Identification of Source-water Oxygen isotopes in trees Toolkit (ISO-Tool) for deciphering historical water use by forest trees

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Key Points:

- A toolkit for determining the oxygen isotopic signature of historical source water to trees is presented.
- The parameterization of ISO-Tool is subdivided based on data availability and output resolution.
- The tool is designed to retrospectively assess water source usage by plants at annual and sub-annual timescales.

ABSTRACT

Hydrological regimes are being perturbed under climate change due to the regional expression of the water cycle across the globe, leading to alterations in the spatial and temporal distribution of water near the Earth's surface. Water is a critical resource for forest ecosystems and hydrological limitations on vegetative health are particularly complex. To anticipate how subsurface water availability may evolve in the future and affect the dynamics of plant water-source usage, as well as the health and functioning of vegetation in various biomes, we need a robust, quantitative framework for linking water availability to past plant water-use, which is constrained by historical data. Here, we outline the Identification of Source-water Oxygen isotopes in trees Toolkit (ISO-Tool), designed to retrospectively investigate the dynamics of tree-water uptake. ISO-Tool utilizes tree-ring isotopes ($\delta^{18}O$) combined with a biomechanistic fractionation model to predict the $\delta^{18}O$ of water utilized during any period of growth. Through comparisons with measured $\delta^{18}O$ in local water sources, climatic and hydrological variables, ISO-Tool can reconstruct and inform on past ecohydrological interactions. We provide an overview of the modeling components and data requirements necessary to constrain the retrodictions of source-water $\delta^{18}O$. We demonstrate the utility and efficacy of ISO-Tool for three riparian field sites characterized by differences in climatic, geomorphic and hydrologic complexity. However, ISO-Tool can be applied to a range of vegetated environments where distinct isotopic endmembers exist. We present a set of tool groups, which can be applied adaptively, ensuring that scientific progress in understanding retrospective ecohydrology can be made, even under varying degrees of data availability.

1 INTRODUCTION

1.1 Background

Forests worldwide are becoming increasingly vulnerable to variations in water availability as hydrological regimes respond to climate change (Allen et al., 2010, 2015; Choat et al., 2012; Clark et al., 2011; Hartmann et al., 2013). Yet, despite the fundamental role water plays in the health, productivity and distribution of tree species (Currie & Paquin, 1987; Hsiao, 1973; Schulze et al., 1987; Stephenson, 1990), there remain considerable uncertainties in how terrestrial water availability to forests will evolve under future climate (Allen & Ingram, 2002; Donat et al., 2016; IPCC, 2014; Sippel et al., 2017; Trenberth et al., 2014). Such shortcomings result from the incomplete characterization of moisture sources over a range of timescales, which is further complicated by the contribution of several potential sources to tree-available water. These sources include infiltrated precipitation in the vadose zone and shallow groundwater in the phreatic zone, where the latter can be derived from hyporheic streamflow contributions to shallow water tables (Busch et al., 1992; Evans et al., 2018; Singer et al., 2014; White & Smith, 2013). Therefore, for any interval of time, the particular water source used by a tree is a function of specific tree rooting depths as well as by the time-varying availability of root-zone water, which varies in response to climatic trends and fluctuations (Dawson & Pate, 1996; Snyder & Williams, 2000). The details surrounding these dynamic ecohydrological relationships are poorly understood, a knowledge gap which restricts our ability to anticipate how forests will respond to alterations in hydrological regimes that may affect one or both soil hydrological reservoirs (vadose and phreatic), particularly in regions where water is expected to become a limiting resource to tree growth (Bréda et al., 2006; García-Ruiz et al., 2011; Lindner et al., 2010).

To address this shortcoming, we take a retrospective approach and identify two fundamental questions: 1) What water source was used by a tree during a particular period of growth? 2) Does this water source utilization correspond to the dynamics of root-zone water availability? If these questions can be answered satisfactorily for a particular site, we believe this information on plant-water relationships could dramatically improve studies of ecohydrology, paleoclimate, and land surface dynamics within forest ecosystems.

Severe moisture deficits can reduce tree growth and biomass production (Berner et al., 2017; Charru et al., 2010; Sarris et al., 2011; Silva et al., 2010), increase the susceptibility to pathogen infestations and eventually lead to mortality from hydraulic failure and/or carbon starvation (Allen et al., 2010; Breshears et al., 2005; McDowell et al., 2011; Schlesinger et al., 2016). Through differential responses to moisture stress, individual tree and species' mortality rates can lead to altered stand demographics and composition, and thus ecosystem functioning (Clark et al., 2016; Hansen et al., 2001; Milad et al., 2011), whilst moisture limitations in the rooting zone may also determine whether particular tree species can get recruited and established at riparian sites (Mahoney & Rood, 1998; Singer & Dunne, 2004). These are key concerns, given the significant role trees play globally in carbon and water cycling (Bonan et al., 2008; Ciais et al., 2005; Ellison et al., 2017; Jasechko et al., 2013; Kurz et al., 2008; Settele et al., 2014) and in the provision of ecological services (Anderegg et al., 2013). Critically, forest vulnerability to drought conditions is not restricted to environments typically considered as moisture limited. Amazonian forest mortality was linked to drought conditions experienced in 2005 (Phillips et al., 2009) and 2010 (Lewis et al., 2011), with the later drought spanning 3.2 million km^2 (25 % greater than that of 2005). Furthermore, Chen et al., (2017) attributed trembling aspen die back in western Canadian boreal forests to insufficient water availability.

Retrospective insights into patterns of tree source water use (at seasonal and annual resolution) would be particularly useful for riparian zones, where phreatophytic forest species are highly dependent on the hydrological connectivity between the river and floodplain phreatic aquifer (Singer et al., 2014). Phreatophytes are sensitive to changes in shallow alluvial groundwater availability which can manifest as declines in healthy forest stands, reduced ecological services (Amoros & Bornette, 2002; Steiger et al., 2005; Stromberg et al., 2007) and shifts in the successional states of forest communities (e.g. Stromberg et al., 1996; Shafroth et al., 2000). Information about the timing and origin of tree source waters would also allow for accurate determinations of the ecohydrological impacts arising from river flow regulation practices (i.e. minimum flow requirements), river bed-level changes (e.g. gravel extraction / downstream of dam construction) and to identify critical thresholds for groundwater abstraction. Such information would promote more sustainable water management strategies in forests where water resources are also under increasing population pressures (Jackson et al., 2001).

We believe that a simple, yet effective, methodology for determining historical sources of water used by trees, would be highly valuable in improving scientific enquiry in isotopic ecohydrologic investigations. Such an approach would need to be well defined, easily accessible and adaptable.

In this paper, we build on existing research by combining and enhancing a set of techniques to identify historical water-sources ($\delta^{18}O_{sw}$) used by trees, based on information from tree-ring cellulose ($\delta^{18}O_{cell}$), plant physiology, hydroclimate and a biomechanistic fractionation model (Roden et al., 2000; Barbour et al., 2004). This is presented in the form of a methodological 'toolkit' called the Identification of Source water Oxygen isotope Toolkit (ISO-Tool), for which we identify and explain the necessary data requirements and provide examples of its application. We distill these requirements and data sources and present them in the form of a tiered 'Tool Group' scheme, to provide a means to straightforwardly reconstruct the historical source water signatures of trees at annual or sub-annual scales. Our goal here is not to necessary develop a method for highly accurate characterization of past water usage by plants, but rather to enable researchers to better ascertain likely water sources to plants for particular periods of time, to distinguish between plant water sources within sites for different species, and to identify how plant water sources may vary along hydroclimatic gradients.

1.2 Isotope echoydrology

Stable isotope ratios of oxygen and hydrogen in water ($\delta^{18}O$ and $\delta^{2}H$) have been used to trace the sources of waters used by plants through the comparison of the isotopic signatures of potential endmember sources (e.g. soil, groundwater, surface waters) with those of waters extracted from the xylem (e.g. Bertrand et al., 2014; Dawson & Ehleringer, 1991; Dawson & Pate, 1996; Horton et al., 2003; Jackson et al., 1999; Schulze et al., 1996; White et al., 1985). This is based on broad evidence that no isotopic fractionation occurs between the soil water pool and the plant during root uptake (Allison et al., 1983; White et al., 1985), although $\delta^{2}H$ fractionation has been reported in some halophytes and woody xerophytes (Ellsworth & Williams, 2007; Lin & Sternberg, 1993). This means that the water taken up by a tree retains isotopic information specific to its origin and history within the hydrological cycle at the point of uptake. Characterizing plant source waters via isotope analysis is particularly powerful if potential endmember water sources, e.g. precipitation (*P)* or groundwater (*GW*) are isotopically distinct and locally defined. This a fundamental principle when considering the use of $\delta^{18}O/\delta^{2}H$ for ecohydrological studies (Barbeta et al., 2018).

If combined measurements are made of $\delta^{18}O$ and $\delta^{2}H$ in xylem and potential endmember water sources, information relating to the evaporative history of the water (relative to local precipitation input) can be obtained, although such information is not necessary for identifying plant water sources (Sprenger et al., 2016).

Soil composition, texture and water status (e.g. Chen et al., 2017; Oshun et al., 2016; Vargas et al., 2017) have all been proposed causes of the fractionation of oxygen and hydrogen isotopes in plant-available water, prior to uptake, highlighting the need for careful consideration of these factors during investigations, as well as further research (for an overview, see Barbeta et al., 2018). Nevertheless, if such results are interpreted carefully, then stable isotope analyses remain a powerful method for understanding plant-water interactions. Herein, only $\delta^{18}O$ ecohydrology is discussed, since this isotope ratio functions as a better conservative tracer of water in ecosystems than $\delta^{2}H$ due to its higher mass and binding energy.

Commonly, the distinct hydrological reservoirs i.e. vadose (unsaturated) and phreatic (saturated) zones are characterized by differences in their water $\delta^{18}O$ content and water in these zones is preferentially used by different species (Singer et al., 2014). However, where potential source waters are isotopically similar, disentangling the water source use can be challenging (Drake & Franks, 2003).

Water in the vadose zone typically inherits an isotopic signature reflective of precipitation ($\delta^{18}O_{ppt}$) inputs (Robertson & Gazis, 2006) which varies seasonally as a function of temperature, air mass origin and history (Dansgaard, 1964; Gat, 1996). For temperate environments, this is exemplified by depleted and enriched $\delta^{18}O$ of precipitation in the winter and summer, respectively. The isotopic composition of soil moisture can also represent a time-varying mixture of isotopically separate precipitation events, which may also include the effects of near-surface evaporative enrichment, leading to the development of isotopic profiles in soil water with depth (Allison et al., 1983; Gazis & Feng, 2004; Hsieh et al., 1998; Sprenger et al., 2016).

In contrast, the $\delta^{18}O$ signature of phreatic water typically has low temporal variability, and it is often isotopically depleted in relation to vadose zone moisture, especially if *GW* is sourced from regional snowmelt runoff (colder percolated precipitation) (Gat, 1996) and/or is mixed with streamflow (*Q*) (Dawson & Ehleringer, 1991). However, there may be situations where isotopically distinct groundwaters contribute to a rooting zone. Sargeant and Singer (2016) suggested that isotopically dissimilar waters, derived from different climatic regimes, may interact within a shallow alluvial aquifer receiving both a regionally derived *GW* and water derived from locally infiltrated precipitation. A pragmatic approach would be to isotopically characterize the potential water sources within a field site, ensuring that isotopic separation of plant available waters is possible (Barbareta et al., 2018).

