phillips and Gregg (2003), the isotopic composition calculated for each considered x_j combination (δ_{Ti}) is compared with the measured value ($\delta_{Ti,m}$). The number of combinations depends on the value of the contributing increment (i, %, typically 5 or 10 %) and the combinations for which δ_{Ti} meets the following requirement are selected:

$$\delta_{Ti} \leq \left| \delta_{Ti,m} \pm \tau \right| \quad (10)$$

where τ [-, expressed in ‰], standing for "tolerance", usually accounts for precision of the isotopic measurements or possible errors during sampling and vacuum distillation steps. This multi-source mixing model approach strongly depends on τ and i, which therefore should be carefully chosen by the user, e.g., a smaller i refines the analysis. For this, the program "IsoSource" (https://www.epa.gov/sites/production/files/2015-11/isosourcev1_3_1.zip) is available (Phillips et al., 2005). Wang et al. (2010) compared the outcome of the GI and MS approaches and came to the conclusion that even though the latter did not solve the non-uniqueness problem and provided diffuse patterns of frequency that were difficult to interpret in some cases (e.g., in case of a non-monotonic isotopic profile), it had the advantage over the former method of providing a systematic and quantitative assessment of ranges of relative contributions. Romero-Saltos et al. (2005) extended the model of Phillips and Gregg (2003) by constraining RWU to follow a normal distribution within a delimited 50-cm soil vertical segment of one centimeter vertical resolution and centered around $\bar{z}$, the mean RWU depth. The location of this section and thus $\bar{z}$ is as well obtained by mass balance from inverse modelling similarly to IsoSource (see applications of Grossiord et al., 2014; Rossatto et al., 2013; Stahl et al., 2013).

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Parnell et al. (2010) proposed to overcome two limitations of the approach of Phillips and Gregg (2003), i.e., its inability to (i) account for uncertainty in the estimations of δ_{Ti} and of the water sources isotopic compositions $\delta_{S,j}$, and to (ii) provide a optimal solution rather than ranges of feasible solutions. For doing this, they use a Bayesian framework (for details see Erhardt and Bedrick, 2013; Moore and Semmens, 2008; Parnell et al., 2013), which allows uncertainty in the x_j proportions and incorporates a residual error term ε_j (normally distributed with mean equal to zero and variance σ^2):

$$\delta_{Ti} = \sum_{j=1}^{N} x_j \cdot \delta_{S,j} + \varepsilon_j \qquad (9')$$

Note that the terms of (i) trophic enrichment factor (TEF [-, expressed in ‰], see, e.g., meta-analysis of Vanderklift and Ponsard, 2003) and (ii) isotope concentration dependency (Koch and Phillips, 2002; Phillips and Koch, 2002) originally incorporated in the formulation of Parnell et al. (2010) for other applications are not present in Eq. (9') since (i) no isotopic fractionation during RWU is assumed and (ii) isotope concentration dependency applies only for situations where isotopic compositions of different elements are measured and available.

Parnell et al. (2010) developed the program "Stable Isotope Analysis in R" (SIAR, https://cran.r-project.org/src/contrib/siar_4.2.tar.gz) in which the initial (*a priori*) x_j distribution is by default the Dirichlet distribution, of which information can be partly specified by the user. *A posteriori* x_j distribution is obtained by fitting the linear model to data via a Metropolis-Hasting (Hastings, 1970; Metropolis et al., 1953) Markov Chain Monte Carlo algorithm.

Prechsl et al. (2015) apply both graphical and Bayesian approaches to evaluate the shift in $\bar{z}$ and change of RWU profile following drought treatments (approx. 20 to 40 % precipitation reduction with transparent rainout shelters) in both extensively and intensively managed grasslands. From both approaches it appeared that a shift in $\bar{z}$ was inexistent or not observable from isotopic analyses. Another recent application of the Bayesian approach was performed by Volkmann et al. (2016b), who took advantage of a newly developed soil isotopic monitoring method to confront high frequency δ_S profiles time series to time series of δ_{Ti} (indirectly obtained from the isotopic measurement of the transpired water and assuming isotopic steady state, i.e., $\delta_{Ti} = \delta_T$) following a labelling pulse (see Table 1 for details on the study).

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4 INTER-COMPARISON OF METHODS

We tested and compared the different methods (GI, TM, MS) during a series of virtual experiments in a single isotope framework ($\delta^{18}O$) and at natural isotopic abundance. Mean RWU depths (provided by the GI method) and x_j distribution (provided by the two end-member and multi-source mixing models) were determined from the δ_S profile and the δ_{Ti} value. For each virtual experiment the δ_S profile was prescribed to the different methods, while δ_{Ti} was calculated with the physically based analytical RWU model (referred to as "Couv") of Couvreur et al. (2012).

It has been proved (Couvreur et al., 2012) that this model gives similar results than a 3D physically based model with detailed descriptions of the root architecture and of the water flow in soil and roots. In that sense, this is the best current

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model existing nowadays to simulate water fluxes in a soil-plant system (based on biophysical considerations). Other current models make assumptions or use empirical relations to predict RWU, which are not based on bio-physical considerations only (Jarvis, 2011; Simunek and Hopmans, 2009). Obviously, we do not mean that the model of Couvreur et al. (2012) gives the reality but rather the best estimate of the water flow based on our physical knowledge.

The inter-comparison of models was performed using a single isotope (^{18}O) approach as the focus here was the differences of outcomes rather than the impact of the input isotopic data on these results. The reader is referred to Appendix B1 for a description of the model of Couvreur et al. (2012) and to Appendix B2 on how it was implemented for the inter-comparison.

4.1 Methodology

4.1.1 Scenario definition

We developed eight virtual plausible scenarios of soil-plant systems under different environmental conditions. For each scenario, we set one total soil water potential (H_S) profile and one soil water oxygen isotopic composition (δ_S) profile. These profiles resulted from the combination of a lower boundary condition, i.e., the depth of the groundwater table, and an upper boundary condition, i.e., the soil surface water status. The groundwater table (of water isotopic composition equal to -7‰) was either shallow at -1.25 m depth (prefix "Sh") or deep at -6 m depth (prefix "De"). The soil water potential was considered to be at static equilibrium below the groundwater level. The soil surface was either dry under evaporative conditions (suffix "Dr"), or wet, e.g., shortly after a rain event (suffix "We"). For instance for the scenario "ShDr", we set the δ_S profile to be maximal at the surface, due to evaporation, and minimal from –0.5 m downward, due to the shallow groundwater table location. For the scenario "DeWe", on the other hand, the increase of δ_S towards the surface was not monotonic due to a recent precipitation event (of water isotopic composition equal to -7‰). Finally, we tested two different values of plant transpiration rate (T) and leaf water potential (H_l) with each of these four combinations (i.e., ShDr, ShWe, DeDr, and DeWe). The transpiration rate was either low (e.g., relevant at night, T = 0.01 mm h^{-1}, suffix "_lT") or high (T = 0.30 mm h^{-1}, suffix "_hT"). All eight scenarios relied on a common measured root length density vertical distribution of *Festuca arundinacea*. Table 2 reports the input data. Note that, as hypothetized in Eq. (4b), transpiration and sap flow rates (i.e., per unit of surface area [L T^{-1}]) were considered as equal.

The objective was not to use an advanced numerical model such as, e.g., SiSPAT-Isotope or Soil-litter-iso, to produce these scenarios, but rather use synthetic information based on (i) experimental data and (ii) expert-knowledge which would ideally illustrate the performances or limitations of the different methods.

4.1.2 Setup of the models

The two end-member mixing approach (TM) was tested against the isotopic data for two different cases: (i) two conjoint soil layers spreading from 0 – 0.225 m and 0.225 – 2.00 m and (ii) two disjoint soil layers spreading from 0 – 0.225 m and 1.75 – 2.00 m. The latter case was designed to evaluate the impact of lacunar soil isotopic information on the calculation of x, i.e.,

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when not all potential water sources are properly identified. Representative values of water oxygen isotopic compositions for these soil layers ($\delta_{S,J}$, $J \in$ [I,II]) were obtained from the mass balance (Eq. (5)) after interpolation of the measured soil water content and δ_S profiles at a 0.01 m vertical resolution.

For the multi-source mixing models of Phillips and Gregg (2003) (IsoSource) and Parnell et al. (2010) (SIAR), the number of potential water sources was initially fixed to three, i.e., water from the soil layers I (0.000-0.050 m), II (0.050-0.225 m), and III (0.225-2.000 m). Upper and lower boundaries of these layers were defined to reflect the exponentially shaped (monotonic) δ_S profiles (experiments ShDr and DeDr) or to smooth the non-monotonic δ_S profiles observed during experiments ShWe and DeWe. IsoSource and SIAR were tested for eight soil layers (i.e., as many layers as measurement points, I: 0.000-0.020, II: 0.020-0.050, III: 0.050-0.110, IV: 0.110-0.225, V: 0.225-0.400; VI: 0.400-0.750, VII: 0.750-1.500, and VIII: 1.500-2.000 m) as well. Increment and tolerance in IsoSource were fixed to 10% and 0.25‰, respectively. Similarly to the TM approach, profiles of $\delta_{S,J}$ ($J \in$ [I,III] or [I,VIII]) were obtained from the mass balance (Eq. (5)) after interpolation of the measured soil water content and δ_S profiles at a 0.01 m vertical resolution.

Finally, for the SIAR model, uncertainty associated with δ_S measurements was set to 0.2 ‰ and the number of iterations was fixed to 500000 and number of iterations to be discarded to 50000.

For a detailed description of the inter-comparison methodology, the reader is referred to Appendix C.

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4.2 Results and discussion

Figure 5 displays x_{Couv}, the $\frac{S(z)dz}{T/(\Delta x \cdot \Delta y)}$ ratios (solid colored lines) simulated by the analytical model of Couvreur et al. (2012) for the eight scenarios together with uncertainty (shaded areas) and the corresponding δ_{Ti_Couv} (±1sd) (for a description on how uncertainty was assessed, refer to Appendix C). In general, at high T the compensation was negligible and the S profile was mainly proportional to the RLD profile (Fig. 5b, d, f, and h). The only exception was a soil with deep groundwater table and dry surface, where this dry layer limited RWU (DeDr_hT). At lower transpiration demand, the S profile predicted by the Couvreur et al. (2012) model generally differed from the RLD profile (Fig. 5a, c , e, and g). This is due to the fact that the second term of Eq. (1) (i.e., S_{comp}, see Eq. (B4) and (B4') in Appendix B) was proportionally larger. Water uptake from the upper layer was always more than proportional to the RLD, when this layer was wetter, and vice versa. Water release to the soil (i.e., HR) was observed only for the soil with the deep groundwater table and dry upper layer (DeDr_hT, Fig. 5e). From the graphical method GI, either a single or two distinct solutions for $\bar{z}$ (displayed as gray-shaded horizontal stripes) were retrieved, depending on the monotonic/non-monotonic character of the δ_S profile, and ranged between –0.02 and –0.95 m.

