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Sub-annual variability in historical water source use by Mediterranean riparian trees.

Abstract:

Our study investigated the seasonal variability in historical water source use of *Fraxinus excelsior* and *Populus nigra*. We utilized a new method which combines tree-ring isotopes and isotope modelling to determine how tree water use varied at the sub-annual level over 10 consecutive growing seasons (2000-2010). We conducted tree-ring micro-slicing to produce highly resolved cellulose $\delta^{18}\text{O}$ records and back calculated the $\delta^{18}\text{O}$ signature of the source water used for growth of each micro-slice. We compared these results to regional water $\delta^{18}\text{O}$ signatures to infer seasonal hydrological partitioning. *Fraxinus* was dependent on non-growing and growing season rainfall from the vadose zone whilst *Populus* relied on hyporheic and regional groundwater. We observed a convergence in water use of both species from 2007 which is attributed to a decline in phreatic water access to *Populus*.

Project objectives and context:

Climate dynamically controls water availability to forest trees. The signatures of tree water use in response to climatically driven water availability are preserved within tree-ring cellulose ($\delta^{18}\text{O}_{\text{cell}}$), but they are not well understood. This limits scientific capability to anticipate how variability and trends in climate will control water availability at the root zone and its uptake by plants. This is particularly relevant in riparian systems where there are strong connections between vegetation and hydrology and where trees may access various water sources based on rooting depth and climatic forcing. The susceptibility of riparian forests to changes in the availability of water within terrestrial storage reservoirs (*i.e.* vadose and phreatic zones) is well appreciated. Yet there is a lack of information regarding the seasonal progression of water partitioning within these floodplain reservoirs and its uptake by trees. Such seasonal variability in water source availability and water use may complicate interpretation of annual tree ring isotopes because mean values for a particular year may not be reflective of the dominant climatic forcing (*e.g.* precipitation-derived soil water *v.* streamflow-driven phreatic water). This limitation may prove problematic for predicting climatic responses of forests in the Mediterranean, where hydrological regimes are predicted to be strongly influenced by rising temperatures and changes to the quantity and timing of precipitation.

We aimed to assess the utility of sub-annual tree-ring $\delta^{18}\text{O}$ analyses for interpreting the historical, seasonal water use of riparian trees as a function of regional hydrology and climate. We analyzed the $\delta^{18}\text{O}_{\text{cell}}$ of micro-slices from ten consecutive tree rings of two co-occurring tree species; *Fraxinus excelsior* and *Populus nigra*. The streamside trees were sampled from along the Rhône River, southern France (Donzère).

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Methodologies:

We cored co-located streamside trees of *F. excelsior* and *P. nigra* (DBH of 37 cm and 70 cm respectively) for isotopic analyses using a 5-mm increment borer. *Fraxinus* is shallowly rooted within the vadose zone whilst *Populus* is roots deeper into the phreatic zone.

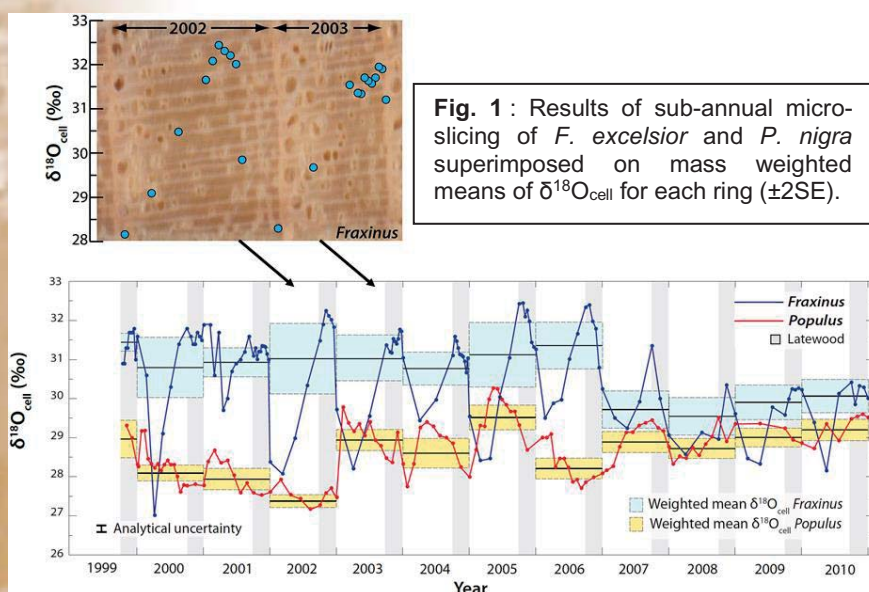
We micro-sliced the annual rings of each tree (2000-2010) using a sledge microtome to produce 252 samples which then underwent α -cellulose extraction and isotopically analyzed (Fig. 1). The $\delta^{18}\text{O}_{\text{cell}}$ signature was then deconvolved to determine the source water ($\delta^{18}\text{O}_{\text{modsw}}$) used at the time of its formation using a mechanistic model, driven by climate and physiological variables.