1.3 Source water availability

In environments where both vadose and shallow phreatic waters are available, tree species can employ different physiological strategies for obtaining water. Deeply rooted phreatophytic species prefer phreatic water sources derived from shallow aquifers (Busch et al., 1992) and capillary rise, yet may also exhibit opportunistic behavior, switching to shallow soil moisture (or using combination of both) under periods of water deficit (Singer et al. 2013, 2014; Snyder & Williams, 2000; Sun et al., 2016). Shallowly rooted species are unable to access deeper phreatic water, so they rely on vadose moisture which is sensitive to balance between precipitation inputs and near-surface evaporation, although it is possible that capillary rise during a period of elevated water table can supply phreatic water to the unsaturated zone (Sánchez-Pérez et al., 2008). Additionally, plant roots can redistribute water across a soil-water potential gradient (hydraulic redistribution), both vertically and laterally (Brooks et al., 2002; Caldwell et al., 1998; Richards & Caldwell, 1987), allowing water from different depths and distances to be utilized by neighboring plants (Dawson, 1993), and complicating source-water identification. Studies which provide detailed ecohydrological information are typically based on comparisons between the contemporaneous measurements of tree xylem waters with those of local water sources (e.g. Plamboeck et al., 1999; Sánchez-Pérez et al., 2008). Whilst direct analysis of xylem δ^{18}O circumvents the leaf fractionation and exchange mechanisms which mask the source water δ^{18}O information stored in $\delta^{18}O_{cell}$ (McCarroll & Loader, 2004), studies of this sort are limited by the temporal domain of field work (typically 2-3 years), restricting the development of broader conclusions about ecohydrological interactions (Pettit & Froend, 2018). Long-term, seasonal reconstructions of tree source-waters δ^{18}O could yield potentially powerful new information about water availability to trees, and thus hydrological processes, whilst also providing historical context for real-time investigations.

1.4 Tree-ring oxygen isotopes

In order to gain retrospective insights into plant-water interactions over longer timescales, tree-ring isotopes represent an under-utilized excellent library of accurately dated isotopic information on tree water usage. The oxygen isotope ratio ($^{18}O/^{16}O$) contained within tree-ring cellulose ($\delta^{18}O_{cell}$) can be used to characterize the isotopic signature of the source water(s) ($\delta^{18}O_{sw}$) used during the time of ring formation, thereby providing an extended record of ecohydrological processes (McCarroll & Loader, 2004). Tree-ring $\delta^{18}O$ fractionation theory is largely well established (McCarroll & Loader, 2004), although some uncertainties remain regarding the timing and transfer of photosynthates from source to sink tissues, which is relevant for finer scale studies (Gessler et al., 2009; Offerman et al., 2011; Ogée et al., 2009). Whilst there is the possibility for the remobilization of stored carbohydrates, formed at an early period, this more evident in $\delta^{13}C$ measurements than those of $\delta^{18}O$ in tree rings (Hill et al., 1995)

The $\delta^{18}O_{cell}$ records an integrated isotopic signal of three components: (a) the signatures of trees' source water taken up from the rooting zone; (b) leaf-water enrichment as a function of evaporation (Dongmann et al., 1974; Flanagan et al., 1991); and (c) the biochemical fractionation that occurs during photosynthesis (Sternberg et al., 1986; Yakir & DeNiro, 1990). A final mechanism during cellulose synthesis allows for a proportion of oxygen atoms in sucrose to exchange with $\delta^{18}O_{sw}$, damping the leaf-level fractionation effects (Farquhar et al., 1998; Hill et al., 1995; Roden et al., 2000). While there is a consistent enrichment (27 ± 4 ‰) of photosynthate $\delta^{18}O$, compared with leaf water ($\delta^{18}O_{lw}$), leaf water enrichment is much more variable responding to atmospheric conditions and leaf level gas exchange relating to species' physiology (McCarroll & Loader, 2004; Roden et al., 2000).

Studies utilizing tree-ring $\delta^{18}O_{cell}$ have been able to provide insights into historical water availability to trees, although use of the 'raw' $\delta^{18}O_{cell}$ to infer water source assumes that climatic variables and tree-physiological responses are uniform across a study site or between sites, and the relative differences measured in $\delta^{18}O_{cell}$ are therefore solely a function of $\delta^{18}O_{sw}$ differences. For example, Marshall and Monserud (2006) suggested that differences observed in tree-ring $\delta^{18}O_{cell}$ of three co-located species over eight decades could be attributed to shifts in tree water source use, whilst Singer et al. (2013) suggested that fluctuations in floodplain hydrology strongly controlled the source water availability and utilization for two tree species with contrasting rooting profiles. However, in order to provide direct comparisons with endmember water sources, it is necessary to determine the $\delta^{18}O_{sw}$ from the $\delta^{18}O_{cell}$ value. Using detailed measurements of the primary controlling variables of $\delta^{18}O$ fractionation in leaves (E - transpiration, g_s - stomatal conductance, $\delta^{18}O_{wv}$ – atmospheric water vapor $\delta^{18}O$, RH – relative humidity and T – air temperature), it is possible to model the relationship between xylem water ($\delta^{18}O_{xyl}$) and $\delta^{18}O_{cell}$,to varying degrees, based on the quality of input data (Barbour et al., 2004; Roden et al., 2000). This relationship can be used to inversely hindcast (model) the δ^{18}O of source waters used for the formation of each tree ring ($\delta^{18}O_{msw}$) (Bose et al., 2016; Sargeant & Singer, 2016; Singer et al., 2014). Earlier work by Anderson et al., (2002) demonstrated the potential for reconstructing historical $\delta^{18}O_{ppt}$ from $\delta^{18}O_{cell}$ by calibrating the model (incorporating climate variables and tree growth) against records of $\delta^{18}O_{ppt}$.

The model calculations of $\delta^{18}O_{msw}$ can then be verified against field measurements of the evolving isotopic composition of contributing water sources (*P*, *GW*). Using this approach, direct comparisons between $\delta^{18}O_{msw}$ with local endmember water source δ^{18}O have suggested that co-occurring tree species with distinct rooting depths (e.g. *Fraxinus* spp. and *Populus* spp.) often access and utilize different mixes of water sources at annual and sub-annual timescales, as a function of fluctuating hydro-climate and relative depths to local GW (Sargeant & Singer, 2016; Singer et al., 2014).

Identifying tree source water(s) requires information on how the potential local endmembers vary in their δ^{18}O signature on both annual and sub-annual timescales, which is particularly complex in situations where there may exist more than one potential water source available for tree growth (Sargeant & Singer, 2016; Singer et al., 2014). Furthermore, fluctuations in source water mixtures modify the isotopic signature of root-available water, thus challenging interpretations of water sources consistently available to trees (Busch et al., 1992; Dawson & Ehleringer, 1991; Sánchez-Pérez et al., 2008; Snyder & Williams, 2000). Despite these challenges, the identification of $\delta^{18}O_{sw}$ is critically important, especially considering that changes in soil water content may outpace the ability for new root growth to track such shifts (Plamboeck et al., 1999).

We demonstrate our methodology for three Mediterranean, riparian forest sites, at both annual and sub-annual resolutions, highlighting the ability of the ISO-Tool to discern valuable ecohydrological information at different timescales. Whilst our examples are based on riparian forests, ISO-Tool is also suitable for other forested environments where a distinct isotopic separation exists between potential water sources used for tree growth over different time periods. Our aim is to provide a new suite of methods to enable a greater understanding of forest ecohydrology in response to climatic fluctuations and trends in subsurface hydrology.

2 METHODS

2.1 Identification of Source water Oxygen isotope ratios in trees Toolkit (ISO-Toolkit)

The core principle of this research is that $\delta^{18}O_{cell}$ can be deconvolved to the $\delta^{18}O_{sw}$ taken up from the rooting zone during a particular growing season. The method utilizes an iterative modeling approach to model the source water $\delta^{18}O_{sw}$ signature ($\delta^{18}O_{msw}$), which is then directly comparable to the δ^{18}O of potential endmember water sources. In this section, we explore the calculations of $\delta^{18}O_{msw}$ and how the user defined input variables are used. We then analyze the sensitivity of the mechanistic model to these different input variables. Subsequently, we describe how key variables can be constrained in order to improve the accuracy of the $\delta^{18}O_{msw}$ calculations and we outline the data and methods that can be used to help interpret the model output. Combined, these form a methodological toolkit, which can be utilized for determining historical plant water use in a variety of forest ecosystems.

An overview of ISO-Tool is shown schematically in Figure 1. ISO-Tool, an open-source code available in two forms, enables the back-calculation of δ^{18}O of water sources used by plants based on measured $\delta^{18}O_{cell}$, climate and plant physiological variables. This code is based on the Barbour et al. (2004) model for plant δ^{18}O fractionation but modified to invert the problem.

The required user inputs of the toolkit are predefined in the following sections, but the manner in which these are constrained is governed by specific Tool Group selections. These data are added to the input file and must comprise of an average value with an estimate of standard deviation (SD) . From these, the model generates normal distributions that are repeatedly sampled by Monte-Carlo simulation, which produces an error margin of ±2 SD. From the mean input values, the model also calculates the mean $\delta^{18}O_{msw}$ value. The mean and standard deviation error bounds are produced as a plot and an associated output file is generated. The modeling script is editable to enable a 'bespoke' analysis through the modification of individual parameters (detailed below), but which are not currently included as requirements within the input file. Presently, the model uses an optimization routine to predict the δ^{18}O value of source water, $\delta^{18}O_{msw}$. The model results ($\delta^{18}O_{msw}$) can then be interpreted by the user from a selection of possible techniques contained within the Tool Groups necessary to characterize source water availability to trees.

The $\delta^{18}O_{msw}$ modeling script is provided as a Matlab code (doi: 10.5281/zenodo/1161221) with the input and output files in .csv (.txt) format. The model is provided at: https://github.com/blissville71/InverseBarbourModel. Here, the user will find downloadable files of the model as a Matlab code (includes Monte-Carlo simulations) and a Microsoft Excel version (excludes Monte-Carlo simulations), plus an example input file and accompanying instructions /overview for the model's rationale and use.

2.2 Modeling source water δ^{18}O ($\delta^{18}O_{msw}$)

The $\delta^{18}O_{msw}$ is predicted from a known $\delta^{18}O_{cell}$ by accounting for the tree-level fractionations and exchange processes which alter the $\delta^{18}O_{sw}$ signature until cellulose formation. In Figure 2a-d, the key components of the model are shown, as well as how required user input data is used in these equations, with an accompanying conceptualization in Figure 2e.

The extent to which transpiration enriches $\delta^{18}O_{sw}$ at the sites of evaporation (Δ_e) in the leaf, is fundamental in determining the recorded variability in $\delta^{18}O_{cell}$ values. The Δ_e model is based on the work by Craig and Gordon (1965) and later modified for the leaf environment (Dongmann et al., 1974; Farquhar & Lloyd, 1993; Flannagan et al., 1991):

$$\Delta_e = (1+\varepsilon^*)\left[(1+\varepsilon_k)\left(1-\frac{e_a}{e_i}\right)+\frac{e_a}{e_i}\,(1+\Delta_v)\right]-1 \tag{1}$$

which can be approximated as:

$$\Delta_e \approx \varepsilon^* + \varepsilon_k + (\Delta_v - \varepsilon_k)\frac{e_a}{e_i} \tag{2}$$

The evaporative enrichment of source water within the leaf is given in Figure 2a & e, and assumes an isotopic steady state, which is appropriate for our purposes since we rely on photosynthetically derived substrates ($\delta^{18}O_{cell}$), reflecting daytime leaf conditions during which an isotopic steady state is approached (Cernusak et al., 2016). Within the model, T_l is assigned as T+1 (°C), as a simplifying assumption. An energy balance equation could be incorporated to compute a realistic T_l, but it would require additional data inputs (e.g. wind speed, leaf width, photosynthetically active radiation) that are typically unavailable for historical reconstruction (Barbour et al., 2000; Lorrey et al., 2016).

