Sub-daily stable water isotope dynamics of urban tree xylem water and ambient vapor

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Abstract. ~~Urban vegetation is vulnerable to rising temperatures and reduced rainfall, which reduces the cooling function of urban green spaces (UGS).~~ The sub-daily dynamics of ~~UGS~~ vegetation mediated water cycling and how this changes over the growing season remains largely unexplored due to measurement constraints. The monitoring of long-term in situ high-resolution stable water ~~stable~~ isotopes can provide valuable insights into how trees and the surrounding atmosphere ~~internally~~ cycle water under different conditions. In this study, we analyzed a sub-daily (~3-4 hourly) dataset of atmospheric water vapor (δ_v) and tree stem xylem water (δ_{xyl}) in an urban tree stand in Berlin, Germany. We compared the diurnal (24 h) patterns of water cycling in δ_v and~~,~~ δ_{xyl} values, as well as~~and~~ ecohydrological variables during a summer drought (01.07.-14.08.) followed by a rewetting period (15.08.-30.09.) in 2022. Over the summer drought, water cycling was predominantly radiation driven, with highest vapor pressure deficit (VPD) rates in the afternoons and persistantly dry soils. We found systematic behaviour in both δ_v and δ_{xyl} signatures during the summer drought and δ_v values were~~as~~ characterized by a daytime depletion in heavy isotopes, driven by local evaporation and atmospheric factors (i.e., entrainment). The mean amplitude between day- and night-time values of δ_v during drought was 26 ‰ for δ^2H. Daytime enrichment in δ_{xyl} values, with maximal isotopic enrichment in afternoons, was consistent with diurnal hydroclimatic cycles, maximum potential evaporation (PET) of ~ 0.75 mm h^{-1} limited sap flow sourced from enriched soil water at the topsoil and stomatal regulation of transpiration. The mean amplitude between day- and night-time values of δ_{xyl} during drought was 38 ‰ for δ^2H. The trees showed lower twig water potential and sap flux relative to VPD in the afternoons, as well as stagnated night-time stem swelling, but the mature trees could overall sustain their physiological functioning. During rewetting, the ~~UGS~~ water cycle of the green space was precipitation driven, while ~~potential evapotranspiration (PET)~~ maximum PET rates decreased to 0.5 mm h^{-1}. The systematic diurnal cycling of δ_v values was mostly discontinued due to lower soil and canopy evaporation. Only δ_v values just above the grassland surface (0.15 m) showed a significant daytime enrichment in heavy isotopes (amplitude ~ 36 ‰ δ^2H) hinting for evapotranspiration~~ET~~ fluxes promoted by high moisture stored in soil and vegetation surfaces and transpiration of superficially enriched soil water. δ_{xyl} values were~~was~~ still characterized by significant daytime enrichment, however, with sub-daily amplitudes of 20 ‰ δ^2H almost~~more than~~ halved compared to the drought period, when hydraulic conductance was restricted. Our continuous, sub-daily dataset of δ_v and δ_{xyl} values provides unique insights on the complex SWI dynamics within trees and the surrounding atmosphere. It has~~ve~~ the potential to help constrain ecohydrological models towards prediction of climate change impacts on ~~UGS~~water cycling within vegetated areas. ~~Urban planning should consider a "mosaic" of urban vegetation types together with resilient species composition to maximize cooling benefits throughout the 24-hour cycle.~~

1 Introduction

~~Climate extremes such as drought and flooding are worldwide increasing in frequency and intensity (IPCC, 2023). These extreme events have special impacts on city ecosystems (Dodman et al., 2023), e.g. with urban heat island effects (Oke, 1976). Urban green spaces (UGS) are especially vulnerable to rising temperatures and lower rainfall (Ordóñez and Duinker, 2014; Miller et al., 2020; Szalińska et al., 2018). In Berlin, Germany, urban forests and especially single urban street trees have shown rising mortalities in recent years (Hurley and Heinrich, 2024; SenMVKU, 2021, 2024). At the same time, urban dwellers benefit from well-functioning urban green spaces, with enhanced amenity, biodiversity and the cooling potential from evapotranspiration (ET) all enhancing general wellbeing (McPhearson et al., 2015). This emphasizes the need to understand UGS water cycling and physiological responses (e.g. plant water transport, ET processes) to predict further impact of climate variability and change on UGS.~~