Figure 6a displays the relative contribution to T of the uppermost layer 0 – 0.225 m in case of two conjoint soil layers as computed with the TM approach and a comparison with the results of the analytical model. Except for the very last two virtual experiments with the deep groundwater table and wet upper layer at both low and high transpiration rates (i.e.,

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DeWe_lT and DeWe_hT), there was a very good agreement between the analytical model and the two end-member mixing model: absolute difference between x_{Couv} and x_{TM} ranged between 1.5% (ShDr_lT) and 6.3% (ShDr_hT). For the experiment with the deep groundwater table and dry upper layer at low transpiration rate (DeDr_lT), the TM approach estimated that x was equal to 12.3% while the analytical model simulated hydraulic redistribution, i.e., excluded the layer 0 – 0.225 m as potential source. The significant difference between results of the two models during experiments DeWe_lT and DeWe_hT and the higher standard error associated with x_{TM} (σ_x, displayed in the form of error bars in Figure 6) were due to the small difference between the isotopic compositions of the defined soil water sources $\delta_{S,I}$ (–6.0 ‰) and $\delta_{S,II}$ (–5.3 ‰) as illustrated in section §3.2.1. Figure 6b gives the relative contribution to T of the layer 1.75 –2.00 m in case of two disjoint soil layers, i.e., when not all potential water sources are accounted for into the calculation of $\delta_{S,I}$ and $\delta_{S,II}$. In this case there were important disparities between x_{TM} and x_{Couv}. The mean absolute difference between these two estimates was equal to 43,5 (±17.8)%. Omitting some of the potential water sources contributing to T had in this second case the consequence of artificially overestimating the contribution of the lowest layer. We therefore suggest to always attempting to fully characterize the soil isotopic profile before aggregating the isotopic information when defining the two water sources.

Figure 7 gives the relative contributions from soil layers I, II, and III (upper, middle, and lower panel, respectively) to T provided by IsoSource, the multi-source mixing model of Phillips and Gregg (2003) (x_{IsoS}, in %, displayed in the form of gray histograms) and by SIAR, the Bayesian method of Parnell et al. (2010) (x_{SIAR}, in %, gray probability density curves). The colored vertical lines are x_{I_Couv}, x_{II_Couv}, and x_{III_Couv}, the simulated $\frac{S(z)dz}{T/(\Delta x \cdot \Delta y)}$ ratios from layers I, II, and III. The color-shaded areas associated with x_{I_Couv}, x_{II_Couv}, and x_{III_Couv} refer to their uncertainty by accounting for the uncertainty of the input data. As for Fig. 5, δ_{Ti_Couv} is reported above each plot along with its standard deviation. x_{J_IsoS} probability distribution was observed to be either narrow (e.g., for the experiment with the deep groundwater table and dry upper layer at low transpiration rate – DeDr_lT / layer I, Fig. 7m) or broad (e.g., for the experiment with the deep groundwater table and wet upper layer at high transpiration rate – DeWe_hT / layer I), i.e., the range of the possible solutions for x_{J_IsoS} was relatively small or large (10 and 100% respectively for these two examples). In general, both IsoSource and SIAR results were in good agreement: the x_{SIAR} most frequent value (MFV, at the peak of the density distribution curve) was in most cases either located near the median value of the x_{IsoS} probability range (e.g., for the experiment with the shallow groundwater table and wet upper layer at low transpiration rate – ShWe_lT / layer I, Fig. 7g) or matched exactly the x_{IsoS} unique value (i.e., for the experiment with the deep groundwater table and dry upper layer at low transpiration rate – DeDr_lT / layer I, Fig. 7m). In contrast, the statistical methods succeeded best in providing x estimates similar to those of the model of Couvreur et al. (2012) in case of a shallow groundwater table and at low T only (Fig. 7a-c and g-i), thus when water availability was high and root compensation was low. In these cases, x_{I_Couv} was included in the estimated x_{J_IsoS} range and the mean absolute difference (MD) between x_{J_Couv} and x_{SIAR} MFV was equal to 8.6%. This difference was the greatest

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(129.2%) for experiment DeDr_lT when hydraulic redistribution by the roots was simulated by the analytical model (Fig. 7m-o).

When considering eight soil layers instead of three, uncertainties in the assessment of the relative contributions to *T* as determined by IsoSource increased. The estimated probability ranges increased in most of the cases (results not shown). However, it considerably improved the results of the bayesian model: the mean absolute difference between x_{J_Couv} and the most frequent x_{SIAR} value was equal to 4.7% for the scenarios with a shallow groundwater table and low transpiration rate and equal to 52.1% in case of hydraulic redistribution by the roots (Table 3).

Independent of the number of defined soil layers, lowering the value of increment to 5% in IsoSource refined the analysis where the probability distribution was already narrow (i.e., in the case of a well identified x_{IsoS} value, e.g., Fig. 7m) while it produced distributions that were flatter and contained less gaps when no clear solutions had emerged before (results not shown). Artificially increasing the value of tolerance had the consequence that more solutions to Eq. (10) were found for each experiment / transpiration value / layer combinations and *vice versa* (results not shown). An increase or decrease of a factor 2 of the number of runs as well as the number of runs to be discarded from the analysis had only a marginal impact on the density distribution curves obtained with the SIAR model in the case of three or four soil layers.

The modelling exercise illustrated the disparities of outcome between the graphical method on the one hand and the statistical and mechanistic methods on the other: there simply cannot be a single or multiple "root water uptake depths" but rather a continuous RWU profile or statistical solutions of contribution to transpiration (provided by IsoSource and SIAR). Significant changes of δ_{Ti} do not necessarily mean important changes in the depth of RWU but rather slight (nevertheless significant) modification of the RWU profile. The authors believe that the relatively novel statistical tools presented in this review should therefore be preferred over the graphical inference method, especially since the two former are available as user-friendly programs and packages and do not require significant computing time, therefore can be run locally on a personal computer. As highlighted in this series of virtual experiments, the Bayesian method showed for the case of two and three soil layers much more convincing results than the method of Phillips and Gregg (2003). The Bayesian method was particularly efficient in the case of eight soil layers, illustrating the interest of reaching the best vertical resolution and maximizing the number of identified potential sources (Table 3). Note that no prior information on the relative contributions to *T* from the different soil layers was used when running the SIAR program, i.e., the authors opted for flat priors. This can be changed by the user, based on additional collected data such as, for instance, information of root architecture and function across the soil profile or information on soil hydraulic properties and water status.

One can show from this inter-comparison of methods that labelling of soil water in either ^{18}O or ^{2}H has potentials for improving the different methods presented here theoretically if water is taken up by the roots from the labeled region predominantly. However, this was never the case when considering the results of the analytical model. A dual isotope (^{18}O or ^{2}H) labelling pulse experiment that would artificially disconnect the strong link between $\delta^{18}O$ and $\delta^{2}H$ would on the other hand much more constrain the inverse problem and provide more accurate estimates

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5 CHALLENGES AND PROGRESSES

5.1 Off-line destructive versus on-line nondestructive isotopic measurements in plant and soil waters

For determination of δ_S, soil profiles are usually destructively sampled, typically with an auger down to a depth of a few centimeters (Rothfuss et al., 2010) to a few meters (Moreira et al., 2000) (see Table 1), depending on the depths of the root system and of the water table. The sampling depth resolution should, when possible, match the exponential decrease of isotopic composition (Wang et al., 2010) and it should capture sudden variations with time at the soil surface due to precipitation, i.e., be maximal at the surface and minimal deeper in the soil profile where isotopic dynamics are less pronounced. Not doing this can lead to a situation where source partitioning is not feasible from isotopic measurements. Under field conditions (i.e., ~95% of the studies reviewed in this work, summarized in Table 1) soil material is generally not a limiting factor, thus, can be sampled twice or thrice to average out or characterize lateral heterogeneity without significant disturbance of the soil.

Water from plant and soil materials is predominantly extracted by cryogenic vacuum distillation (Araguás-Araguás et al., 1995; Ingraham and Shadel, 1992; Koeniger et al., 2011; Orlowski et al., 2013; West et al., 2006). Accuracy of this extraction method was shown to be maximal at higher water content and for sandy soils and lower for soils with high clay content (e.g., Koeniger et al., 2011; West et al., 2006). In the latter case, extraction times should be longer and temperatures higher to mobilize water strongly bound to clay particles, which has a distinct isotopic composition from that of pore "bulk" water (Araguás-Araguás et al., 1995; Ingraham and Shadel, 1992; Oerter et al., 2014; Sofer and Gat, 1972).

Certainly one of the main limitations of all isotopic approaches for quantifying RWU is the destructive character of isotopic sampling (see section 3.1) and associated offline analyses (sections 2.2 and 2.3). This usually leads to poor spatial (maximum a few cm^2) as well as temporal (minimum hourly) resolution of the inferred results, when comparing with measuring frequency of other soil and plant state variables, e.g., soil water content and potential, and leaf water potential (section 3.2.2). In addition, one may question the representativeness of plant samples, in which tissues (and thus water) with very different water residence time is mixed.