Although boundary layer conductance is an important component of ε_k, difficulties in determining time-varying values (Brenner & Jarvis, 1995) may necessitate the use of a fixed value of 1 mol m^2s^{-1} (Barbour et al., 2004). In reality, boundary layer conductance varies as a function of leaf shape, size and thickness, stomatal density, wind velocities and energy balance (Buhay et al., 1996; Jarvis & McNaughton, 1986; Schuepp, 1993; Stokes et al., 2006). Constraining all of these parameters requires a much more detailed investigation beyond the scope of this study. However, both leaf temperature (offset from air temperature) and boundary layer conductance values can be assigned at the user's discretion.

The magnitude of leaf water evaporative enrichment has been shown to be over-predicted by the equation in Figure 2a (Cernusak et al., 2016 and references therein). Farquhar and Lloyd, (1993) proposed that such discrepancies resulted from a Péclet effect, whereby the advection of unenriched source water via transpiration is opposed by the diffusion of enriched water to and from the sites of evaporation, respectively, operating over a given distance divided by the molar density of water and diffusivity of $H_2{}^{18}O$ in water (Figure 2b, c & e). As such, under high transpiration rates, the level of leaf water enrichment declines. Values of *L* (mm) can be calculated as a function of *E* based on the study of Song et al., (2013). They developed a regression between *L* and *E* for several different tree species ($L = 2.36 \times 10^{-5} E^{-1.20}$, $R^2 = 0.813$), where the regression function is expressed in meters (m). We included this relationship within our code so *L* is computed only based on *E* (obviating direct measurements of *L*). We also utilized the R-squared value to provide an error around these estimates. Barbour et al. (2004) showed that the inclusion of the Péclet effect improved their model estimates of the isotopic signature in cellulose (relative to source water), accounting for 89 % of the variability in their study.

During photosynthesis, sucrose molecules are enriched +27±4 ‰ above leaf water $\delta^{18}O$ as the result of carbonyl-bound oxygen atom exchange between triose phosphates and the medium water (Sternberg et al., 1986; Yakir & DeNiro, 1990). It is this sucrose which is utilized to form cellulose, a process by which a proportion of intermediary molecules are able to exchange with unenriched xylem water ($\delta^{18}O_{sw}$) (Farquhar et al., 1998; Hill et al., 1995) (Figure 2d & e). The fraction of oxygen atoms undergoing this exchange is controlled by the proportion of unenriched source water within the cell during cellulose synthesis. The fraction of exchanged oxygen atoms is reported as 0.42 for many tree species (Roden et al., 2000), whilst the source water content is assumed to be at unity for large, mature trees where the distance between leaf and sink tissue is considerable (Barbour et al., 2002). The overall effect of this process is to dampen evaporative enrichment signature transferred to the cellulose molecule at the leaf level.

2.3 Sensitivity analyses

We conducted a series of sensitivity analyses on the calculation of $\delta^{18}O_{msw}$ in response to variations in *T*, *RH*, $\delta^{18}O_{wv}$, as well as to paired values of g_s and *E*. We began by varying each of these input variables independently and then advanced the analysis through a covariance of two variables

(Figure 3). During each sensitivity test, variables not under analysis were kept constant as indicated in Figure 3 'Default values'. Leaf gas exchange parameters used in all model runs are those from Singer et al., (2014) for *Fraxinus excelsior*.

2.3.1 $\delta^{18}O_{cell}$, $\delta^{18}O_{wv}$ and RH

The $\delta^{18}O_{msw}$ predictions respond primarily to changes in *RH*, $\delta^{18}O_{wv}$ and $\delta^{18}O_{cell}$ when each respective input is varied independently (Figure 3a). It should be noted that these results are only representative of the interactions occurring between changing variable and the default values of the remaining inputs indicated in Figure 3a.

We included $\delta^{18}O_{cell}$ to illustrate the positive response we expect on $\delta^{18}O_{msw}$ if all other variables are constant, thus, Δ_e is static so with increasing $\delta^{18}O_{cell}$ there must be a corresponding enrichment in $\delta^{18}O_{msw}$ (+1.5‰/‰). For $\delta^{18}O_{wv}$, a negative relationship exists with $\delta^{18}O_{msw}$ (-0.6‰/‰) (Figure 3a). The dependence of Δ_e on $\delta^{18}O_{wv}$ can be shown using equation (2). If $e_a/e_i = 1$ (saturated conditions), then $\Delta_e = \varepsilon^* + \Delta_v$ (Cernusak et al., 2016), because enrichment in $\delta^{18}O_{wv}$ causes depletion in $\delta^{18}O_{msw}$ in compensation. For *RH* there is a strong, positive, curvilinear relationship with $\delta^{18}O_{msw}$, so as *RH* increases, Δ_e decreases. This arises because $\delta^{18}O_{msw}$ must undergo enrichment to maintain a given $\delta^{18}O_{cell}$.

2.3.2 T, g_s and E

When *T* (i.e. T_l) was varied from 2-40 °C, $\delta^{18}O_{msw}$ was shown to enrich by 3.3‰, a relatively weak effect on Δ_e over this large temperature range, compared to that of $\delta^{18}O_{wv}$ and *RH*. As T_l increases, the equilibrium fractionation factor, ε^*, is reduced causing a decline in Δ_e. This produces an enrichment of $\delta^{18}O_{msw}$ to maintain the static input $\delta^{18}O_{cell}$ value.

In order to test the sensitivity of g_s (mol m^{-2}s^{-1}) and *E* (mmol m^{-2}s^{-1}), whilst also accounting for the physiological coupling between the two processes, these two variables were paired based on a simple expression derived from Fick's law of diffusion where Δw is the leaf-to-air vapour pressure gradient (Dawson, 1996; Pearcy et al., 1989):

$$E = g_s \Delta w \quad (3)$$

Calculations were conducted using the Roden model of evaporative enrichment (Roden & Ehleringer, 2000) in an Excel file format available at ftp://ecophys.biology.utah.edu/tree_ring/ (Barbour et al., 2004). Input values of g_s ranged from 0.05 – 1.00 mol $m^{-2}s^{-1}$ at 101.3 kPa to generate paired estimates of *E* with a subsequent range of 0.40 – 4.20 mmol $m^{-2}s^{-1}$. We recommend caution in interpreting the results on the g_s/E pairing sensitivity test because we have forced the dependence between the two. In reality, these variables might be expected to behave distinctly with variations in climate, subsurface water availability and between species. The effect of g_s and *E* in the model is shown in Figure 3a. It indicates a negative relationship between g_s / *E* and $\delta^{18}O_{msw}$ leaf water. The level of leaf water enrichment declines (at a constant e_a) with increasing g_s due to a reduction in leaf temperature and intercellular vapour pressure caused by increasing *E* (Barbour et al., 2007).

2.3.3 Model sensitivity to covarying parameters

We covaried input parameters to identify those which most strongly affect predictions (retrodictions) of $\delta^{18}O_{msw}$ (Figure 3b-g). The $\delta^{18}O_{cell}$ was kept constant at 30 ‰. The $\delta^{18}O_{cell}$ represents the starting point for the model calculations, and all other variables interact independently of it. The variance of air *T* was shown to have very little interaction with other variables, as shifts in $\delta^{18}O_{msw}$ are predominantly controlled *RH*, $\delta^{18}O_{wv}$ and g_s/E (Figure 3b, d & g, respectively). *RH* had the greatest interaction with $\delta^{18}O_{wv}$ (Figure 3c) and g_s/E (Figure 3f), producing a range in $\delta^{18}O_{msw}$ of 29.1 ‰ and 21.5 %, respectively for the range of plotted values. The interaction between $\delta^{18}O_{wv}$ and g_s/E (Figure 3e) induced a 10.7 ‰ change in $\delta^{18}O_{msw}$ over the range values for each respective variable. Since the range in co-variables presented are unlikely to represent field conditions, we varied the input values (*T*, *RH*, $\delta^{18}O_{wv}$) using the range of variance observed for a study site in SE France for the growing seasons (May-Sept) of 2000-2010. The results are shown as grey shading in Figure 3b-d and indicate that under the growing season climatic conditions, *RH* and $\delta^{18}O_{wv}$ remain the primary interacting controls of $\delta^{18}O_{msw}$, producing variations up to 6.1 ‰ over their respective ranges (Figure 3c). The effects were smaller for *T-RH* and *T*-$\delta^{18}O_{wv}$, which produced $\delta^{18}O_{msw}$ ranges of 4.5 ‰ and 3.3 ‰, respectively (Figure 3b and d).

The sensitivity analyses allow for straightforward identification of how the input variables to the biomechanistic model affect the predictions of $\delta^{18}O_{msw}$. By constraining the relevant variables and increasing the accuracy of the input data, the reliability of model output obviously also increases, and thus the characterization of the source water utilized by a tree during a particular time period is improved. It is evident from the sensitivity analyses that $\delta^{18}O_{wv}$, *RH* and g_s/E require the greatest constraints since their variability can introduce significant shifts in back-calculated values of $\delta^{18}O_{msw}$.

Through sensitivity analyses, we identified the required environmental (T, RH, $\delta^{18}O_{wv}$) and physiological (g_s, E) input variables responsible for modulating leaf level $\delta^{18}O$ enrichment. By utilizing the model in inverse mode, for a known $\delta^{18}O_{cell}$, and driving it with time-dependent input variables, it is possible to calculate $\delta^{18}O_{msw}$ taken up by the tree.

2.4 Tool Groups – constraining input variables and interpretative techniques

In this section we outline how the necessary model input variables can be obtained and summarize the interpretative techniques required to explain the resulting $\delta^{18}O_{msw}$ values within a hydrological context. We begin by explaining the sampling and extraction procedures of tree-ring cellulose at annual and sub-annual resolutions, the essential input of the $\delta^{18}O_{msw}$ model. Following this, we present three different tiers of data or 'Tool Groups' within ISO-Tool (Figure 4), which highlight the various approaches that can be drawn on to obtain values of T, RH, $\delta^{18}O_{wv}$, g_s/E required for model calculations and the various ways in which these results can be interpreted. The calculated $\delta^{18}O_{msw}$ values are most useful if they can be compared to the potential water source endmembers which, in turn, require knowledge of the hydrological processes which control the availability of a particular water source to the tree's rooting zone.

The idea is that Tool Group A represents the optimal suite of techniques and its data inputs should be used whenever and wherever possible. However, when data limitations prevent the use of Tool Group A for particular variable, the second Tool Group (B) should be employed, where possible…and so on. Thus, in a real application, due to universal constraints on data, a researcher is likely to draw relevant data from all three tool groups. In the worst-case scenario, one could use data entirely from Tool Group C and still make progress in water source characterization from tree ring cellulose. The rationale for this classification is to highlight the potential to undertake research into historical ecohydrology even when the most desirable information is unavailable. Of course, the research question also governs which tool group is utilized. A critical point is that prior to conducting isotopic source water investigations, the location of study must exhibit isotopically distinct, potential endmember water sources (isotopic separation), which can be confirmed through exploratory $\delta^{18}O$ analyses or from wider literature/ database searches. We encourage researchers to make additions and refinements to the ISO-Tool.