We compared the sub-annual $\delta^{18}\text{O}_{\text{modsw}}$ signatures of each tree to local and regional water sources ($\delta^{18}\text{O}$) which may contribute to water uptake at the different rooting depths. We sampled the Rhône, Ardèche and shallow phreatic waters (5 m depth) and developed isotopic signatures of precipitation ($\delta^{18}\text{O}_{\text{ppt}}$) for growing and non-growing seasons.

Main results:

Potential source water $\delta^{18}\text{O}$

The Rhône River $\delta^{18}\text{O}$ was significantly more depleted than the Ardèche River and local surface waters, indicating a snowmelt origin. The Ardèche River and local tributaries (Central Massif origin) and shallow phreatic waters are relatively enriched and isotopically similar suggesting a common, regional recharge zone. The time series of calculated mean monthly precipitation $\delta^{18}\text{O}$ displayed the expected seasonality of enriched summer and depleted winter precipitation. We assessed the isotopic signature of seasonal precipitation contributions (NGS/GS $\delta^{18}\text{O}_{\text{ppt}}$) by weighting the mean values of $\delta^{18}\text{O}$ by monthly precipitation totals. The seasonal difference in $\delta^{18}\text{O}_{\text{ppt}}$ was 1.6‰ (higher in the GS). The strong isotopic differences between NGS and GS precipitation allow for the seasonal discrimination of moisture inputs within the vadose zone. Hyporheic discharge provides highly depleted source water to the phreatic zone which contrasts to the enriched regional groundwater in this site. These differences provide good potential to identify the source of water delivered to contrasting rooting zones of *Fraxinus* and *Populus*.



Cellulosic oxygen ($\delta^{18}\text{O}_{\text{cell}}$).

F. excelsior had a higher sub-annual variability in $\delta^{18}\text{O}_{\text{cell}}$ over the decade compared to *P. nigra* (SD = 1.2‰ and 0.7‰ respectively), whilst the series means revealed that *Fraxinus* $\delta^{18}\text{O}_{\text{cell}}$ was substantially more enriched (30.7‰) than *Populus* (28.7‰) (Fig. 1). We also observed an apparent shift towards inter-species $\delta^{18}\text{O}_{\text{cell}}$ coherence following the year 2006, concomitant with a reduction in sub-annual $\delta^{18}\text{O}_{\text{cell}}$ variability for both trees (Fig. 1). Visual comparison of micro-slice $\delta^{18}\text{O}_{\text{cell}}$ against mass-weighted $\delta^{18}\text{O}_{\text{cell}}$ of whole rings demonstrated that considerable

isotopic information is masked through whole-ring analyses, e.g. the difference between the weighted mean $\delta^{18}\text{O}_{\text{cell}}$ of *Fraxinus* in 2001 and 2002 is only 0.1‰, yet these years are markedly different in their seasonal pattern of $\delta^{18}\text{O}_{\text{cell}}$. The strong variability in sub-annual $\delta^{18}\text{O}_{\text{cell}}$ for both species suggests that important seasonal information relating to tree-level and climatic processes is retained within each ring. The $\delta^{18}\text{O}_{\text{cell}}$ results indicate a period where the isotopic values of both species synchronize which may be a record of a change in hydrological conditions.

Modelled source-water ($\delta^{18}\text{O}_{\text{modsw}}$)

Overall, *Fraxinus* demonstrated a more pronounced trend in its seasonal $\delta^{18}\text{O}_{\text{modsw}}$ compared to *Populus*, as well as a more enriched (-6.7‰) $\delta^{18}\text{O}_{\text{modsw}}$ than *Populus* (-9.2‰) ($T_{246} = 8.42, p < 0.001$) which indicates differences in source water usages. Generally, the sub-annual progression of $\delta^{18}\text{O}_{\text{modsw}}$ in *Fraxinus* followed a pattern of depleted water in the earlywood followed by progressive enrichment into the latewood fraction. The sub-annual $\delta^{18}\text{O}_{\text{modsw}}$ of *Fraxinus* shows uptake of vadose zone moisture derived from NGS (earlywood) and GS (latewood) precipitation (Fig.2). From 2007 *Fraxinus* appears to rely on only NGS precipitation for growth. For *P. nigra* the sub-annual pattern of $\delta^{18}\text{O}_{\text{modsw}}$ suggests that it apparently uses phreatic water derived from two distinct sources, depleted river water and enriched regional groundwater, producing a pattern of seasonal variation in $\delta^{18}\text{O}_{\text{modsw}}$ (Fig.3). As an explanation we suggest a ‘bank storage’ effect, whereby shallow alluvial water sourced from the Massif Central (enriched $\delta^{18}\text{O}$) fills up the floodplain phreatic zone during low river levels which is then displaced by the Rhône snowmelt pulse (depleted $\delta^{18}\text{O}$) in spring. Post-2007 this pattern is completely disrupted and there is a strong similarity between ($\delta^{18}\text{O}_{\text{ppt}}$) and *Populus* $\delta^{18}\text{O}_{\text{modsw}}$ which suggests this species is relying on vadose zone water from 2007-2010 (Fig. 2).