Recently developed methods take advantage of laser-based spectroscopy which allows in-situ, on-line, and continuous isotopic measurements in the gas phase at high frequency. These methods rely on coupling a laser spectrometer (e.g., Wavelength-Scanned Cavity Ring-Down Spectroscopy – WS-CRDS, Picarro Inc., Santa Clara, CA, USA; Cavity-Ringdown Laser Absorption Spectroscopy – CRLAS and Off-Axis Integrated Cavity Output Spectroscopy - ICOS, Los Gatos Research, Los Gatos, USA) with specific soil gas sampling probes consisting of gas-permeable microporous polypropylene membranes or tubing. These membranes or tubing exhibit strong hydrophobic properties while their microporous structures allow the intrusion and collection of soil water vapor. Several authors (Gaj et al., 2015; Gangi et al., 2015; Herbstritt et al., 2012; Oerter et al., 2016; Rothfuss et al., 2013; Sprenger et al., 2015; Volkmann and Weiler, 2014) could determine the soil liquid water isotopic composition in a nondestructive (yet invasive) manner from that measured in the collected soil water vapor

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For grasses and nonwoody plants the root crown (e.g., Leroux et al., 1995), the aerial nodal roots (e.g., Asbjornsen et al., 2007), the meristematic petiole, or else the collars (e.g., tillers) at the base of the plant (e.g., Dawson and Pate, 1996; Sánchez-Perez et al., 2008) can be sampled for determination of δ_{Tr}. In the case of ligneous plants the fully suberized stem (Asbjornsen et al., 2007) or sapwood (e.g., White et al., 1985) is sampled. Special attention is to be given to remove any organ potentially transpiring that would have a water isotopic composition not representative of δ_{Tr}, e.g., dead material or the sheath of the oldest living leaf around tillers (Barnard et al., 2006; Durand et al., 2007). Non-conducting heartwood should discarded from conducting sapwood (White et al., 1985).¶
5.2 Off-line destructive versus on-line nondestructive isotopic measurements in plant and soil waters

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considering thermodynamic equilibrium between vapor and liquid phase in the soil. In contrast to "traditional" isotopic methods, these novel isotopic monitoring methods have also the distinct advantage of determining soil liquid water isotopic composition at very low water content, since water vapor, in contrast to soil liquid water, is not limited for analysis. These novel methods allow a vertical resolution down to 1 cm and an approximately hourly time-resolution. However, they do not allow horizontal resolution along the tube and the laser spectrometers could be, as pointed out by Gralher et al. (2016) for the specific case of a Picarro WS-CRDS, significantly sensitive to the carrier gas used. In their opinion papers, McDonnell (2014) and Orlowski et al. (2016a) urged for a comparison between methods, which was addressed by Orlowski et al. (2016b) and Pratt et al. (2016) (for vapor measurements only).

In the coming years, effort should be made towards developing novel methods for a direct and nondestructive determination of δ_{Ti} based on the use of gas-permeable membranes, which was recently initiated for trees (Volkmann et al., 2016a). This should be further tested for other (non-woody) plant species. This will imply the major challenge of not disrupting the water columns in the active xylem vessels when installing such a membrane-based system. Another potential issue to be investigated is the species-specific extent of water exchange between xylem and phloem conductive tissues which might lead to isotopic "contamination" of the xylem sap water (Farquhar et al., 2007).

5.2 Call for a coupled experiments-modelling approach for determination of plant water sources on the basis of isotopic data

In order to fully benefit from the potential of water stable isotopic analysis as tools for partitioning transpiration flux, the authors call for the development of approaches making use of physically based models for RWU and isotopic fractionation to analyze experimental data, especially since several soil-vegetation-atmosphere transfer (SVAT) models are available that can simulate flow of isotopologues in the soil and the plant (i.e., SiSPAT-Isotope, Braud et al., 2005; Soil-litter-iso, Haverd and Cuntz, 2010; R-SWMS, Meunier et al., 2017; TOUGHREACT, Singleton et al., 2004; HYDRUS, Sutanto et al., 2012).

To the authors' knowledge, there are only a few studies which attempted to do so. Rothfuss et al. (2012) ran an experiment under controlled laboratory conditions where they measured on four dates (corresponding to four different stages of vegetation and therefore root development) soil water potential and isotopic composition profiles, and root length density distribution profiles. In their experiment, the isotopic composition of transpiration was known. The authors used a global optimization algorithm to obtain the set of parameter of SiSPAT-Isotope that best reflected the experimental dataset. Distributions of RWU could be determined on these four dates. Also, in the study of Mazzacavallo and Kulmatiski (2015), the RWU model of HYDRUS could be parameterized during a labelling (heavy water ^2H_2O) pulse experiment on the basis of measurements of xylem water hydrogen and oxygen isotopic compositions. This provided insights into the existence of niche complementarity between tree (mopane) and grasses species. Note, however, that this HYDRUS version did not incorporate isotopic transport through the soil and the roots.

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5.3 Isotopic assessment of hydraulic redistribution¶
Hydraulic redistribution has been observed using isotopic measurements in a number of studies (e.g., Caldwell and Richards, 1989; Dawson, 1993; Kurz-Besson et al., 2006). However, in contrast to nondestructive "traditional" methods allowing for direct monitoring of redistribution dynamics (i.e., psychrometry, time domain reflectometry, and frequency domain capacitance, Brooks et al., 2002; Dawson, 1996; Richards and Caldwell, 1987; Wan et al., 2000), isotopic methods provide a destructive and indirect assessment. These methods are based on (i) labelling of soil or roots of deep-rooted plants at a given depth in the soil or at a certain location in the experimental field and (ii) measuring the δ_{Ti} of plants not having access to labeled water (i.e., of which the roots do not reach the isotopic labeled depth or location). When hydraulic redistribution occurs, the xylem sap water (of measured isotopic composition $\delta_{Ti,m}$) of these plants can be conceptualized as a mixture of antecedent soil water (at natural isotopic abundance) and isotopically enriched water released to the soil by the deep-rooted vegetation. From simple mass balance at the release location, δ_S at a given depth z in the soil and at time (t+Δt) deviates from that at time t as a function of the (negative) S (i.e., hydraulic redistribution) at time t and change of soil volumetric water content (θ): ¶
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Another example is the work of Ogle et al. (2004) who could reconstruct active root area and RWU profiles from isotopic measurements using the 1D analytical macroscopic model of Campbell (1991) in a Bayesian framework (root area profile and deconvolution algorithm – RAPID). By assuming normal a priori distributions for the xylem water oxygen and hydrogen isotopic compositions and considering prior knowledge on RWU distribution (i.e., synthetic information based on measurements of other studies), Ogle et al. (2004) obtained a posteriori distributions of x of a desert shrub (Larrea tridentate).

Simple analytical models, such as the formulation of Couvreur et al. (2012), can be applied and confronted with isotopic data. In comparison with statistical tools, such physical models provide profiles with high spatial resolution and lower uncertainty, on the condition that all required (isotopic) data is available. We recognize that in comparison with the statistical and conceptual methodologies presented in this review, using a physical (analytical or numerical) model implies the measurements of additional state variables to be fed as input to the model, and of one parameter (K_{plant}) (when considering the assumption K_{plant} = K_{comp} valid, see Appendix B). Some of these variables are laborious to obtain (e.g., *RLD*) or not straightforward to measure (H_S, H_L, and T) – especially in the field – but are mandatory to be able to determine contributions to T across a set of identified water sources. In addition, they are necessary to gain insights into soil-plant interactions, e.g., dynamics of root function (active versus non-active roots in the soil profile) in water uptake and, thus, quantify the disconnection between measured *RLD* and the prognostic variable *SSF* (see Appendix B1). For doing this, controlled conditions in state-of-the-art climatic chambers are ideal, as they allow for a reduction of the inherent spatial heterogeneity present under natural conditions and, thus, the deconvolution of environmental effects on RWU. Experimental facilities that not only control atmospheric forcing (soil upper boundary conditions for latent and heat flow), but impose lower boundaries for the soil compartment (e.g., drainage and capillary rise dynamics) and provide means to close the hydrological balance are required. Moreover, macrocosm experiments (~m^3 scale) should be favored over mesocosm (~dm^3 scale) experiments to avoid or reduce inherent side effects that would ultimately hamper mimicking natural conditions.

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6 CONCLUSION

Root water uptake is a key process in the global water cycle. More than 50% of total terrestrial evapotranspiration crosses plant roots to go back to the atmosphere (Jasechko et al., 2013). Despite its importance, quantification of RWU remains difficult due to the opaque nature of the soil and the spatial and temporal variability of the uptake process.

Water stable isotopic analysis is a powerful and valuable tool for the assessment of plant water sources. In an inverse modelling framework, isotopic analysis of plant tissues and soil also allow for obtaining species-specific parametrization of physically based analytical and numerical RWU models. They provide a unique way to tackle the difficulty of disentangling actual RWU profiles with root traits and characteristics. Yet, our literature review revealed that isotopic data have been up to now mainly used to assess water sources under natural ecosystems using statistical approaches. Only 4% of current scientific publications demonstrate the use of a physically based model for analyzing isotopic data.

Three methods (representing 90% of the studies) have been used for partitioning water sources: the "direct inference" method, the two end-member mixing model and two examples of multi-source mixing models. We performed a comparison between these methods. We could quantify the impact of the definition of the plant water sources (i.e., whether they are spatially disjoint or not and whether their isotopic compositions values are significantly different or not) on the outcome of the two end-member mixing model. We highlighted the importance of systematically reporting uncertainties along with estimates of contribution to *T* of given plant water sources. The inter-comparison also illustrated the limitations of the graphical inference method and the multi-source mixing model of Phillips and Gregg (2003), whereas it underlined the good performance of the Bayesian approach of (Parnell et al., 2010), which uses a more rigorous statistical framework, if the number of considered water sources matches the number of isotopic measurements in the soil profile. However, contrary to the analytical model none of the graphical and statistical methods could locate and quantify hydraulic redistribution of water.

Finally, the authors call for a generalization of coupled approaches relying on the confrontation between labelling experiments under controlled conditions and three dimensional RWU numerical modelling. This type of approach could be used in agronomy and agriculture to quantify root water uptake as a function of plant genotype, soil structure and climate.

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AUTHOR CONTRIBUTION

Y. Rothfuss reviewed the published literature. Y. Rothfuss and M. Javaux designed the virtual experiments, analysed, and discussed the obtained results.

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TABLES

Table 1

Table 1: Summary of the reviewed studies that use one of either the three methods (graphical inference), two-end members mixing model, and "multi-source mixing models) for plant water sources partitioning.