For an overview of the techniques listed in Figure 4, please see the supporting information. A more detailed discussion of the methodologies for Tool Group A can be found in supporting text S1 (Barbour & Farquhar, 2000; Beyer et al., 2016; Böttcher et al., 2014; Busch et al., 1992; Cocozza et al., 2016; Cuny et al., 2015; David et al., 2013; Dawson et al., 2002; Delattre et al., 2015; Gröning et al., 2012; Hao et al., 2013; IAEA/GNIP precipitation sampling guide V2.02, 2014; Jarvis, 1995; Lambs et al., 2002; Meinzer et al., 1999; Parnell et al., 2008, 2010; Pearcy et al., 1989; Phillips & Gregg 2003; Robock et al., 2000; Rossi et al., 2006; Rundel & Jarrell,1989; S.U. et al., 2014; Scott et al., 2004; Snyder & Williams, 2000; Song et al., 2013; Soudant et al., 2016; Sprenger et al., 2016; Stokes, 2004; Volkmann & Weiler, 2014; West et al., 2006; White & Smith, 2013; Zencich et al., 2002; Zweifel et al., 2001), Tool Group B in supporting text S2 (Berkelhammer & Stott, 2009: Bowen & Revenaugh, 2003; Bowen & Wilkinson, 2002; Bowen et al., 2005; Bowen, 2017; Delatrre et al., 2015; Entekhabi et al., 2010; GNIP, IAEA/WMO, 2017; Granier et al., 1999; GSOD – 'Global Surface Summary of the Day', 2018; Hsieh et al., 1998; Jonard et al., 2011; Jones, 1998; McNaughton & Jarvis, 1991; Oren et al., 1999; Richardson et al., 2007; Schwartz et al., 2002; Sprenger et al., 2016; Srivastava, 2017; Vicente-Serrano et al., 2010; West et al., 2006; Yale University, 2017) and for Tool Group C, in supporting text S3 (Bowen et al., 2005; Bowen, 2017; Celle-Jeanton et al., 2001; Delattre et al., 2015; Horita & Wesolowski, 1994; GNIP/GNIR, IAEA/WMO, 2017; Jacob & Sonntag, 1991; Majoube, 1971; NOAA – 'National Oceanic Atmospheric Administration', 2018; Poyatos et al., 2016; Sargeant & Singer, 2016; Singer et al., 2014; Suni et al., 2003; Wen et al., 2010). This is not designed to be an exhaustive review of all possible techniques for the interpretation of $\delta^{18}O_{msw}$, but to broadly identify the tools which could be utilized in source-water characterization.

2.4.1 Tree-ring $\delta^{18}O_{cell}$

The tree(s) chosen for isotopic analysis generally reflect particular research questions, but they would ideally be visually healthy individual specimens with distinguishable, annual growth rings in order to determine the associated climatic variables needed for modeling. Otherwise, it is challenging to constrain the timing of water use.

After tree selection, tree-rings can be collected the form of tree-cores, obtained by an increment borer (e.g. at least 5 mm diameter) at breast height. Extracted tree-cores are 'bladed' to expose a uniform surface to maximize ring visibility. Cores should not be mounted with adhesive to prevent contamination of wood material and ethanol should be used to clean equipment. The tree-rings corresponding to the years of interest can be identified through visual cross-dating or standard dendrochronological methods whereby ring widths are measured under a microscope using a tree-ring measurement program such as ‘Measure J2X Tree-Ring Measuring Programme’. Validation of cross-dating can be achieved using a cross-correlation software such as COFECHA (Holmes, 1983). Alternatively, the cores may be scanned combined and ring-widths measured digitally with the coordinate measuring and cross dating software programs CooRecoder and CDendro, respectively (Larsson, 2014). Individual rings of interest are dissected with a scalpel and homogenized in preparation α-cellulose extraction.

Sub-annual isotopic analysis of tree rings has been shown to contain additional information that is masked by annual (homogenized) whole-ring analyses and which may be important for understanding the seasonal dynamics of water availability (e.g. Roden et al., 2009; Sargeant & Singer, 2016). Tree-cores can be collected and processed as above but with each whole ring divided into sub-annual segments using a scalpel or microtome (e.g. Gärtner et al., 2014; Helle & Schleser, 2004). The number of divisions is determined by the researcher and we recommend conducting trials on surplus rings to ensure that each slice yields enough material cellulose mass for isotopic analysis.

Tree-ring α-cellulose is the preferred material for isotopic analysis since it retains the $\delta^{18}O$ information from the time of formation without undergoing any subsequent isotopic exchange (Wright, 2008). In comparison, other components of whole wood material (e.g. hemicellulose, lignin, lipids and waxes) can exchange oxygen and may also represent different periods of synthesis (Battipaglia et al., 2008; Gray & Thompson, 1977). The modified Brendel (MBrendel) method (Gaudinski et al., 2005), allows for batch processing with minimal laboratory equipment. McCarroll and Loader (2004) suggest that for softwoods, the high quantity of resins and extractions can be removed by a Soxhlet apparatus and a toluene-ethanol solution.

The α-cellulose can be analyzed for $^{18}O/^{16}O$ using an online, continuous flow system of a TC/EA (Temperature Conversion Elemental Analyzer) connected to an Isotope Ratio Mass Spectrometer (IRMS). Results are reported in per mil (‰) deviation from Vienna Standard Mean Ocean Water (VSMOW $\delta^{18}O = 2.0052 \times 10^{-3}$ ‰) (equation [3], where R_s is the isotopic ratio of the sample and R_{std} is that of the standard). This follows correction to the IAEA-CH3 (cellulose [Hunsinger et al., 2010]) standard, co-run with an internal lab standard and the effects of drift and linearity are accounted for to obtain $\delta^{18}O_{cell}$:

$$\delta^{18}O_{cell}\ (‰) = \left(\frac{R_s - R_{std}}{R_{std}}\right) \cdot 10^3 \tag{3}$$

3 ISO-TOOL APPLICATIONS

In this section, we present three example applications of ISO-Tool to demonstrate its broad utility. Our examples illustrate water source characterizations drawing on components from each Tool Group for constraining model inputs and the interpretation of results (Figure 4). The sites are all located along the Rhône River, SE France (Table S1), and although we illustrate how ISO-Tool usage in riparian environments, we emphasize that it can be employed in any site where isotopically distinct water sources are present and where tree rings record annual growth. The $\delta^{18}O_{cell}$ results from which $\delta^{18}O_{msw}$ were calculated are in Figure S1a-c. We refer the reader to Figure 4 for each of the following case studies.

Statistical analyses were conducted using Minitab (version 17) and are reported relative to the 95% significance level. All statistical tests were conducted following the determination of sample set normality with the Anderson-Darling (A-D) test and analysis and equal variance using the Levene test. For the comparison of 2-sample means we used the T-test (*T*) or Mann-Whitney (Wilcoxon rank) test (*U*), whilst for >2 datasets an ANOVA (*F*-test) and post-hoc test (Tukey-Kramer/Games-Howell) was used to determine statistically similar groups.

3.1 Example 1: Minimum flow restoration, Pierre-Bénite (PB)

Riparian forests are often the focus of restoration schemes which aim to improve the level of hydrological connectivity through the raising of minimum discharge levels below dams to benefit aquatic ecology as well as riparian forests, but this has never been shown convincingly. This example is based on data from the Pierre-Bénite (PB) site where water managers increased the minimum dry-season river flow from 10 m/s to 100 m/s in the year 2000 to benefit aquatic ecology. This produced a mean water table rise within the floodplain of ~0.5 m (Amoros et al., 2005; Singer et al., 2014). In Singer et al., (2014), analysis of annual tree-ring $\delta^{18}O_{cell}$ records from two cohorts of *Populus nigra* situated at relatively 'high' and 'low' floodplain elevations suggested that the flow restoration enabled phreatic water to become available to *Populus* rooted at low floodplain elevations. Since $\delta^{18}O_{cell}$ cannot be directly compared with local water source $\delta^{18}O$ signatures, we applied ISO-Tool to evaluate the conclusions of Singer et al., (2014).

Whole ring (annually resolved) $\delta^{18}O_{cell}$ was used in this example (Figure S1a), with climate records of T and RH, corresponding to the observed growing season of May-September, obtained from a local climate station (meteofrance.com, 2017). The $\delta^{18}O_{wv}$ values were calculated using an equilibrium fraction factor (Majoube, 1971) using records of T and GNIP (IAEA/WMO, 2017)-OIPC (Online Isotopes in Precipitation Calculator) (Bowen, 2017; Bowen et al., 2005) estimates of $\delta^{18}O_{ppt}$, assuming that $\delta^{18}O_{wv}$ was in isotopic equilibrium with $\delta^{18}O_{ppt}$. Monthly estimates of $\delta^{18}O_{ppt}$ were obtained from the records of two equidistant GNIP (IAEA/WMO, 2017) monitoring stations (Figure S2a-b), averaged and correlated to monthly δ^{18}O values for the site, obtained from the 'Online Isotopes in Precipitation Calculator' (Bowen, 2017; Bowen et al., 2005) (Figure S2c). Literature-derived values of g_s/E, were used. In situ measurements of $\delta^{18}O_{RW}$ were unavailable, thus necessitating the use of $\delta^{18}O_{RW}$ from 34 km downstream. Seasonal $\delta^{18}O_{ppt}$ for each year were computed by weighting the monthly $\delta^{18}O_{ppt}$ values by the corresponding P totals recorded at the climate station. Piezometric measurements of water table elevation were available for the study period (Figure S3).

In Figure 5a, the $\delta^{18}O_{msw}$ time series of each cohort is shown. Although there is a separation in cohort water use from 2000 onwards, with the 'high' cohort utilizing more enriched $\delta^{18}O_{msw}$ than the 'low' cohort (+0.9 ‰), it is not statistically significant (T_{18} = 1.68, p = 0.11). Neither the 'high' or 'low' poplar trees displayed a shift in $\delta^{18}O_{msw}$ following the flow restoration, drawing on an isotopically similar water source during both periods ('high': T_{19} = -1.20, p = 0.244; 'low': T_{19} = -0.65, p = 0.542). The implementation of a minimum river flow was seemingly insufficient to provide sustained phreatic water access to either cohort of trees. Instead, both cohorts seemingly relied on different mixtures of seasonal precipitation. It is possible that the water table elevation did make some portion of phreatic water available to *Populus* at low elevations, e.g. by capillary rise (Sánchez-Pérez et al., 2008), but its signature is masked by mixing with precipitation-sourced vadose moisture (Figure 5a). The lack of clear evidence of a phreatic water signature in $\delta^{18}O_{msw}$ of either cohort after the flow restoration may be due to a combination of insufficient river flow to raise the water table relative to the fixed rooting architecture for mature trees of this species. It is possible that these *Populus* trees previously developed extensive vadose zone roots at the expense of deeper, vertical roots during the period when phreatic water was unavailable (i.e. pre-2000). This dimorphic rooting characteristic is advantageous in environments where phreatic and vadose zone moisture are seasonally variable (Singer et al., 2014).

3.2 Example 2: Sub-annual water source use, Donzère-Mondragon (DM)

Seasonal variability in water sources may exert important controls on growing season water availability and corresponding tree health, which could be masked by whole tree-ring isotopic analysis (Sargeant & Singer, 2016). At the Donzère-Mondragon (DM) site we employed ISO-Tool to determine the sub-annual progression of $\delta^{18}O_{msw}$ of two co-located (<5 m apart), streamside individuals of *Fraxinus excelsior* (roots restricted to the vadose zone by a coarse gravel layer) and *Populus nigra* (roots capable of phreatic zone access). The two-species approach can be used to investigate the seasonal dynamics of water partitioning within different hydrological reservoirs.

We utilized the $\delta^{18}O_{cell}$ from Sargeant and Singer (2016) (Figure S1b), but employ a longer growing season (MJJAS vs. MJJA) and the use of update to date GNIP (IAEA/WMO, 2017) records and the latest version of the OIPC (Figure S4). Sub-annual patterns and inter-species differences in $\delta^{18}O_{msw}$ are evident wherein *Fraxinus* $\delta^{18}O_{msw}$ is enriched by +2.4 ‰ compared to *Populus* ($U = 17211$, $p < 0.001$) (Figure 5b) but a $\delta^{18}O_{msw}$ convergence for both species from 2007-2010 ($T_{58} = 0.59$, $p = 0.557$).