Fig. 2

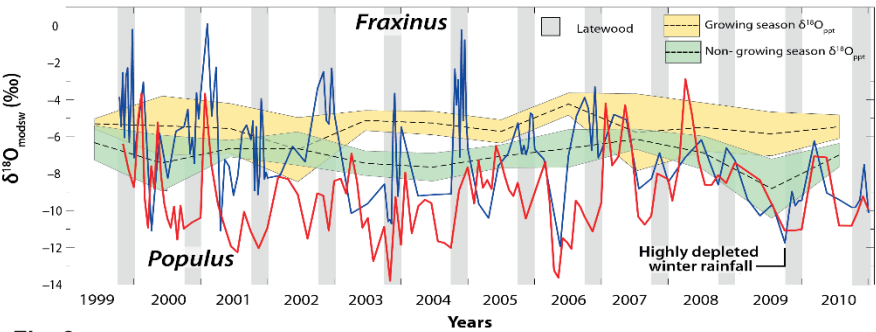
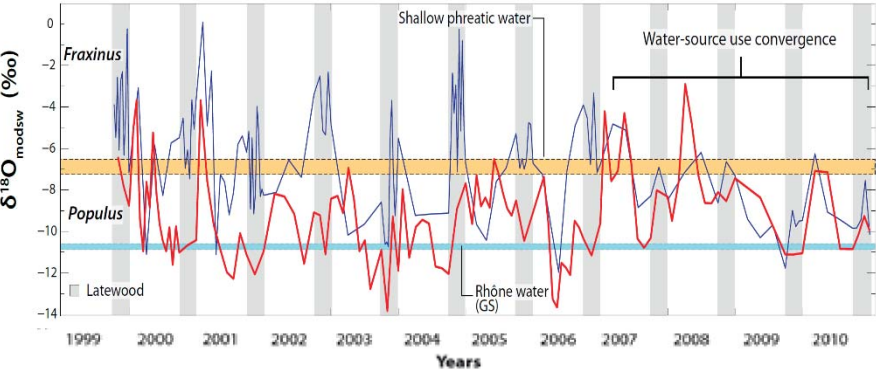


Fig. 3



Figures 2: Time series of growing season and non-growing season $\delta^{18}\text{O}_{\text{ppt}}$ in relation to both species $\delta^{18}\text{O}_{\text{modsw}}$. Coloured spread is ± 2 SE.
Figure 3: $\delta^{18}\text{O}_{\text{modsw}}$ sub-annual tree source waters and mean Rhône and shallow phreatic waters (± 2 SE)

The convergence in $\delta^{18}\text{O}_{\text{modsw}}$ for both *Fraxinus* and *Populus* after 2007 suggests that *P. nigra* became disconnected from its phreatic water source, which we interpret as a decline of the near-channel floodplain water table. However, discharge data do not support a reduction in streamflow. We therefore investigated whether an alternative mechanism may have led to a reduction in water table height. Channel bathymetry data for the Rhône River adjacent to our study site indicated that this section of river has undergone a progressive pattern of intermittent channel incision. Most importantly, between 1998 and 2007 the channel incised by about 2 m, and the greatest rate of riverbed down-cutting occurred between 2003 and 2007, resulting in 1.5 m of incision. Since channel

elevation affects local river stage, river stage affects lateral hyporheic flow, and hyporheic flow affects floodplain water table elevation, these data provide evidence that the phreatic water table declined substantially in the period leading up to 2007, perhaps crossing a threshold for separating *P. nigra* roots from the phreatic water source. We found that substantially more isotopic information is obtained through micro-slicing of individual tree-rings compared to whole ring analyses alone and this information provides a window into patterns of seasonal water use by riparian trees obtaining water from different floodplain water sources. To our knowledge this is the first study to interpret micro-slice $\delta^{18}\text{O}_{\text{cell}}$ variations on a historical timescale of decades in terms of seasonal water-source fluxes and uptake from the rooting zones through the use of back-calculated $\delta^{18}\text{O}_{\text{modsw}}$ values. These back calculations produce an isotopic signature that is directly comparable to the $\delta^{18}\text{O}$ of measured and reconstructed endmember water sources enabling a dynamic analysis of how fluctuations in hydrology affect trees and forests.

Perspectives:

This research is the first to describe the variability in subsurface hydrology on seasonal timescales using tree ring isotopes. It presents great promise for the development and evaluation of new river restoration strategies such as minimum flow restoration, in terms of their benefits to riparian forests

Practitioners' benefits:

We envisage such data to be of benefit to resource managers working to restore riparian systems in areas which have undergone human alteration as well providing key historical and baseline data for anticipating ecohydrological consequences of climate change.

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