Experimental conditions (field: F / laboratory: L)	Authors
	Graphical inference
F (tropical)	Leroux et al., 1995
F (semi-arid; cold desert, subhumid) F (temperate semi-arid savanna) F (tropical forest / savanna) F (eastern Amazon) F (desert)	Thorburn and Ehleringer, 1995 Weltzin and McPherson, 1997 Jackson et al., 2009 Moreira et al., 2000 Chimner and Cooper, 2004
F (shrub-steppe) F (cold continental -semiarid)	Kulmatiski et al., 2006 Li et al., 2007
F (warm temperate / monsoon climate) F (tropical)	Wang et al., 2010 Stahl et al., 2013
	Two-end members mixing model White et al., 1985
F (temperate)	Dawson and Ehleringer, 1991
F (riparian zone)	Brunel et al., 1995
F (aeolian sand dune) F (mediterranean)	Dawson and Pate, 1996
Field conditions (subtropical) F (semi-arid)	McCole and Stern, 2007 Goebel et al., 2015
	Multi-source mixing model
F (cornfield, prairie, oak savanna, and woodland) F (warm temperate / monsoon climate)	Asbjornsen et al., 2007 Wang et al., 2010
F (desert) F (temperate)	Huang and Zhang, 2015 Prechsl et al., 2015
F (temperate)	Volkmann et al., 2016

Plant species
*Hyparrhenia diplandra, Andropogon schirensis, Imperata cylindrica (*grasses*), Cussonia barteri, Crossopteryx febrifuga, Bridelia ferruginea (*shrubs*)*
Eucalyptus largiflorens, camaldulensis, Acer negundo and *grandidentatum, Atriplex canescens, Chrysothamnus, nauseosus, Vanclevea stylosa*
Quercus emoryi Torr., Trachypogon montufari (H.B.K.) Nees. (deciduous) *Qualea grandiflora Mart., Q. parviflora Mart., Kielmeyera coriacea (Spr.) Mart., Pterodon pubescens Benth., Dalbergia myscolobium Benth. / (*evergreen*) Didymopanax macrocarpum, Sclerolobium paniculatum, Miconia ferruginata, Roupala montana*
*(*invasive*) Solanum crinitum Lamb. (*native*) Panicum maximum Jacq.*
Sarcobatus vermiculatus, Chrysothamnus nauseosus, and *Chrysothamnus greenei*
*(*invasive*) Centaurea diffusa, (*native*) Pseudoroegneria spicata; Bromus tectorum L.*
Larix sibirica
*Summer corn and cotton (*species not specified*)*
tropical rainforest trees
Taxodium distichum / Pinus strobus
Acer grandidentatum Nutt., A negundo L., Quercus gambelii Nutt.
"Mallee Tree" *(Eucalyptus sp.)*
*Banksia prionotes, Dryandra sessilis, Grevillea (*species unknown*)*
Juniperus ashei
Gossypium hirsutum L.
Quercus macrocarpa, Umus americana L. (trees), Zea mays L. (crop), and *Andropogon gerardii (grass)*
Summer corn and cotton (species not specified)
Caragana korshinskii and *Artemisia ordosica*
Phleum pratense, Lolium multiflorum, Poa pratensis, Taraxacum officinale, Trifolium repens, Rumex obtusifolius, Trisetum flavescens, Phleum rhaeticum, Carum carvi, and *Achillea millefolium, Rumex alpestris, Taraxacum officinale and Trifolium, pratense.* *Quercus petraea* and *Fagus sylvatica*

SAMPLES FOR ISOTOPIC MEASUREMENTS **Soil profile (soil depth: SD [m] / increment: I [m] / number of profiles: Nps / Replicates)**	**Roots profile (soil depth: SD [m] / increment: I [m] / number of profiles: Npr)**
0.10 < SD < 2.00 / 0.01 < I < 0.10 / R = 3	SD = 1.80 / I = 0.10 / R = 16
No profiles, but soil directly surrounding roots are sampled SD = 1.50 / I = 0.05 / 3 < R < 4	No profiles, but single roots sampled after excavation none
SD = 5.00 (depending on the site) R = 2 / 0.05 < I < 0.20	none
4 < SD < 6 / 0.05 < I < 2.00	SD = 4 / 0.25 < I < 0.50 / R = 3
(1^{st} campaign) SD = 0.6 / I = 0.10 / R= 2 at each site / 4 < Nps (per site) < 6 / (2^{nd} campaign) SD = 2.1 / 0.2 < I < 0.30 / Nps = 10	none (reference made to Cooper and Chimner, unpublished data)
1.05 < SD < 2.20 / 0.10 < I < 0.60	1.20 < SD < 2.20 / I = 0.15
SD = 1.00 / 0.05 < I < 0.30	none
SD = 1.50 / 0.05 < I < 0.30 / Nps = 7	none
SD = 2.00 / 0.20 < I < 0.30 / R = 6	none (reference made to other literature)
none	none
SD = 0.50	none
50 < SD < 4.2 / 0.10 < I < 0.25	none
none (sand around the root system)	none (qualitative observation)
SD = 0.30 / 0.05 < I < 0.10 / 4 < Nps (per site) < 5	none (reference made to other literature)
SD = 0.3 / I ~ 0.02 / Nps = 4 per irrigation treatment	none
1.40 < SD < 2.00 / 0.05 < I < 0.20 / R=2 per site	none
SD = 1.50 / 0.05 < I < 0.30 / Nps = 7	none
SD = 2.00 / 0.05 < I < 0.50	none
0.30 < SD < 0.40 / 0.04 < I < 0.10 / R = 3	SD = 0.30 / 0.075 < I < 0.125 / 6 < Npr < 7
SD = 0.60 / 0.05 < I < 0.10 / Nps > 17	SD = 0.60 / 0.05 < I < 0.10 / R = 4

Natural Abundance: NAb / labelling Experiment: LE	Water extraction method (cryogenic vacuum distillation: Cr / azeotropic distillation Az / direct equilibration: GI / mild vacuum distiilation: Mi)	Plant (organ: O / number of samples: Ns / replicates: R / temporal resolution: TR [hrs])
Nab	Cr	O: sapwood trunks (shrub), Crown (grasses) / 8 < Ns < 24 / 0.5 < TR < 1
Nab	Cr / Az	O: non-green, suberised stems / Ns = 3
Nab	Cr	O: stem with phloem tissue / R = 4 (tree and sapling) / O: stem without green tissue / R = 4 (seedling) / O: culm base with sheaths removed / 3 < R < 4
Nab	Cr	O: wood or suberized, mature, stem segments (outer bark and phloem are removed) / R =2
LE	Cr	O: well suberized stems (trees) / thick fleshy culms covered with dry leaves (grass) / 3 < R < 5
Nab	Cr	O: fully suberized stem sections from the base of plants / (1st campaign, S. Vermiculatus) 4 < Ns (per site) < 8 / R =3 / (1st campaign, C. nauseosus) 5 < Ns (per site) < 6 / R = 3 / (2nd campaign) 3 < Ns < 5 (depending on the species)
Nab	Cr	O: stem
Nab	Cr	O: stem / Ns (per sampling date) = 5
Nab	Cr	O: stems (epidermis contacted with air was removed) / Ns = 7 / TR = 1 per vegetation stage
LE	Cr	O: branch (length = 0.07 m; diameter = 0.1 – 0.3 m). Bark tissue is immediately removed
Nab	none (Sap flow water)	O: wood samples taken at breast height
Nab	Cr	O: mature suberized stems
Nab	Az	O: twigs (bark is removed) / R = 2
Nab	Mi	O: roots, trunks, stem base
Nab	Cr	O: stem
Nab	Cr	O: meristematic petiole reduced in size to 5mm. / 14 < Ns < 17 (depending on the irragtion treatment) / R = 2 / TR = 1
Nab	Di	O: stem (trees); aerial nodal roots just above the soil surface (Zea mays L.); stem (grass) / Ns = 2 per specie
Nab	Cr	O: stems (epidermis contacted with air was removed) / Ns = 7 / TR = 1 per vegetation stage
Nab	Cr	O: twigs (1–2 cm of stem with bark immediately removed) / R = 3
NAb	Cr	O: root crown / 2 < Ns < 10
LE	none	none (measurement of transpiration isotopic composition)

Single: S / Dual: D / "Double Single": DS" isotope approach
S ($\delta^{18}O$)
S ($\delta^{2}H$)
D
S ($\delta^{2}H$)
S ($\delta^{2}H$)
S ($\delta^{18}O$)
DS
DS
DS
D
S ($\delta^{2}H$)
S ($\delta^{2}H$)
D
S ($\delta^{2}H$)
S ($\delta^{18}O$)
S ($\delta^{18}O$)
S ($\delta^{18}O$)
DS
DS
DS
S ($\delta^{2}H$)

Main results (RWU depth: z_{RWU} [m] / soil depth z [m] / fraction of *transpiration*: x / Source: So)

$0.00 < z_{RWU} < 0.05$ (grasses, early morning) / $0.05 < z_{RWU} < 0.10$ (grasses, midday) / $z_{RWU} = 0.30$ or $z_{RWU} > 1.50$ (shrubs, no unique solution)

Dominant source: groundwater (Mountain and floodplain) / $0.3 < z_{RWU} < 0.4$ (cold desert)

$z_{RWU} > 0.50$ (trees and sapling) / $z_{RWU} < 0.15$ (2-months-old seedling) / $0.20 < z_{RWU} < 0.35$ (1- and 2-year-old seedlings and grasses)

$z_{RWU} < 2.00$ (four evergreen and one deciduous species) / $z_{RWU} > 2.00$ (three deciduous and one evergreen species)

Fraction of root water uptake from the labeled region $x = 0.20$ (Solanum crinitum Lamb.) $z_{RWU} < 1.00$ (P. maximum Jacq.)

$0.00 < z_{RWU} < 0.50$ (C. nauseosus, pre-monsoon and monsoon periods) / (S. vermiculatus and C. nauseosus) dominant source: groundwater (pre-monsoon period) and switched to precipitation recharged water ($0.30 < z_{RWU} < 0.40$, during mansoon).

$z_{RWU} = 0.15$ (Bromus tectorum L., early season) / $z_{RWU} = 1.20$ (Centaurea diffusa Lam, late season)

$0.10 < z_{RWU} < 0.40$ from $\delta^{18}O$ meas / $0 < z_{RWU} < 0.80$ from $\delta^{2}H$ meas
$z_{RWU} = 0.10$ (Corn, jointing stage) / $z_{RWU} = 0.50$ (Corn, flowering stage) /

$z_{RWU} = 0.10$ (Corn, full ripe stage) / $z_{RWU} = 0.40$ (Cotton, seedling stage) / $z_{RWU} = 0.50$ (Cotton, bud stage) / $z_{RWU} = 1.10$ (Cotton, bolls open stage)

$z_{RWU} > 1.00$ (dry periods, tall trees) / More diffuse z_{RWU} for shorter trees

Groundwater: $0.46 < x < 0.64$ wet site) / $0.16 < x < 0.25$ (intermediate site)

So: Groundwater (streamside mature trees) / So: stream water (younger streamside trees) / So: Precipitation (younger non-streamside trees)

$0 < z_{RWU} < 0.4$ with $0.7 < x < 0.9$ (1st site) / $0 < z_{RWU} < 1.5$ with $x = 0.07$ (2nd site)

So: deeper soil layers (dry season) / So: shallow soil layers (wet season)

$z_{RWU} > 0.30$ m (hot, dry summer) / $0.10 < z_{RWU} < 0.30$

Evidence for shifting to rainwater predominantly

$0.0 < z_{RWU} < 0.20$ m with $x < 45\%$ and $x < 36\%$ (crop and grass, resp.) / $0.00 < z_{RWU} < 0.20$ m with $x < 40\%$ and $x < 20\%$ and $z_{RWU} > 0.60$ m with $x < 60\%$ and $x < 80\%$ (Q. macrocarpa and U. americana L., resp.)