Prior to 2007, *Fraxinus*' $\delta^{18}O_{msw}$ generally follows a seasonal pattern, shifting from depleted earlywood (EW) to enriched latewood (LW) (+1.5‰). This suggests the use of non-growing season (NGS) $\delta^{18}O_{ppt}$ for EW ($U = 1083$, $p = 0.716$) and growing season (GS) $\delta^{18}O_{ppt}$ LW ($U = 1318$, $p = 0.053$) growth, since phreatic water is typically unavailable to *Fraxinus* roots due to the presence of a local gravel layer in floodplain soils (Singer et al., 2013, 2014). These water sources correspond to the evolving isotopic signature of vadose zone water during the growing season. However, in 2001 and 2003 the $\delta^{18}O_{msw}$ and sub-annual pattern for *Fraxinus* is depleted compared with $\delta^{18}O_{ppt}$. This may result from overbank flooding and/or a very elevated water table in these years of high streamflow (Sargeant & Singer, 2016), which delivers isotopically depleted water to the vadose zone. For this same period (2000-2006), the *Populus* tree exhibits much smaller swings in seasonal water use and it appears to have used a mix of NGS $\delta^{18}O_{ppt}$ and phreatic water for both EW and LW.

During the water-use convergence period, *Fraxinus* $\delta^{18}O_{msw}$ is similar to NGS and GS $\delta^{18}O_{ppt}$, ($F_{3,35} = 2.96$, $p = 0.047$) but distinct from $\delta^{18}O_{RW}$ ($U = 737$, $p < 0.001$). Notably, *Populus* underwent a shift in $\delta^{18}O_{msw}$ to that of $\delta^{18}O_{ppt}$ for both parts of the growing season ($F_{3,36} = 8.10$, $p < 0.001$). This convergence water source use between these species indicates *Populus* switched from phreatic to vadose zone moisture uptake (e.g., use of NGS $\delta^{18}O_{ppt}$ in 2009, Figure 5b). The *Populus* water source shift suggests that the phreatic reservoir became inaccessible. An ancillary dataset provides evidence of local river incision of ~1.5 m (Figure S5) between 2003-2007 (Parrot, 2015). Downcutting of the riverbed reduces local river stage and by extension, lateral hyporheic flow into the floodplain, leading to a water table decline. Thus, *Populus* roots apparently became stranded from the phreatic zone by river incision and were subsequently forced to rely on vadose zone water.

3.3 Example 3: Annual vs. sub-annual water source use, Mas Thibert (MT)

There are open questions as to whether gravel layers in river floodplains impede access to phreatic water with river floodplains for shallow-rooting species such as *Fraxinus* (Singer et al., 2014), and whether seasonal patterns of water use for such species are consistent across its distribution within the same region.

$\delta^{18}O_{wv}$ measurements taken from the nearby (7 km away) monitoring station of Delattre et al., (2015) to reconstruct historical $\delta^{18}O_{wv}$ and $\delta^{18}O_{ppt}$ for our study period (Figure S6) along with climate data (400 m away) sourced from MeteoFrance (meteofrance.com, 2017). This dataset and associated reconstruction enabled more accurate (nearly) site-based estimates of $\delta^{18}O_{wv}$ to the $\delta^{18}O_{msw}$ and seasonal $\delta^{18}O_{ppt}$, as opposed to those obtained from the nearest GNIP station (IAEA/WMO, 2017) at Avignon (~46 km north). We used reported values of leaf gas exchange (g_s/E) for each species in similar environmental conditions. The stomatal conductance / transpiration rates for *Fraxinus* were 0.145 ±0.065 mol $m^{-2}s^{-1}$ / 2.85 ±1.05 mmol $m^{-2}s^{-1}$ (Lemoine et al., 2001) and for *Populus* were 0.1625 ±0.1225 mol $m^{-2}s^{-1}$ /2.65 ±1.85 mmol $m^{-2}s^{-1}$ (Lambs et al., 2006).

Figure 5c demonstrates that a high variability in water source use ($\delta^{18}O_{msw}$) is dampened within the whole-ring series. The sub-annual $\delta^{18}O_{msw}$ within a single year of growth can range from 1.7 ‰ (2004) to 10.5 ‰ (2009), whilst the range in recorded annual $\delta^{18}O_{msw}$ values is 4.8 ‰. The year 2009 exhibits a substantial difference (8.5 ‰) between annual $\delta^{18}O_{msw}$ (-5.4 ‰) and the third LW value of $\delta^{18}O_{msw}$ (+3.1 ‰). This suggests that sub-annual information on water source uses can provide a more robust characterization of water use than annual data, and this information would enable better understanding plant-water relations.

The $\delta^{18}O_{msw}$ in EW is generally enriched by +2.0 ‰ compared to that in LW (T_{52} = 2.91, p = 0.005), but see 2006 and 2009 when this pattern is reversed. Interestingly, the general pattern of enriched EW and depleted LW contrasts to the seasonal pattern of water use by the same species at DM (Figure 5b). This suggests differential seasonal availability of water at particular rooting depths between the two sites. River water is indistinguishable from shallow phreatic water (T_{16} = -1.00, p = 0.333) at MT, indicating that hyporheic flow from the Rhône is the main source of water to the alluvial aquifer. There is also a clear separation between the means of NGS and GS $\delta^{18}O_{ppt}$ (T_{20} = -2.61, p = 0.017) at this site because of a markedly warmer growing season that delivers isotopically enriched precipitation. Once infiltrated into the vadose zone, this water becomes further enriched by evaporation before uptake by *Fraxinus*.

Despite the absence of a gravel layer impeding *Fraxinus* rooting depth at MT, it still apparently relies on infiltrated precipitation. The greater enrichment in $\delta^{18}O_{msw}$ for EW growth compared with LW may be driven by high spring-time evaporative enrichment of shallow vadose zone moisture arising from the strong and dry, northerly 'Mistral' winds, whilst the LW $\delta^{18}O_{msw}$ may correspond to a relatively lessened evaporative enrichment controlled by summer temperatures.

4 DISCUSSION AND CONCLUSION

The 'Identification of Source-water Oxygen isotopes in trees Toolkit' (ISO-Tool), presented here, is designed to provide the necessary techniques to reconstruct the historical $\delta^{18}O_{sw}$ signatures used by trees for annual or sub-annual periods and to interpret these signatures in terms of hydroclimatic variability. ISO-Tool is designed to be used with three hierarchical 'Tool Groups' with different data requirements (and thus output resolution). These 'Tool Groups' enable investigations of tree water source use under various conditions of data availability. By bringing together techniques from multiple research fields (e.g. dendrochronology, stable isotopes, hydrological data analysis, tree physiology, ecohydrology) into a single and straightforward application framework, our aim is for ISO-Tool to be easily accessible to scientific researchers interested to retrospectively identify water sources to plants for a range of applications (e.g., to relate them to xylem water isotopes). We highlighted the utility of the toolkit under varying scenarios of data availability and provided several applications: restoration assessment (PB); seasonal water source use (DM) and a comparative analysis of low and high resolution $\delta^{18}O_{cell}$ sampling (MT).

The underlying principle of ISO-Tool is that the $\delta^{18}O_{sw}$ utilized for any period can be obtained by reversing the fractionation and exchange mechanisms responsible for producing the discrepancy between the $\delta^{18}O$ of root zone moisture and that which is recorded in tree-ring in cellulose. Singer et al., (2014) and Sargeant and Singer (2016) utilized versions of this inverse modeling technique to determine the isotopic signature of water sources used by riparian trees at annual and sub-annual resolution, respectively. Recent work by Bose et al., (2016) reconstructed the isotopic value of soil water for trees over a larger spatial scale using thirteen $\delta^{18}O_{cell}$ datasets. The present paper formalizes such methods into a set of tools for assessing historical water use by plants.

The flexible modeling framework allows the user to define the values of specific parameters (e.g. leaf temperature and boundary layer conductance), circumventing the reliance on default values which may improve in accuracy as research in these topic areas advances. Additionally, if the researcher is able to provide more accurate estimates for such parameters, they can be easily incorporated. Advancement of the modeling component will necessitation the inclusion of post-photosynthetic metabolism and transport mechanisms (Gessler et al., 2014). As such, we acknowledge that the calculated $\delta^{18}O_{msw}$ values may not represent the *absolute* δ^{18}O values of water utilized by the tree, yet they remain valuable for interpreting ecohydrological interactions as long as isotopically distinct endmembers are present.

We have shown the ISO-Tool capability to add value to analyses of restoration efforts, wherein the back-calculated source waters from a particular tree can be used to assess whether it benefited from increased flow support of an elevated floodplain water table (PB). We also applied ISO-Tool to ascertain water use on sub-annual timescales, and this was demonstrated to be much more powerful than annual analyses, providing useful information on the seasonal variability of water sources during an annual growth cycle (DM and MT). This latter work pointed to strong seasonal differences in water usage for the same species at different locations along the Rhône River, a result that would not appear in annual data.

The back-calculation of tree $\delta^{18}O_{sw}$, is a more robust technique than $\delta^{18}O_{cell}$ for determining the water source utilized by trees. We suggest that ISO-Tool is well suited for site-based studies and those along climatic transects, as it is capable of shedding light on the nature of hydrological partitioning within the plant rooting zones.

We developed a new tool capable of providing estimates of the δ^{18}O of source-water(s) utilized by trees and incorporating a hierarchical data quality scheme for the constraint of model variables and interpretative techniques of model output, based on available data sources. We foresee ISO-Tool being useful in a wide range of ecohydrological applications with retrospective insights into source-water utilization by trees becoming an increasingly diagnostic tool under future hydroclimatic changes.

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References

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1-55.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest ecology and management*, *259*(4), 660-684.

Allen, M. R., & Ingram, W. J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature*, *419*(6903), 224.

Allison, G. B., Barnes, C. J., Hughes, M. W., & Leaney, F. W. J. (1984). Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. *Isotopes Hydrology, IAEA, Vienna*, 105-122.

Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater biology*, *47*(4), 761-776.

Amoros, C., Elger, A., Dufour, S., Grosprêtre, L., Piégay, H., & Henry, C. (2005). Flood scouring and groundwater supply in side-channel rehabilitation of the Rhône river, France. *Arch. Hydrobiol*, *155*, 147-167.

Anderegg, W. R., Kane, J. M., & Anderegg, L. D. (2013). Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature climate change*, *3*(1), 30.

Anderson, W. T., Bernasconi, S. M., McKenzie, J. A., Saurer, M., & Schweingruber, F. (2002). Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century. *Chemical Geology*, *182*(2-4), 121-137.

Barbeta, A., Ogée, J., & Peñuelas, J. (2018). Stable-Isotope Techniques to Investigate Sources of Plant Water. In *Advances in Plant Ecophysiology Techniques* (pp. 439-456). Springer, Cham.

Barbour, M. M. (2007). Stable oxygen isotope composition of plant tissue: a review. *Functional Plant Biology*, *34*(2), 83-94.

Barbour, M. M., & Farquhar, G. D. (2000). Relative humidity-and ABA-induced variation in carbon and oxygen isotope ratios of cotton leaves. *Plant, Cell & Environment*, *23*(5), 473-485.

Barbour, M. M., Fischer, R. A., Sayre, K. D., & Farquhar, G. D. (2000). Oxygen isotope ratio of leaf and grain material correlates with stomatal conductance and grain yield in irrigated wheat. *Functional Plant Biology*, *27*(7), 625-637.

Barbour, M. M., Roden, J. S., Farquhar, G. D., & Ehleringer, J. R. (2004). Expressing leaf water and cellulose oxygen isotope ratios as enrichment above source water reveals evidence of a Péclet effect. *Oecologia*, *138*(3), 426-435.