$0 < z_{RWU} < 0.20$ with $96 < x < 99$ (Corn, jointing stage) / $0.20 < z_{RWU} < 0.50$ cm with $58 < x < 85$ (Corn, flowering stage), $0.00 < z_{RWU} < 0.20$ with $69 < x < 76$ (Corn, full ripe stage) // $0.00 < z_{RWU} < 0.20$ with $27 < x < 49$ (Cotton, seedling stage), $0.20 < z_{RWU} < 0.50$ cm with $79 < x < 84$ (Cotton, bud stage) / $0.50 < z_{RWU} < 0.90$ with $30 < x < 92$ (Cotton, blooming stage) / $z_{RWU} > 90$ cm with $69 < x < 92$ (Cotton, boll open stage)

$0.1 < z_{RWU} < 1.0$ (wet seasons) / z_{RWU} not affected by small rainfall events / $z_{RWU} > 1.00$ with x observed to increase from 2 (± 0.7) to 10 (± 1.4)% for both plants after large rainfall event.

$0 < z_{RWU} < 0.10$ with $0.43 < x < 0.68$ (Drought treatment) / $0 < z_{RWU} < 0.10$ with $0.04 < x < 0.37$ and $0.20 < z_{RWU} < 0.35$ with $0.29 < x < 0.48$ (control treatment)

constant RWU depth profile with $0.15 < x < 0.18$ (beech) / $x < 0.15$ for $z < 0.20$ and $0.15 < x < 0.25$ for $z > 0.30$ (beech/oak mixture and oak monoculture)

Deleted:

Table 2

SOIL DATA	Shallow groundwater table (Sh)						Deep groundwater table (De)						*RLD* (cm cm^{-3})
z (m)	Dry surface conditions (ShDr)			Wet surface conditions (ShWe)			Dry surface conditions (DeDr)			Wet surface conditions (DeWe)			
	θ (cm^3 cm^{-3})	H_S (cm)	δ_S (‰)	θ (cm^3 cm^{-3})	H_S (cm)	δ_S (‰)	θ (cm^3 cm^{-3})	H_S (cm)	δ_S (‰)	θ (cm^3 cm^{-3})	H_S (cm)	δ_S (‰)	
-0.01	0.235	-454	5	0.372	-2	-7	0.044	-9875	11	0.372	-51	-5	6.0
-0.03	0.325	-267	3	0.372	-8	-6	0.055	-3581	7	0.371	-77	-5,5	3.0
-0.07	0.347	-215	1	0.372	-11	-5	0.081	-1661	1	0.372	-14	-7	2.0
-0.15	0.360	-179	-4	0.372	-70	-6	0.105	-1165	-3,5	0.135	-869	-3,5	0.8
-0.30	0.367	-155	-6	0.370	-125	-6,5	0.122	-989	-4	0.134	-889	-4	0.5
-0.50	0.371	-135	-7	0.371	-135	-7	0.165	-730	-5	0.165	-730	-5	0.4
-1.00	0.372	-125	-7	0.372	-125	-7	0.210	-620	-6	0.210	-620	-6	0.3
-2.00	0.372	-125	-7	0.372	-15	-7	0.259	-600	-7	0.259	-600	-7	0.2
PLANT DATA	T (mm h^{-1})	H_L (cm)		T (mm h^{-1})	H_L (cm)		T (mm h^{-1})	H_L (cm)		T (mm h^{-1})	H_L (cm)		
lT	0.01	-587		0.01	-491		0.01	-2347		0.01	-918		
hT	0.30	-12330		0.30	-12234		0.30	-14090		0.30	-12661		

Table 2: Soil, plant, and isotopic synthetic input data for the different modelling approaches (depth (*z*) profiles of soil water content θ, total soil water potential H_S, soil water oxygen isotopic composition δ_S, root length density *RLD*, transpiration rate *T*, and leaf water potential H_L) "collected" during eight virtual experiments differing in the depth of the groundwater table (Shallow –Sh / Deep – De) and the water status at the soil surface (Dry – Dr / Wet – We).

Table 3

Soil layer (m)	Shallow groundwater table (Sh)							
	Dry surface conditions (ShDr)				Wet surface conditions (ShWe)			
	Low *T* (ShDr_lT)		High *T* (ShDr_hT)		Low *T* (ShWe_lT)		High *T* (ShWe_hT)	
	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)
0-0.02	1(0-35)	5(1)	6(0-37)	11(1)	18(0-48)	13(1)	16(0-53)	11 (1)
0.02-0.05	1(0-35)	7(1)	5(0-38)	9(1)	13 (0-42)	10 (1)	7 (0-43)	9(1)
0.05-0.11	3(0-41)	11(1)	10(0-48)	11(1)	11(0-41)	13(1)	7 (0-41)	11 (1)
0.11-0.225	15(0-57)	10(1)	14(0-47)	10(1)	11 (0-46)	10(1)	3 (0-43)	10(1)
0.225-0.4	19(0-57)	11(0)	16(0-55)	10(0)	16(0-53)	9(0)	16 (0-49)	10(0)
0.4-0.75	16(0-55)	16(0)	17(0-48)	14 (0)	18(0-44)	13(1)	15 (0-48)	14 (0)
0.75-1.5	17(0-52)	27(2)	18(0-46)	23 (2)	16(0-48)	21(2)	16 (0-53)	23(2)
1.5-2	17(0-59)	14(2)	17(0-47)	12(2)	15 (0-52)	11(2)	16(0-51)	12(2)

Soil layer (m)	Deep groundwater table (De)							
	Dry surface conditions (DeDr)				Wet surface conditions (DeWe)			
	Low *T* (DeDr_lT)		High *T* (DeDr_hT)		Low *T* (DeWe_lT)		High *T* (DeWe_hT)	
	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)	x_{SIAR} mfv(range) (%)	x_{Couv} (1sd) (%)
0-0.02	1(0-42)	-170(16)	1(0-41)	5(1)	2(0-49)	24(2)	10(0-52)	12(1)
0.02-0.05	1(0-42)	-17(1)	2(0-45)	8(1)	17(0-55)	18 (2)	13(0-54)	9(1)
0.05-0.11	1(0-44)	19(6)	5(0-47)	12(1)	16 (0-58)	21(2)	16(0-51)	12(1)
0.11-0.225	3(0-55)	28(5)	11(0-51)	10 (1)	1(0-39)	3(0)	12(0-43)	12(1)
0.225-0.4	7(0-75)	33 (4)	17(0-51)	11(0)	0,8(0-38)	1 (0)	9(0-38)	10(0)
0.4-0.75	15(0-68)	57 (3)	17(0-56)	16(0)	5(0-46)	7(1)	15(0-53)	14 (0)
0.75-1.5	16(0-74)	98(1)	16(0-54)	26(2)	16 (0-51)	17(2)	16(0-45)	23(2)
1.5-2	17(0-76)	51 (4)	18(0-53)	13 (2)	18(0-53)	9 (2)	16(0-46)	12(2)

Table 3: Most frequent value (mfv) and range of the density distribution curve of the relative contribution to transpiration across eight defined soil layers as determined by the Bayesian method of Parnell et al. (2010) (x_{SIAR}, %) and mean relative contribution (with standard deviation) provided by the analytical model of Couvreur et al. (2012) (x_{Couv}, %). Profiles of relative contribution were computed for eight soil-plant virtual experiments differing in the depth of the groundwater table (shallow – Sh / deep –De), the soil surface water status (dry – Dr / wet – We), and the plant transpiration rate (low – lT / high – hT).

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FIGURES

Figure 1

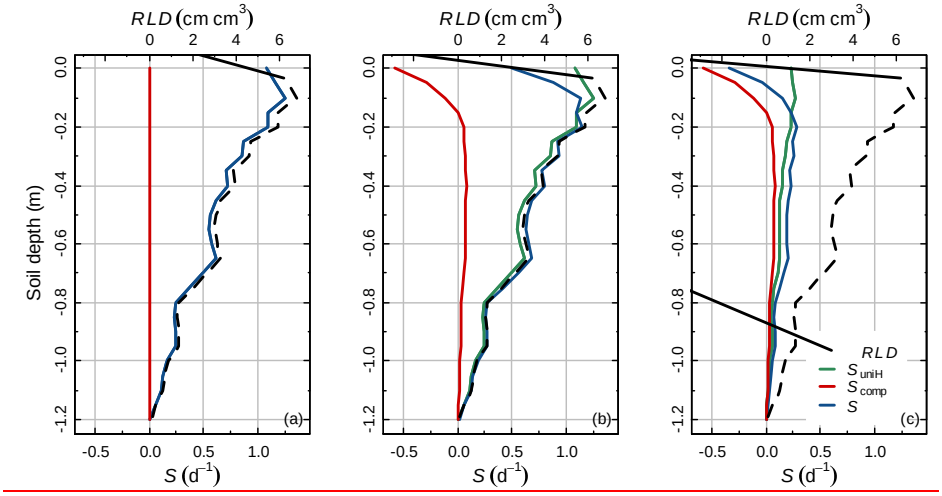

Figure 1: Some examples of root water uptake sink term (S, in d^{-1}) profiles (blue lines) conceptualized as the sum of S_{uniH} (green lines), the root water uptake term proportional to root length density RLD (dotted black line) and the compensatory root water uptake (S_{comp}, red lines). (a) $S_{comp} = 0$ (no root compensation) leading to $S = S_{uniH}$. (b) $S_{comp} \neq 0$ and becomes negative towards the surface but remains smaller (in absolute term) than S_{uniH}. (c) $S_{comp} \neq 0$ and is negative at the surface while is greater than S_{uniH} for $z > -0.08$ m. In the last case, S is negative at the surface, meaning hydraulic lift is observed.