Barbour, M. M., Walcroft, A. S., & Farquhar, G. D. (2002). Seasonal variation in δ13C and δ18O of cellulose from growth rings of Pinus radiata. *Plant, Cell & Environment*, *25*(11), 1483-1499.

Battipaglia, G., Jäggi, M., Saurer, M., Siegwolf, R. T., & Cotrufo, M. F. (2008). Climatic sensitivity of δ18O in the wood and cellulose of tree rings: Results from a mixed stand of Acer pseudoplatanus L. and Fagus sylvatica L. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *261*(1-2), 193-202.

Beijing, China. *Journal of Geophysical Research: Atmospheres*, *115*(D1).

Berkelhammer, M., & Stott, L. D. (2009). Modeled and observed intra-ring δ18O cycles within late Holocene Bristlecone Pine tree samples. *Chemical Geology*, *264*(1-4), 13-23.

Berner, L. T., Law, B. E., & Hudiburg, T. W. (2017). Water availability limits tree productivity, carbon stocks, and carbon residence time in mature forests across the western US. *Biogeosciences*, *14*(2), 365-378.

Bertrand, G., Masini, J., Goldscheider, N., Meeks, J., Lavastre, V., Celle-Jeanton, H., et al. (2014). Determination of spatiotemporal variability of tree water uptake using stable isotopes (δ18O, δ2H) in an alluvial system supplied by a high-altitude watershed, Pfyn forest, Switzerland. *Ecohydrology*, *7*(2), 319-333.

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J. T., Wanke, H., & Himmelsbach, T. (2016). A deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, *533*, 627-643.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *science*, *320*(5882), 1444-1449.

Bose, T., Sengupta, S., Chakraborty, S., & Borgaonkar, H. (2016). Reconstruction of soil water oxygen isotope values from tree ring cellulose and its implications for paleoclimate studies. *Quaternary International*, *425*, 387-398.

Böttcher, K., Aurela, M., Kervinen, M., Markkanen, T., Mattila, O. P., Kolari, P., et al. (2014). MODIS time-series-derived indicators for the beginning of the growing season in boreal coniferous forest—A comparison with CO2 flux measurements and phenological observations in Finland. *Remote Sensing of Environment*, *140*, 625-638.

Bowen, G. J. (2017) The Online Isotopes in Precipitation Calculator, version 3.1. Accessible at http://www.waterisotopes.org. [Accessed May 2017].

Bowen, G. J., & Revenaugh, J. (2003). Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research*, *39*(10).

Bowen, G. J., & Wilkinson, B. (2002). Spatial distribution of δ18O in meteoric precipitation. *Geology*, *30*(4), 315-318.

Bowen, G. J., Wassenaar, L. I., & Hobson, K. A. (2005). Global application of stable hydrogen and oxygen isotopes to wildlife forensics. *Oecologia*, *143*(3), 337-348.

Bréda, N., Huc, R., Granier, A., & Dreyer, E. (2006). Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science*, *63*(6), 625-644.

Brenner, A. J., & Jarvis, P. G. (1995). A heated leaf replica technique for determination of leaf boundary layer conductance in the field. *Agricultural and Forest Meteorology*, *72*(3-4), 261-275.

Breshears, D. D., Cobb, N. S., Rich, P. M., Price, K. P., Allen, C. D., Balice, R. G., et al.(2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, *102*(42), 15144-15148.

Brooks, J. R., Meinzer, F. C., Coulombe, R., & Gregg, J. (2002). Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. *Tree physiology*, *22*(15-16), 1107-1117.

Buhay, W. M., Edwards, T. W. D., & Aravena, R. (1996). Evaluating kinetic fractionation factors used for reconstructions from oxgen and hydrogen isotope ratios in plant water and cellulose. *Geochimica et Cosmochimica Acta*, *60*(12), 2209-2218.

Busch, D. E., Ingraham, N. L., & Smith, S. D. (1992). Water uptake in woody riparian phreatophytes of the southwestern United States: a stable isotope study. *Ecological Applications*, *2*(4), 450-459.

Caldwell, M. M., Dawson, T. E., & Richards, J. H. (1998). Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia*, *113*(2), 151-161.

Celle-Jeanton, H., Travi, Y., & Blavoux, B. (2001). Isotopic typology of the precipitation in the Western

Cernusak, L. A., Barbour, M. M., Arndt, S. K., Cheesman, A. W., English, N. B., Feild, T. S., et al. (2016). Stable isotopes in leaf water of terrestrial plants. *Plant, Cell & Environment*, *39*(5), 1087-1102.

Charru, M., Seynave, I., Morneau, F., & Bontemps, J. D. (2010). Recent changes in forest productivity: an analysis of national forest inventory data for common beech (Fagus sylvatica L.) in north-eastern France. *Forest Ecology and Management*, *260*(5), 864-874.

Chen, L., Huang, J. G., Alam, S. A., Zhai, L., Dawson, A., Stadt, K. J., & Comeau, P. G. (2017). Drought causes reduced growth of trembling aspen in western Canada. *Global change biology*, *23*(7), 2887-2902.

Choat, B., Jansen, S., Brodribb, T. J., Cochard, H., Delzon, S., Bhaskar, R., et al. (2012). Global convergence in the vulnerability of forests to drought. *Nature*, *491*(7426), 752.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., et al. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, *437*(7058), 529.

Clark, J. S., Bell, D. M., Hersh, M. H., & Nichols, L. (2011). Climate change vulnerability of forest biodiversity: climate and competition tracking of demographic rates. *Global Change Biology*, *17*(5), 1834-1849.

Clark, J. S., Iverson, L., Woodall, C. W., Allen, C. D., Bell, D. M., Bragg, D. C., et al. (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, *22*(7), 2329-2352.

Cocozza, C., Palombo, C., Tognetti, R., La Porta, N., Anichini, M., Giovannelli, A., et al. (2016). Monitoring intra-annual dynamics of wood formation with microcores and dendrometers in Picea abies at two different altitudes. *Tree physiology*, *36*(7), 832-846.Mediterranean region at three different time scales. *Geophysical Research Letters*, *28*(7), 1215-1218.

Craig H, Gordon L. 1965. Deuterium and oxygen-18 variations in the ocean and marine atmosphere. In Proceedings of a conference on Stable isotopes in Oceanographic studies and Paleotemperatures, Spoleto, Italy.

Cuny, H. E., Rathgeber, C. B., Frank, D., Fonti, P., Mäkinen, H., Prislan, P., et al. (2015). Woody biomass production lags stem-girth increase by over one month in coniferous forests. *Nature Plants*, *1*(11), 15160.

Currie, D. J., & Paquin, V. (1987). Large-scale biogeographical patterns of species richness of trees. *Nature*, *329*(6137), 326.

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, *16*(4), 436-468.

David, T. S., Pinto, C. A., Nadezhdina, N., Kurz-Besson, C., Henriques, M. O., Quilhó, T., et al. (2013). Root functioning, tree water use and hydraulic redistribution in Quercus suber trees: A modeling approach based on root sap flow. Forest Ecology and Management, 307, 136-146.

Dawson, T. E. (1993). Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. *Oecologia*, *95*(4), 565-574.

Dawson, T. E. (1996). Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree size and hydraulic lift. *Tree physiology*, *16*(1-2), 263-272.

Dawson, T. E., & Ehleringer, J. R. (1991). Streamside trees that do not use stream water. *Nature*, *350*(6316), 335.

Dawson, T. E., & Pate, J. S. (1996). Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia*, *107*(1), 13-20.

Dawson, T. E., Mambelli, S., Plamboeck, A. H., Templer, P. H., & Tu, K. P. (2002). Stable isotopes in plant ecology. *Annual review of ecology and systematics*, *33*(1), 507-559.

Delattre, H., Vallet-Coulomb, C., & Sonzogni, C. (2015). Deuterium excess in the atmospheric water vapour of a Mediterranean coastal wetland: regional vs. local signatures. *Atmospheric Chemistry and Physics*, *15*(17), 10167-10181.

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., & Maher, N. (2016). More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, *6*(5), 508.

Dongmann, G., Nürnberg, H. W., Förstel, H., & Wagener, K. (1974). On the enrichment of H 2 18 O in the leaves of transpiring plants. *Radiation and environmental biophysics*, *11*(1), 41-52.

Drake, P. L., & Franks, P. J. (2003). Water resource partitioning, stem xylem hydraulic properties, and plant water use strategies in a seasonally dry riparian tropical rainforest. *Oecologia*, *137*(3), 321-329.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., et al. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, *43*, 51-61.

Ellsworth, P. Z., & Williams, D. G. (2007). Hydrogen isotope fractionation during water uptake by woody xerophytes. *Plant and Soil*, *291*(1-2), 93-107.

Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., et al. (2010). The soil moisture active passive (SMAP) mission. *Proceedings of the IEEE*, *98*(5), 704-716.

Evans, C. M., Dritschel, D. G., & Singer, M. B. (2018). Modeling subsurface hydrology in floodplains. *Water Resources Research*, *54*(3), 1428-1459.

Farquhar, G. D., & Lloyd, J. (1993). Carbon and oxygen isotope effects in the exchange of carbon dioxide between terrestrial plants and the atmosphere. In *Stable isotopes and plant carbon-water relations* (pp. 47-70).

Farquhar, G.D., Barbour, M.M., & Henry, B.K .(1998) Interpretation of oxygen isotope composition of leaf material. In Griffiths, H. (1998). *Stable isotopes: integration of biological, ecological and geochemical processes* (p. 438). Oxford: Bios scientific publishers.

Flanagan, L. B., & Ehleringer, J. R. (1991). Stable isotope composition of stem and leaf water: applications to the study of plant water use. *Functional Ecology*, *5*(2), 270-277.

Flanagan, L. B., Comstock, J. P., & Ehleringer, J. R. (1991). Comparison of modeled and observed environmental influences on the stable oxygen and hydrogen isotope composition of leaf water in Phaseolus vulgaris L. *Plant Physiology*, *96*(2), 588-596.

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. *Earth-Science Reviews*, *105*(3-4), 121-139.

Gärtner, H., Lucchinetti, S., & Schweingruber, F. H. (2014). New perspectives for wood anatomical analysis in dendrosciences: the GSL1-microtome. *Dendrochronologia*, *32*(1), 47-51.

Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences*, *24*(1), 225-262.

Gaudinski, J. B., Dawson, T. E., Quideau, S., Schuur, E. A., Roden, J. S., Trumbore, S. E., ... & Wasylishen, R. E. (2005). Comparative analysis of cellulose preparation techniques for use with 13C, 14C, and 18O isotopic measurements. *Analytical Chemistry*, *77*(22), 7212-7224.

Gazis, C., & Feng, X. (2004). A stable isotope study of soil water: evidence for mixing and preferential flow paths. *Geoderma*, *119*(1-2), 97-111.

Gessler, A., Brandes, E., Buchmann, N., Helle, G., Rennenberg, H., & Barnard, R. L. (2009). Tracing carbon and oxygen isotope signals from newly assimilated sugars in the leaves to the tree-ring archive. *Plant, Cell & Environment*, *32*(7), 780-795.

Gessler, A., Ferrio, J. P., Hommel, R., Treydte, K., Werner, R. A., & Monson, R. K. (2014). Stable isotopes in tree rings: towards a mechanistic understanding of isotope fractionation and mixing processes from the leaves to the wood. *Tree physiology*, *34*(8), 796-818.

Granier, A., Bréda, N., Biron, P., & Villette, S. (1999). A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. *Ecological modelling*, *116*(2-3), 269-283.

Gray, J., & Thompson, P. (1977). Climatic information from 18O/16O analysis of cellulose, lignin and whole wood from tree rings. *Nature*, *270*(5639), 708.

Gröning, M., Lutz, H. O., Roller-Lutz, Z., Kralik, M., Gourcy, L., & Pöltenstein, L. (2012). A simple rain collector preventing water re-evaporation dedicated for δ18O and δ2H analysis of cumulative precipitation samples. *Journal of hydrology*, *448*, 195-200.

GSOD – 'Global Surface Summary of the Day'. Accessible at: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00516 [Accessed Dec. 2018].

Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iverson, L. R., Currie, D. J., et al. (2001). Global change in forests: responses of species, communities, and biomes: interactions between climate change and land use are projected to cause large shifts in biodiversity. *AIBS Bulletin*, *51*(9), 765-779.

Hao, X. M., Li, Y., & Deng, H. J. (2013). Assessment of hydraulic redistribution on desert riparian forests in an extremely arid area. *Environmental monitoring and assessment*, *185*(12), 10027-10038.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Helle, G., & Schleser, G. H. (2004). Beyond CO2-fixation by Rubisco–an interpretation of 13C/12C variations in tree rings from novel intra-seasonal studies on broad-leaf trees. *Plant, Cell & Environment*, *27*(3), 367-380.

Hill, S. A., Waterhouse, J. S., Field, E. M., Switsur, V. R., & Ap Rees, T. (1995). Rapid recycling of triose phosphates in oak stem tissue. *Plant, Cell & Environment*, *18*(8), 931-936.

Holmes, R. L. (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-ring bulletin*.

Horita, J., & Wesolowski, D. J. (1994). Liquid-vapor fractionation of oxygen and hydrogen isotopes of water from the freezing to the critical temperature. *Geochimica et Cosmochimica Acta*, *58*(16), 3425-3437.

Horton, J. L., Hart, S. C., & Kolb, T. E. (2003). Physiological condition and water source use of Sonoran Desert riparian trees at the Bill Williams River, Arizona, USA. *Isotopes in Environmental and Health Studies*, *39*(1), 69-82.

Hsiao, T. C. (1973). Plant responses to water stress. *Annual review of plant physiology*, *24*(1), 519-570.

Hsieh, J. C., Chadwick, O. A., Kelly, E. F., & Savin, S. M. (1998). Oxygen isotopic composition of soil water: quantifying evaporation and transpiration. *Geoderma*, *82*(1-3), 269-293.

Hunsinger, G. B., Hagopian, W. M., & Jahren, A. H. (2010). Offline oxygen isotope analysis of organic compounds with high N: O. *Rapid Communications in Mass Spectrometry*, *24*(21), 3182-3186.

IAEA/WMO (2017). Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html [Accessed May 2017].

IAEA/WMO (2017). Global Network of Isotopes in Rivers. The GNIR Database. Accessible at: http://www-naweb.iaea.org/napc/ih/IHS_resources_gnir.html [Accessed May 2017].

Jackson, P. C., Meinzer, F. C., Bustamante, M., Goldstein, G., Franco, A., Rundel, P. W., et al. (1999). Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. *Tree physiology*, *19*(11), 717-724.

Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., & Running, S. W. (2001). Water in a changing world. *Ecological applications*, *11*(4), 1027-1045.

Jacob, H., & Sonntag, C. (1991). An 8-year record of the seasonal variation of 2H and 18O in atmospheric water vapour and precipitation at Heidelberg, Germany. *Tellus B*, *43*(3), 291-300.

Jarvis, P. G. (1995). Scaling processes and problems. *Plant, Cell & Environment*, *18*(10), 1079-1089.

Jarvis, P. G., & McNaughton, K. G. (1986). Stomatal control of transpiration: scaling up from leaf to region. In *Advances in ecological research* (Vol. 15, pp. 1-49). Academic Press.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347.

Jonard, F., André, F., Ponette, Q., Vincke, C., & Jonard, M. (2011). Sap flux density and stomatal conductance of European beech and common oak trees in pure and mixed stands during the summer drought of 2003. *Journal of hydrology*, *409*(1-2), 371-381.

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., ... & Safranyik, L. (2008). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, *452*(7190), 987.

Lambs, L., Loubiat, M., Girel, J., Tissier, J., Peltier, J. P., & Marigo, G. (2006). Survival and acclimatation of Populus nigra to drier conditions after damming of an alpine river, southeast France. Annals of Forest Science, 63(4), 377-385.

Lambs, L., Loudes, J., & Berthelot, M. (2002). The use of the stable oxygen isotope (18 O) to trace the distribution and uptake of water in riparian woodlands. *Nukleonika*, *47*, 71-74.

Larsson, L. (2014). CooRecorder and Cdendro programs of the CooRecorder/Cdendro package version 7.7.

Lemoine, D., Peltier, J. P., & Marigo, G. (2001). Comparative studies of the water relations and the hydraulic characteristics in Fraxinus excelsior, Acer pseudoplatanus and A. opalus trees under soil water contrasted conditions. Annals of forest science, 58(7), 723-731.

Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M., & Nepstad, D. (2011). The 2010 amazon drought. *Science*, *331*(6017), 554-554.

Lin, G., & da SL Sternberg, L. (1993). Hydrogen isotopic fractionation by plant roots during water uptake in coastal wetland plants. In *Stable isotopes and plant carbon-water relations* (pp. 497-510).

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., ... & Lexer, M. J. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest ecology and management*, *259*(4), 698-709.

Lorrey, A. M., Brookman, T. H., Evans, M. N., Fauchereau, N. C., Macinnis-Ng, C., Barbour, M. M., et al. (2016). Stable oxygen isotope signatures of early season wood in New Zealand kauri (Agathis australis) tree rings: Prospects for palaeoclimate reconstruction. *Dendrochronologia*, *40*, 50-63.

Luz, B., Kolodny, Y., & Horowitz, M. (1984). Fractionation of oxygen isotopes between mammalian bone-phosphate and environmental drinking water. *Geochimica et Cosmochimica Acta*, *48*(8), 1689-1693.

Majoube, M. (1971). Oxygen-18 and deuterium fractionation between water and steam (in French). *Journal de Chimie Physique et de Physico-Chimie Biologique*, *68*, 1423-1436.

Mahoney, J. M., & Rood, S. B. (1998). Streamflow requirements for cottonwood seedling recruitment-An integrative model. *Wetlands*, *18*(4), 634-645.

Marshall, J. D., & Monserud, R. A. (2006). Co-occurring species differ in tree-ring δ18O trends. *Tree physiology*, *26*(8), 1055-1066.

MATLAB (R2015b), The MathWorks, Inc., Natick, Massachusetts, United States. (n.d)

McCarroll, D., & Loader, N. J. (2004). Stable isotopes in tree rings. *Quaternary Science Reviews*, *23*(7-8), 771-801.

McDowell, N. G., Beerling, D. J., Breshears, D. D., Fisher, R. A., Raffa, K. F., & Stitt, M. (2011). The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in ecology & evolution*, *26*(10), 523-532.

McNaughton, K. G., & Jarvis, P. G. (1991). Effects of spatial scale on stomatal control of transpiration. *Agricultural and Forest Meteorology*, *54*(2-4), 279-302.

Meinzer, F. C., Andrade, J. L., Goldstein, G., Holbrook, N. M., Cavelier, J., & Wright, S. J. (1999). Partitioning of soil water among canopy trees in a seasonally dry tropical forest. *Oecologia*, *121*(3), 293-301.

Merlivat, L. (1978). Molecular diffusivities of H 2 16 O, HD 16 O, and H 2 18 O in gases. *The Journal of Chemical Physics*, *69*(6), 2864-2871.

MeteoFrance – Accessible at: meteofrance.com [Accessed February 2017]

Milad, M., Schaich, H., Bürgi, M., & Konold, W. (2011). Climate change and nature conservation in Central European forests: a review of consequences, concepts and challenges. *Forest ecology and management*, *261*(4), 829-843.

Mintab (version 17), Minitab Inc. (n.d)

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of hydrology*, *391*(1-2), 202-216.

NOAA – 'National Oceanic Atmospheric Administration' Accessible at: https://www.esrl.noaa.gov/psd/data/gridded. [Accessed Dec. 2018].

Offermann, C., Ferrio, J. P., Holst, J., Grote, R., Siegwolf, R., Kayler, Z., & Gessler, A. (2011). The long way down—are carbon and oxygen isotope signals in the tree ring uncoupled from canopy physiological processes?. *Tree Physiology*, *31*(10), 1088-1102.

Ogée, J., Barbour, M. M., Wingate, L., Bert, D., Bosc, A., Stievenard, M., ... & Dewar, R. C. (2009). A single-substrate model to interpret intra-annual stable isotope signals in tree-ring cellulose. *Plant, Cell & Environment*, *32*(8), 1071-1090.

Oren, R., Sperry, J. S., Katul, G. G., Pataki, D. E., Ewers, B. E., Phillips, N., & Schäfer, K. V. R. (1999). Survey and synthesis of intra-and interspecific variation in stomatal sensitivity to vapour pressure deficit. *Plant, Cell & Environment*, *22*(12), 1515-1526.

Oshun, J., Dietrich, W. E., Dawson, T. E., & Fung, I. (2016). Dynamic, structured heterogeneity of water isotopes inside hillslopes. *Water Resources Research*, *52*(1), 164-189.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., et al. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). IPCC.

Parnell, A. C., Inger, R., Bearhop, S., & Jackson, A. L. (2010). Source partitioning using stable isotopes: coping with too much variation. *PloS one*, *5*(3), e9672.

Parnell, A., Inger, R., Bearhop, S., & Jackson, A. L. (2008). Stable isotope analysis in R (SIAR).

Parrot, E. (2015). Analyse spatio-temporelle de la morphologie du chenal du Rhône du Léman a la Méditerranéen (PhD Thesis), ENS, Lyon: 466

Pearcy, R.W., E.-D. Schulze and R. Zimmermann. (1989) Measurements of transpiration and leaf conductance. In Pearcy, R.W., Ehleringer, J.R., Mooney, H. and Rundel, P.W. (Eds.), *Plant physiological ecology: field methods and instrumentation* (pp. 137-160). Springer, Dordrecht.

Pettit, N. E., & Froend, R. H. (2018). How important is groundwater availability and stream perenniality to riparian and floodplain tree growth?. *Hydrological Processes*, *32*(10), 1502-1514.

Phillips, D. L., & Gregg, J. W. (2003). Source partitioning using stable isotopes: coping with too many sources. *Oecologia*, *136*(2), 261-269.

Phillips, O. L., Aragão, L. E., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., ... & Van Der Heijden, G. (2009). Drought sensitivity of the Amazon rainforest. *Science*, *323*(5919), 1344-1347.

Plamboeck, A. H., Grip, H., & Nygren, U. (1999). A hydrological tracer study of water uptake depth in a Scots pine forest under two different water regimes. *Oecologia*, *119*(3), 452-460.

Poyatos, R., Granda, V., Molowny-Horas, R., Mencuccini, M., Steppe, K., & Martínez-Vilalta, J. (2016). SAPFLUXNET: towards a global database of sap flow measurements. *Tree physiology*, *36*(12), 1449-1455.

Richards, J. H., & Caldwell, M. M. (1987). Hydraulic lift: substantial nocturnal water transport between soil layers by Artemisia tridentata roots. *Oecologia*, *73*(4), 486-489.

Richardson, A. D., Jenkins, J. P., Braswell, B. H., Hollinger, D. Y., Ollinger, S. V., & Smith, M. L. (2007). Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia*, *152*(2), 323-334.

Robertson, J. A., & Gazis, C. A. (2006). An oxygen isotope study of seasonal trends in soil water fluxes at two sites along a climate gradient in Washington state (USA). *Journal of Hydrology*, *328*(1-2), 375-387.