Figure 2

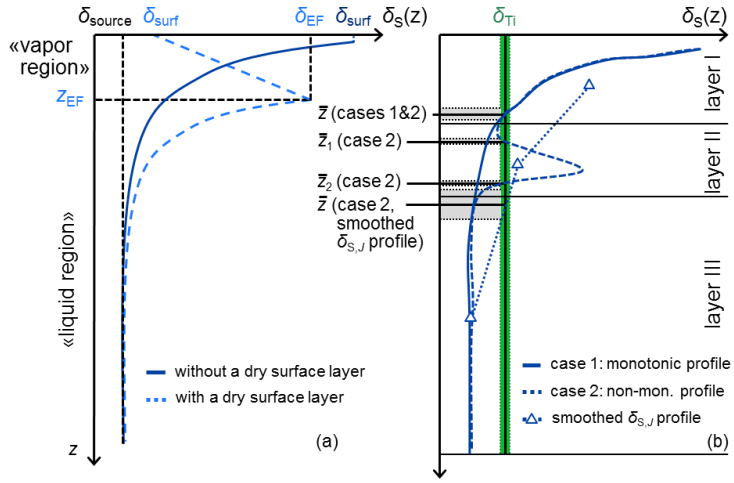

Figure 2: (a) Simulated soil water isotopic composition (δ_S) profiles for a water saturated (dark blue line) and unsaturated (light blue dotted line) soil following Barnes and Allison (1983). Indices "surf" and "EF" refer to soil surface and Evaporation Front. "vapor" and "liquid" regions refer to soil regions where water flow occurs predominantly in the liquid and vapor phase, respectively. (b) Illustration of the "graphical inference" method for determining the "mean root water uptake depth" ($\bar{z}$). "Ti" stands for the sap xylem water at the plant tiller. Case 1: one unique solution is found; case 2: more than one solution is found. Smoothed profile is designated by the symbols). $\bar{z}$ range is indicated by the gray horizontal stripes.

Figure 3

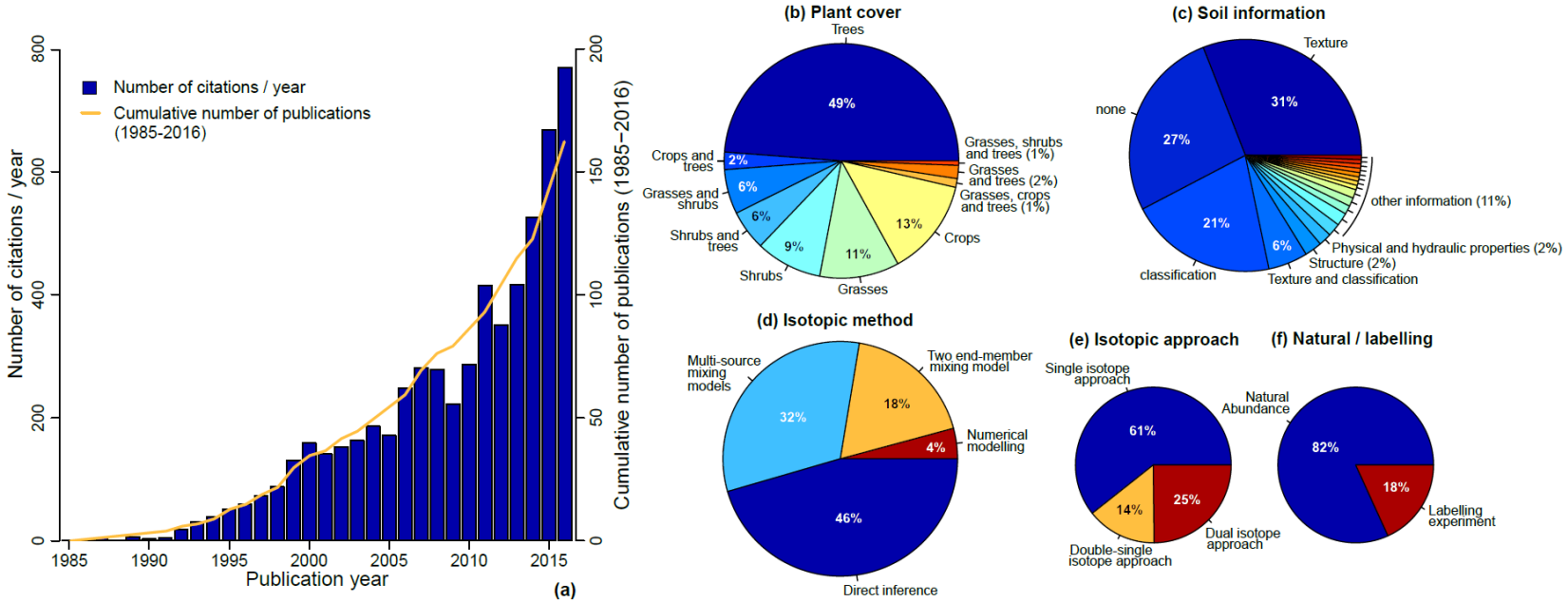

Figure 3: Evolution of the number of citations per year and cumulative number of publications from 1985 to 2016 (a). Details are given on the plant cover (b), the available soil information (c), the applied isotopic method (d) and approach (e), and the type of experiment (f).

Figure 4

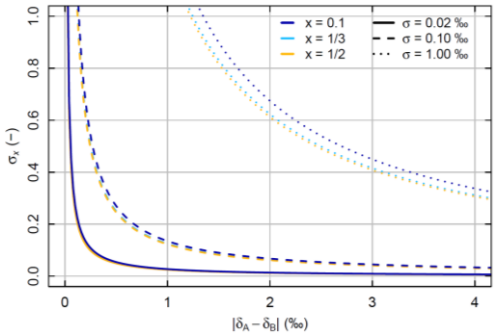

Figure 4: Standard error (σ_x) associated with the estimation of the relative contribution (x) of source A water to root water uptake in case of two distinct sources (A and B of isotopic compositions δ_A and δ_B). Three x values (0.1, dark blue color; 1/3, light blue; ½, orange) and three values of standard errors associated with sampling and measurement of δ_A, δ_B, and of the isotopic composition of the tiller sap water (δ_{Ti}) (0.02, solid line; 0.10 and 1.00, dashed lines) are tested.

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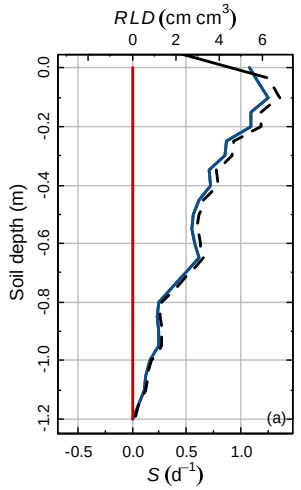

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Figure 1: Some examples of root water uptake sink term (S, in d^{-1}) profiles (blue lines) conceptualized as the sum of S_{uniH} (green lines), the root water uptake term proportional to root length density *RLD* (dotted black line) and the compensatory root water uptake (S_{comp}, red lines). (a) $S_{comp} = 0$ (no root compensation) leading to $S = S_{uniH}$. (b) $S_{comp} \neq 0$ and becomes negative towards the surface but remains smaller (in absolute term) than S_{uniH}. (c) $S_{comp} \neq 0$ and is negative at the surface while is greater than S_{uniH} for z > –0.08 m. In the last case, S is negative at the surface, meaning hydraulic lift is observed.

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Figure 2¶

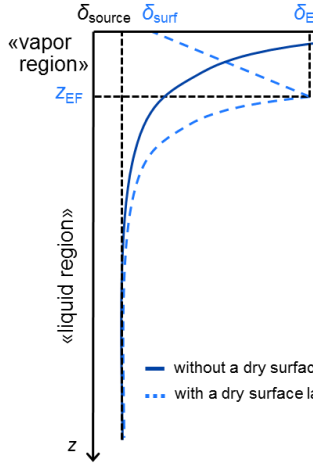

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Figure 2: (a) Simulated soil water isotopic composition (δ_S) profiles for a ...

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Figure 5

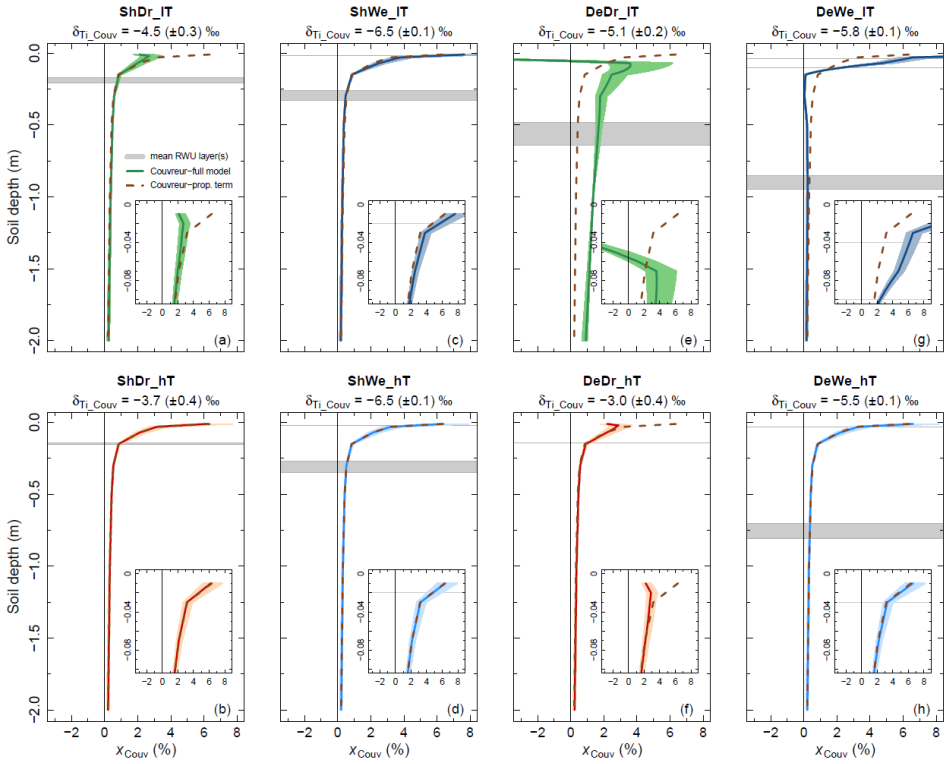

Figure 5: Simulated depth (z, in m) profiles of x_{Couv} (%) (solid colored lines), the simulated relative contributions to transpiration provided by the model of Couvreur et al. (2012) for experiments "ShDr" (soil with shallow groundwater table and relatively dry soil surface), "ShWe" (soil with shallow groundwater table after a rainfall event)", "DeDr" (soil with deep groundwater table with relatively dry soil surface), "DeWe" (soil with deep groundwater table and wet soil surface). Suffices "lT" and "hT" refer to "low" and "high" transpiration rate simulations. The color-shaded areas depict the uncertainty of the model estimates on the account of the precision of the measurements. The horizontal gray-shaded areas delimit the mean root water uptake layer(s) obtained by the "graphical inference" method. At the bottom right corner of each plot is a detail presented for $z \geq -0.10$ m. Finally, results from the first term of the model of Couvreur et al. (2012) which considers uptake proportional to root length density is plotted as a dashed brown line for comparison. Note that negative x_{Couv} means hydraulic redistribution by the roots.