Robock, A., Vinnikov, K. Y., Srinivasan, G., Entin, J. K., Hollinger, S. E., Speranskaya, N. A., et al. (2000). The global soil moisture data bank. *Bulletin of the American Meteorological Society*, *81*(6), 1281-1300.

Roden, J. S., & Ehleringer, J. R. (2000). Hydrogen and oxygen isotope ratios of tree ring cellulose for field-grown riparian trees. *Oecologia*, *123*(4), 481-489.

Roden, J. S., Johnstone, J. A., & Dawson, T. E. (2009). Intra-annual variation in the stable oxygen and carbon isotope ratios of cellulose in tree rings of coast redwood (Sequoia sempervirens). *The Holocene*, *19*(2), 189-197.

Roden, J. S., Lin, G., & Ehleringer, J. R. (2000). A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. *Geochimica et Cosmochimica Acta*, *64*(1), 21-35.

Rossi, S., Anfodillo, T., & Menardi, R. (2006). Trephor: a new tool for sampling microcores from tree stems. *Iawa Journal*, *27*(1), 89-97.

Rundel, P.W., & Jarrell, W. M., (1989). Water in the Environment. In Pearcy, R.W., Ehleringer, J.R., Mooney, H. and Rundel, P.W. (Eds.), *Plant physiological ecology: field methods and instrumentation*. Springer, Dordrecht.

Sánchez-Pérez, J. M., Lucot, E., Bariac, T., & Trémolières, M. (2008). Water uptake by trees in a riparian hardwood forest (Rhine floodplain, France). *Hydrological Processes: An International Journal*, *22*(3), 366-375.

Sargeant, C. I., & Singer, M. B. (2016). Sub-annual variability in historical water source use by Mediterranean riparian trees. *Ecohydrology*, *9*(7), 1328-1345.

Sarris, D., Christodoulakis, D., & Körner, C. (2011). Impact of recent climatic change on growth of low elevation eastern Mediterranean forest trees. *Climatic Change*, *106*(2), 203-223.

Schlesinger, W. H., Dietze, M. C., Jackson, R. B., Phillips, R. P., Rhoades, C. C., Rustad, L. E., & Vose, J. M. (2016). Forest biogeochemistry in response to drought. *Global change biology*, *22*(7), 2318-2328.

Schuepp, P. H. (1993). Tansley review no. 59 leaf boundary layers. *New Phytologist*, *125*(3), 477-507.

Schulze, E. D., Mooney, H. A., Sala, O. E., Jobbagy, E., Buchmann, N., Bauer, G., et al. (1996). Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia. *Oecologia*, *108*(3), 503-511.

Schulze, E. D., Robichaux, R. H., Grace, J., Rundel, P. W., & Ehleringer, J. R. Plant Water Balance. *BioScience*, *37*(1).

Schwartz, M. D., Reed, B. C., & White, M. A. (2002). Assessing satellite-derived start-of-season measures in the conterminous USA. *International Journal of Climatology*, *22*(14), 1793-1805.

Scott, R. L., Edwards, E. A., Shuttleworth, W. J., Huxman, T. E., Watts, C., & Goodrich, D. C. (2004). Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. *Agricultural and Forest Meteorology*, *122*(1-2), 65-84.*Measurement*, *54*, 92-105.

Settele, J., Scholes, R., Betts, R. A., Bunn, S., Leadley, P., Nepstad, D., et al. (2015). Terrestrial and inland water systems. In *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*. Cambridge University Press.

Shafroth, P. B., Stromberg, J. C., & Patten, D. T. (2000). Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist*, 66-76.

Silva, L. C., Anand, M., & Leithead, M. D. (2010). Recent widespread tree growth decline despite increasing atmospheric CO2. *PloS one*, *5*(7), e11543.

Singer, M. B., Sargeant, C. I., Piégay, H., Riquier, J., Wilson, R. J., & Evans, C. M. (2014). Floodplain ecohydrology: Climatic, anthropogenic, and local physical controls on partitioning of water sources to riparian trees. *Water resources research*, *50*(5), 4490-4513.

Singer, M. B., Stella, J. C., Dufour, S., Piégay, H., Wilson, R. J., & Johnstone, L. (2013). Contrasting water-uptake and growth responses to drought in co-occurring riparian tree species. *Ecohydrology*, *6*(3), 402-412.

Singer, M. B., & Dunne, T.(2004). An empirical-stochastic, event-based model for simulating inflow from a tributary network: Theoretical framework and application to the Sacramento River basin, California, *Water Resour. Res.*, *40*(7), W07506, doi:07510.01029/02003WR002725.

Sippel, S., Zscheischler, J., Heimann, M., Lange, H., Mahecha, M. D., van Oldenborgh, G. J., et al. (2016). Have precipitation extremes and annual totals been increasing in the world's dry regions over the last 60 years?. *arXiv preprint arXiv:1609.00154*.

Snyder, K. A., & Williams, D. G. (2000). Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. *Agricultural and Forest Meteorology*, *105*(1-3), 227-240.

Song, X. I. N., Barbour, M. M., Farquhar, G. D., Vann, D. R., & Helliker, B. R. (2013). Transpiration rate relates to within-and across-species variations in effective path length in a leaf water model of oxygen isotope enrichment. *Plant, Cell & Environment*, *36*(7), 1338-1351.

Soudant, A., Loader, N. J., Bäck, J., Levula, J., & Kljun, N. (2016). Intra-annual variability of wood formation and δ13C in tree-rings at Hyytiälä, Finland. *Agricultural and forest meteorology*, *224*, 17-29.

Sprenger, M., Leistert, H., Gimbel, K., & Weiler, M. (2016). Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. *Reviews of Geophysics*, *54*(3), 674-704.

Srivastava, P. K. (2017). Satellite soil moisture: Review of theory and applications in water resources. *Water Resources Management*, *31*(10), 3161-3176.

Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D., & Peiry, J. L. (2005). Hydrogeomorphic processes affecting riparian habitat within alluvial channel–floodplain river systems: a review for the temperate zone. *River Research and Applications*, *21*(7), 719-737.

Stephenson, N. L. (1990). Climatic control of vegetation distribution: the role of the water balance. *The American Naturalist*, *135*(5), 649-670.

Sternberg, L. D. S., Deniro, M. J., & Savidge, R. A. (1986). Oxygen isotope exchange between metabolites and water during biochemical reactions leading to cellulose synthesis. *Plant Physiology*, *82*(2), 423-427.

Stokes, V. (2004). Assessing water use in plants: an introduction and guide to methods of measurement. *SCOTTISH FORESTRY.*, *58*(2), 13-21.

Stokes, V. J., Morecroft, M. D., & Morison, J. I. (2006). Boundary layer conductance for contrasting leaf shapes in a deciduous broadleaved forest canopy. *Agricultural and Forest Meteorology*, *139*(1-2), 40-54.

Stromberg, J. C., & Patten, D. T. (1996). Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. *Regulated Rivers: Research & Management*, *12*(1), 1-12.

Stromberg, J. C., Beauchamp, V. B., Dixon, M. D., Lite, S. J., & Paradzick, C. (2007). Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology*, *52*(4), 651-679.

SU, S. L., Singh, D. N., & Baghini, M. S. (2014). A critical review of soil moisture measurement.

Sun, Z., Long, X., & Ma, R. (2016). Water uptake by saltcedar (Tamarix ramosissima) in a desert riparian forest: responses to intra-annual water table fluctuation. *Hydrological Processes*, *30*(9), 1388-1402.

Suni, T., Berninger, F., Markkanen, T., Keronen, P., Rannik, Ü., & Vesala, T. (2003). Interannual variability and timing of growing-season CO2 exchange in a boreal forest. *Journal of Geophysical Research: Atmospheres*, *108*(D9).

Trenberth, K. E., Dai, A., Van Der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change*, *4*(1), 17.

Vargas, A. I., Schaffer, B., Yuhong, L., & Sternberg, L. D. S. L. (2017). Testing plant use of mobile vs immobile soil water sources using stable isotope experiments. *New Phytologist*, *215*(2), 582-594.

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of climate*, *23*(7), 1696-1718.

Volkmann, T. H., & Weiler, M. (2014). Continual in situ monitoring of pore water stable isotopes in the subsurface. *Hydrology and Earth System Sciences*, *18*(5), 1819-1833.

Wen, X. F., Zhang, S. C., Sun, X. M., Yu, G. R., & Lee, X. (2010). Water vapor and precipitation isotope ratios in

West, A. G., Patrickson, S. J., & Ehleringer, J. R. (2006). Water extraction times for plant and soil materials used in stable isotope analysis. *Rapid Communications in Mass Spectrometry: An International Journal Devoted to the Rapid Dissemination of Up-to-the-Minute Research in Mass Spectrometry*, *20*(8), 1317-1321.

White, J. C., & Smith, W. K. (2013). Water sources in riparian trees of the southern Appalachian foothills, USA: A preliminary study with stable isotope analysis. *Riparian Ecology and Conservation*, *1*, 46-52.

White, J. W., Cook, E. R., & Lawrence, J. R. (1985). The DH ratios of sap in trees: Implications for water sources and tree ring DH ratios. *Geochimica et Cosmochimica Acta*, *49*(1), 237-246.

Yakir, D., & DeNiro, M. J. (1990). Oxygen and hydrogen isotope fractionation during cellulose metabolism in Lemna gibba L. *Plant Physiology*, *93*(1), 325-332.

Yale University (2017) The Stable Water Vapor Isotope Database (SWVID). Accessible at: http://vapor-isotope.yale.edu/ [Accessed 15 Jun 2017].

Zencich, S. J., Froend, R. H., Turner, J. V., & Gailitis, V. (2002). Influence of groundwater depth on the seasonal sources of water accessed by Banksia tree species on a shallow, sandy coastal aquifer. *Oecologia*, *131*(1), 8-19.

Zweifel, R., Item, H., & Häsler, R. (2001). Link between diurnal stem radius changes and tree water relations. *Tree Physiology*, *21*(12-13), 869-877.

FIGURE CAPTIONS

Figure 1: Overview of ISO-Tool and the primary components.

Figure 2: Key model components and how the required user input values are utilized (a-d), with associated terminology, and schematics of each process (e).

Figure 3: Results of sensitivity analyses of independently (a) and co-varied (b-g) input variables on the modeled $\delta^{18}O_{sw}$ value. Sensitivity analyses of co-varied model inputs of (b)T and RH, (c) RH and $\delta^{18}O_{wv}$, (d) T and $\delta^{18}O_{wv}$, (e) $\delta^{18}O_{wv}$ with g_s/E pairing, (f) RH with g_s/E pairing and (g) T with g_s/E pairing. Grey shading in b-d indicates the range of $\delta^{18}O_{msw}$ results produced by varying the respective input variables over their observed range of variance for the DM site (May-Sep: 2000-2010).

Figure 4: The ISO-Toolkit components and interpretative techniques, divided into tool groups based on data availability and resolution, with Tool Group A being the most desirable set of data and interpretative techniques. A review of the mentioned datasets and interpretative techniques is given in the supplementary text material (S1-3).

Figure 5: The mean annual $\delta^{18}O_{msw}$ for *Populus nigra* trees at site PB in relation to potential endmember water sources mean δ^{18}O (a), sub-annual $\delta^{18}O_{msw}$ for *Fraxinus excelsior* and *Populus nigra* at site DM shown in relation to potential endmember water source mean δ^{18}O (b) and the annual and sub-annual $\delta^{18}O_{msw}$ for *Fraxinus excelsior* at site MT (c). Colored banding around all reported $\delta^{18}O_{msw}$ is ± 1SD (based on the output of 1000 Monte Carlo simulations) and endmember water sources are shown as mean δ^{18}O ± 1SD.