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Figure 6

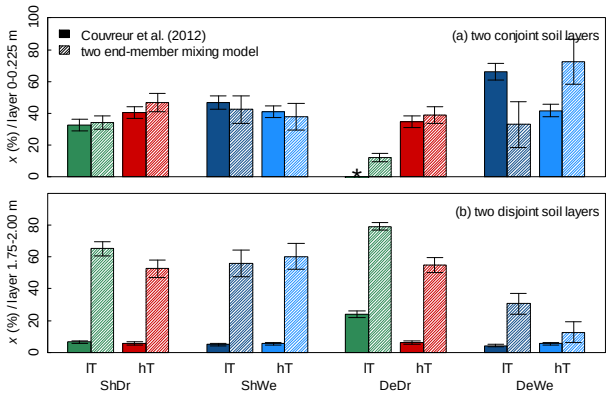

Figure 6: Comparison between relative contributions to transpiration (*x*, in %) simulated by the analytical RWU model of Couvreur et al. (2012) and the two end-member mixing model in case of two defined soil layers. Figure 5a displays *x* from the topmost soil layer (0 – 0.225 m) in case of a two conjoint soil layers (0 – 0.225 m and 0.225 – 2.00 m) whereas Figure 5b displays *x* from the lowest soil layer (1.75 – 2.00 m) in case of a two disjoint soil layers (0 – 0.225 m and 0.225 – 2.00 m), i.e., information on soil water isotopic composition is lacking between 0.225 and 1.75 m. "Sh" ("De") stands for the virtual experiments where the soil has a shallow (deep) groundwater table while "Dr" and "We" stand for when the soil is dry or wet at the surface. Suffices "lT" and "hT" refer to "low" and "high" transpiration rate simulations. "*" refers to when hydraulic redistribution is simulated by the analytical model, leading to a negative *x*. Error bars are either one standard deviation (for the RWU analytical model) or one standard error (for the TM approach).

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Figure 7

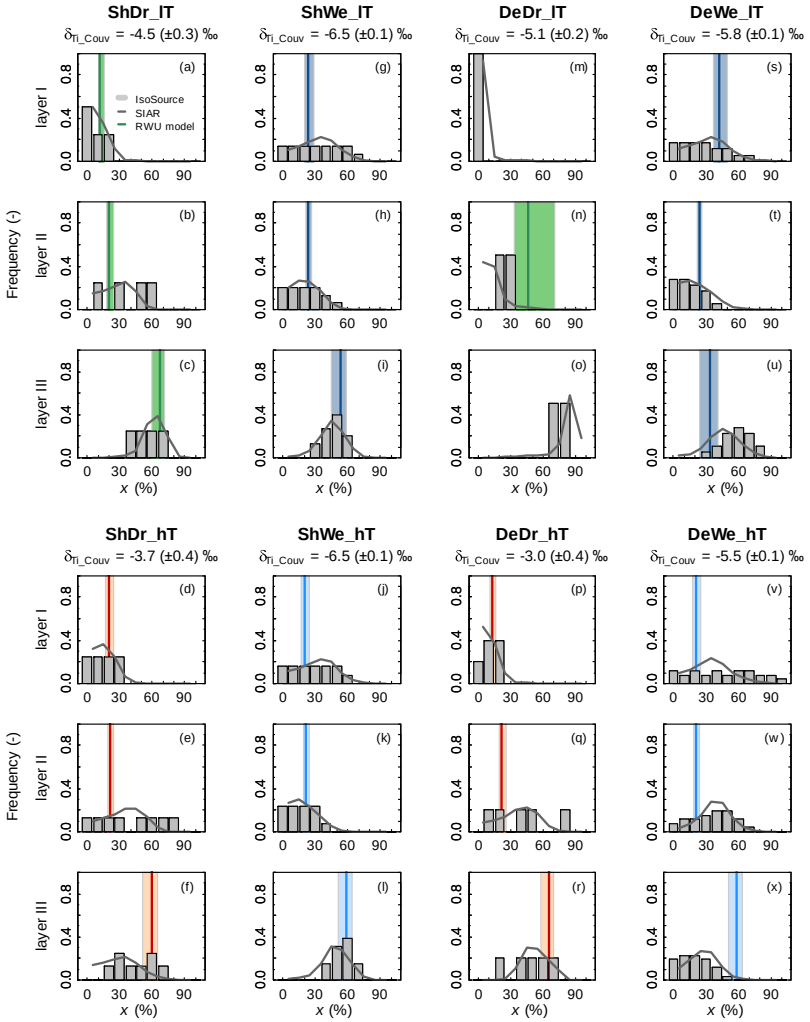

Figure 7: Simulated ranges of possible relative contributions to transpiration from three defined soil layers (I: 0.00 – 0.05 m, II: 0.050 – 0.225 m, and III: 0.225 – 2.000) provided by the multi-source mixing model IsoSource (Phillips and Gregg, 2003) (displayed in the form of gray histograms). Density distribution functions following the Bayesian model SIAR (Parnell et al., 2010) (gray lines). "Sh" ("De") stands for the virtual experiments where the soil has a shallow (deep) groundwater table while "Dr" and "We" stand for when the soil is dry or wet at the surface. Suffices "lT" and "hT" refer to "low" and "high" transpiration rate simulations. The colored vertical lines give x_{I_Couv}, x_{II_Couv}, and x_{III_Couv}, the relative contributions to transpiration from layers I, II, and III simulated by the analytical model of Couvreur et al. (2012). The color-shaded areas associated with x_{I_Couv}, x_{II_Couv}, and x_{III_Couv} refer to their uncertainty associated with input data uncertainty.

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APPENDIX

Appendix A: List of symbols

Symbol	Description	Dimension	Equation number	Measured (m) / simulated (s) / prescribed (p)
C, C_S, C_A, C_B, C_{Ti}	Water stable isotopic concentration, soil water stable isotopic concentration, sources A and B water stable isotopic concentrations, xylem sap water isotopic concentration, root water uptake isotopic concentration	$M\ L^{-3}$	2, 3, 6a, 6b	m s
E, E_i	Evaporation rate for $^1H_2{}^{16}O$ isotopologue, Evaporation rate for $^1H^2H^{16}O$ or $^1H_2{}^{18}O$ isotopologue	$L^3\ T^{-1}$	B1-B4	m/s
h	Matric head	L		m
H_{eq}, H_L, H_S	Soil water equivalent and leaf water potentials, total soil water potential	P		m
J_A, J_B, J_{Ti}	Fluxes of water originating from water sources A and B, and at the plan tiller	$L^3\ T^{-1}$	6b	m
J^i_A, J^i_B, and J^i_{Ti}	Fluxes of isotopologues originating from water sources A and B, and at the plan tiller	$M\ T^{-1}$	6a	m
K_{plant}, K_{comp}	Plant and compensatory conductances to water flow	$L^3\ P^{-1}\ T^{-1}$	B1-B4	m/p
M_w, M_i	Molar masses of water and isotopologue ($^1H^2H^{16}O$ or $^1H_2{}^{18}O$)	$M\ L^{-3}$	3	m
RLD RLD_{1D}	Root length density Root length density per unit of surface area	$L\ L^{-3}$ $L\ L^{-1}$	B3	m/p m/p
R_{ref}	Vienna-Standard Mean Ocean Water (V-SMOW) hydrogen or oxygen stable isotopic ratio	-	3	m
S, S_{uniH}, S_{comp},	Total root water uptake sink term as simulated by the analytical model of Couvreur et al. (2012), Root water uptake sink term under uniform soil water potential distribution, compensatory root water uptake sink term.	$L^3\ L^{-3}\ T^{-1}$	1-4, 6b, B4,B5, 6b	s
SSF	Standard sink fraction	-	B2, B4, B4'	m/p
t, Δt	Time, time step	T	11	m
T	Transpiration flux	$L^3\ T^{-1}$	2, 4a, 4b, B1, B3, B4	m
x, x_j x_{Couv}, x_{J_Couv}, x_{J_IsoS}, x_{J_SIAR}	Contributive proportion to transpiration, source j contributive proportion to transpiration, continuous and integrated (layer J) contributive proportions to transpiration as simulated by the analytical model of Couvreur et al. (2012), integrated (layer J) contributive proportions to transpiration as determined by the IsoSource and SIAR models of Phillips and Gregg (2003) and Parnell et al. (2010). Contributive proportion to transpiration under conditions of uniform soil water potential	-	7, 8b, 9, 9'	s
z, z_j, z_{j+1}, Δz_j, z_{max}, $\bar{z}_{RWU}$	Soil depth, soil depth of layers j and j+1, thickness of soil layer j, depth of the root system, "mean root water uptake depth"	L	4b, 5, B2-B4'	m/p

δ, $\delta^{2}H$, $\delta^{18}O$, δ_{source}, δ_{surf}, δ_{S}, $\delta_{S,j}$, $\delta_{S,J}$, δ_{A}, δ_{B}, δ_{Ti}, $\delta_{Ti,m}$, δ_{Ti_Couv}, δ_{E}	Water stable isotopic composition, water hydrogen and oxygen stable isotopic compositions, source, soil surface, soil water, soil layer *j and J* water isotopic composition, sources A and B water stable isotopic compositions, isotopic composition of xylem sap water at the plant tiller, isotopic composition of xylem sap water measured at the plant tiller, isotopic composition of xylem sap water at the plant tiller as simulated by the model of Couvreur et al. (2012)	- (expressed in ‰)	3-5, 7-9, 11		m/s
ε_j	Residual error term	- (expressed in ‰)	9’		s
θ	Soil volumetric water content	$L^3\ L^{-3}$	5, 11		m
ρ	Volumetric mass of water	$M\ L^{-3}$	3		m
$\sigma_x, \sigma_{\delta_A}, \sigma_{\delta_B}, \sigma_{\delta_{Ti}}$ $\sigma_{\delta_{Ti\_AM}}, \sigma_x$	Sandard errors associated with the measurements of x, δ_A, δ_B, δ_{Ti} and estimated uncertainty of δ_{Ti_Couv} as simulated by the analytical model of Couvreur et al. (2012), error associated with the estimation of the contributive proportion to T of water source A in the case of two distinct sources	- (expressed in ‰)	8a, 8b		s
τ	Isotopic tolerance	- (expressed in ‰)	10		p

Appendix B: The macroscopic RWU model of Couvreur et al. (2012)

B1: Presentation of the model

In the approach of Couvreur et al. (2012), RWU is based on physical equations describing the water flow processes but without the need of the full knowledge of the root system architecture and local hydraulic parameters. Instead, three macroscopic parameters are needed. The first equation defines plant transpiration:

$$J_{\mathrm{Ti}} = K_{\mathrm{plant}} \cdot \left(H_{\mathrm{eq}} - H_{\mathrm{L}}\right) \quad \text{(B1)}$$

where J_{Ti} [L^3 T^{-1}] is the sap flow rate in the root tiller and considered to be equal to the transpiration rate, K_{plant} [L^3 P^{-1} T^{-1}] is the plant conductance to water flow (the first macroscopic parameter of Couvreur et al., 2012's model). H_{L}[P] is the leaf water potential and H_{eq} [P] the "plant averaged soil water potential" defined as the mean soil water potential "sensed" by the plant root system in the one dimensional (vertical) space:

$$H_{\mathrm{eq}} = \int_z SSF(z) \cdot H_{\mathrm{S}}(z) \quad \text{(B2)}$$

where z is the soil depth, H_{S} [P] is the total soil water potential, and SSF [-] the standard sink term fraction (the second macroscopic parameter of the model of Couvreur et al., 2012). SSF is defined as the RWU fraction under the condition of totally uniform soil water potential (i.e., when $H_{\mathrm{S}}(x,y,z) = H_{\mathrm{S}}$ = cst). Under such conditions, if all the root segments had the same radial conductivity (and the xylem conductance would not be limiting), the RWU distribution in a uniform soil water potential profile would be exactly the same as the root length density per unit of surface area ($RLD_{1\mathrm{D}}$ of dimension [L L^{-1}]) profile. SSF could be defined as:

$$SSF(z) = \frac{S_{\mathrm{uniH}}(z)dz}{q_{\mathrm{Ti}}} \approx \frac{RLD_{1\mathrm{D}}(z) \cdot dz}{\int_z RLD_{1\mathrm{D}}(z) \cdot dz} \quad \text{(B3)}$$

where $q_{\mathrm{Ti}} = J_{\mathrm{Ti}}/(\Delta x \cdot \Delta y)$ represents the sap flow rate in the root tiller per unit surface area [L T^{-1}], S_{uniH} [T^{-1}] is the RWU sink term under uniform soil water potential profile. The RWU under conditions of heterogeneous soil water potential is described with the following equation:

$$S(z) = S_{\mathrm{uniH}}(z) + S_{\mathrm{comp}}(z) = q_{\mathrm{Ti}} \cdot SSF(z) + K_{\mathrm{comp}} \cdot \frac{\left(H_{\mathrm{s}}(z) - H_{\mathrm{eq}}\right) \cdot SSF(z)}{V(z)} \quad \text{(B4)}$$

where K_{comp} [L^3 P^{-1} T^{-1}] is the compensatory conductance and S_{comp} [L^3 T^{-1}] the compensatory RWU accounting for the non-uniform distribution of the soil water potential and V(z) is the volume of soil considered. If the soil water potential is uniform, this term vanishes from the equation, as $H_{\mathrm{S}} = H_{\mathrm{eq}}$ for any z, and water is extracted from the soil proportionally to RLD. When the water potential at a certain location is smaller (more negative, which means drier) than H_{eq}, less water is extracted from this location. On the other hand, when the soil is wetter (H_{S} less negative), a larger amount of water can be taken up from the same location as compared. Note that if $H_{\mathrm{S}} < H_{\mathrm{eq}}$ and if the compensatory term is higher than the first one, S can become positive, and water is released to the soil (i.e., hydraulic redistribution). From Eq. (B4), it can be concluded that hydraulic redistribution will preferably occur when q_{Ti} is small and when large soil water potential gradients exist. Plant root hydraulic characteristics will control compensation through the K_{comp} term. The importance of the compensatory RWU

term has been discussed in the literature for a long time (e.g., Jarvis, 1989). Except if plants activate specific mechanisms to avoid it, compensation always takes place under natural conditions due to the spatially heterogeneous distribution of soil water potential (Javaux et al., 2013).

A simplifying hypothesis that can be made (Couvreur et al., 2014; Couvreur et al., 2012) is to consider that K_{plant} and K_{comp} are equal, which substituted in Eq. (B4) leads to:

$$S(z) = SSF(z) \cdot K_{plant} \cdot (H_s(z) - H_L)/V(z) \quad \text{(B4')}$$

Finally, the uptake of water stable isotopologues, i.e., the "isotopic sink term" (S_i [M T^{-1}]) is defined as:

$$S_i(z) = S(z) \cdot C(z) \quad \text{(B5)}$$

where C [M L^{-3}] is the water isotopic concentration.

B2: Running the model for the inter-comparison

The root water uptake (S) depth profiles and corresponding δ_{Ti_Couv} were simulated using the model of Couvreur et al. (2012) (Eq. (B4')) for all eight scenarios. For this, H_S, δ_S, and *RLD* input data were interpolated at a 0.01 m vertical resolution and the resistance of the xylem vessels was assumed to be neglible so that $H_{Ti} = H_L$. A K_{plant} value of 2.47 10^{-6} h^{-1} was taken and was determined based on concomitant T, H_{eq} and H_L data measured for *Festuca arundinacea*. δ_{Ti_Couv} was then calculated from Eq. (4b) (section §2.3). From these simulations, the depth profiles of x_{Couv} (%), the ratio $\frac{S(z)dz}{T/(\Delta x \cdot \Delta y)}$ at each interpolated depth z was determined, and x_{J_Couv}, the ratio $\frac{S(z)dz}{T/(\Delta x \cdot \Delta y)}$ from each of the integrated soil layers J ($J \leq$ III or $J \leq$ VIII) were calculated. In order to account for uncertainty of the input data (i.e., total soil water potential and oxygen isotopic composition H_S and δ_S, and root length density *RLD*), the model was run a 1000 times where a single offset randomly selected between –5 and +5 cm, –0.2 and +0.2 ‰, and –0.1 and +0.1 cm cm^{-3} was added to the initial values (reported Table 2) of H_S, δ_S, and *RLD*, respectively. By doing this we obtained *a posteriori* distributions of S and corresponding δ_{Ti_Couv} standard deviations ($\sigma_{\delta_{Ti\_Couv}}$);

Appendix C: Inter-comparison methodology

The graphical inference method (GI), the two end-member mixing model (TM), and the multi-source mixing models IsoSource (Phillips and Gregg, 2003) and SIAR (Parnell et al., 2010) were compared to each-other in the following manner for each of the eight virtual experiments:

(i) Single (or multiple) mean RWU depth(s) ($\bar{z}$) were graphically identified following the GI method as the depth(s) of the intersection between a vertical line of value $\delta_{\text{Ti\_Couv}}$ with the δ_{S} profile. The uncertainty of method GI was determined on the basis of the $\delta_{\text{Ti\_Couv}}$ *a posteriori* distribution: by taking into account $\sigma_{\delta_{\text{Ti\_Couv}}}$, $\bar{z}$ results were translated into "RWU layers";

(ii) relative contribution of RWU to transpiration (x_{TM}, %) to two defined soil layers (either conjoint: 0 – 0.225 m and 0.225 – 2.00 m or disjoint: 0 – 0.225 m and 1.75 – 2.00 m) were determined using the TM approach. For this, representative values for the water oxygen isotopic compositions of these soil layers were computed using Eq. (5) which uses soil volumetric water content (θ, in $m^3\ m^{-3}$) as input data. θ distribution was obtained from H_{S} distribution and the van Genuchten (1980) closed-form equation. Values for its different parameters, i.e., the soil residual and saturated water contents (θ_{res} and θ_{sat}), and the shape parameters related to air entry potential and pore-size distribution (α and n) were equal to 0.040 and 0.372 $m^3\ m^{-3}$, 0.003 cm^{-1}, and 3.3, respectively;

(iii) Possible range of x_{J_IsoS}, the relative contribution of RWU to transpiration for each of the integrated soil layers following the IsoSource model was computed based on smoothed $\delta_{\text{S},J}$ profile and $\delta_{\text{Ti\_Couv}}$ by solving the following equation:

$$\sum_{J} x_{J\_\text{IsoS}} \cdot \delta_{\text{S},J} \leq \left| \delta_{\text{Ti\_Couv}} \pm t \right| \quad \text{(C1)}$$

with $\tau = \sigma_{\delta_{\text{Ti\_Couv}}}$.

$\delta_{\text{S},J}$ was computed similarly to for the TM method;

(iv) Density distribution of x_{J_SIAR}, the relative contribution of RWU to transpiration for each of the three (or eight) soil layers following the SIAR model was determined based on smoothed $\delta_{\text{S},J}$ profile and $\delta_{\text{Ti\_Couv}}$ data as well. To compare with the IsoSource model (i) the number of δ_{Ti} replicates was fixed to three and equal to $\delta_{\text{Ti\_Couv}} - \sigma_{\delta_{\text{Ti\_Couv}}}$, $\delta_{\text{Ti\_Couv}}$, and $\delta_{\text{Ti\_Couv}} + \sigma_{\delta_{RWU\_Couv}}$, and (ii) x_{J_SIAR} was computed at a 10% increment (*i*). No prior information on the relative contributions to *T* was used to run the model, i.e., we opted for flat priors;

(v) Results obtained at steps (i)-(iv) were compared to each other;

(vi) Sensitivity of IsoSource to the values of *i* and τ, and of SIAR to values of arguments *iterations* and *burnin* were finally briefly tested.

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