~~The ecohydrological dynamics affecting atmospheric water vapor (Kim et al., 2021) and tree xylem water (water flowing through a tree's stem; Köcher et al., 2009) are key indicators of processes underpinning the benefits of UGS (Stevenson et al., 2025) as they provide insights into evapotranspiration (ET), water-limiting conditions, tree functioning and groundwater recharge (Dubbert and Werner, 2019; Wang et al., 2017). These water cycling processes have rarely been investigated on sub-daily scales over prolonged periods mainly due to measurement constraints (Meili et al., 2021), particularly in urban areas. Differentiating between morning, afternoon and nighttime patterns of water fluxes brings a novel perspective to urban ecohydrology (Konarska et al., 2016). Changes over the growing season, along with alternating periods of wet and dry conditions (cf. DWD, 2022a), are of additional importance for a holistic understanding of UGS water regimes. Especially extreme events like summer droughts and subsequent transitions to autumn rewetting, are poorly understood on a sub-daily scale (cf. Marx et al., 2022). Thus, the sub-daily dynamics of UGS water cycling and how they change over the growing season remains largely unexplored (cf. Seeger and Weiler, 2021; Ring et al., 2024), inhibiting understanding of how urban trees use water.~~

Terrestrial vegetation plays a critical role in regulating water and energy fluxes (Asbjornsen et al., 2011; Bernacchi and VanLoocke, 2015). These fluxes are driven by the ecohydrological dynamics of atmospheric vapor and tree-internal water transport, which are essential for assessing evapotranspiration (ET) patterns, water-limiting conditions, tree function, and groundwater recharge (Dubbert and Werner, 2019; Stevenson et al., 2025; Wang et al., 2017). Despite their importance, these water cycling processes have rarely been investigated on sub-daily scales over prolonged periods mainly due to measurement constraints (Warix et al., 2023; Penna et al., 2018; Meili et al., 2021). Differentiating between morning, afternoon and nighttime temporal patterns, including source water partitioning of water fluxes such as hydraulic redistribution, transpiration cycling and relative humidity gradients brings a novel perspective to ecohydrology (Nadezhdina et al., 2010; Konarska et al., 2016; Kim et al., 2021; Stevenson et al., 2023). Seasonal changes, along with alternating wet and dry periods (DWD, 2022a), are of additional importance for a holistic understanding of water regimes in vegetated landscapes. In particular extreme events like summer droughts and subsequent autumn rewetting remain poorly understood at sub-daily scales, limiting insight into tree water use (Marx et al., 2022). As a result, how these sub-daily dynamics evolve over the growing season and affect water cycling has yet to be fully elucidated to predict further impact of climate variability on vegetation water fluxes (Seeger and Weiler, 2021; Ring et al., 2024).

Stable water isotopes (SWI) are useful tools for understanding water cycling in the soil-plant-atmosphere continuum (SPAC) (Tetzlaff et al., 2015). Numerous studies have investigated water cycling through the lens of ~~stable water isotopes~~SWI dynamics in plant xylem water (δ_{xyl}) and atmospheric water vapor (δ_v) in the SPAC (e.g. Orlowski et al., 2023; Dubbert and Werner, 2019). The collection of δ_{xyl} can be performed destructively by drilling xylem cores or clipping branches in the field and most commonly extracting the water via cryogenic vacuum distillation in the lab - mostly at coarse temporal resolution from weeks to months (Tetzlaff et al., 2021) or at higher frequency but usually over a relatively short amount of days (Sohel et al., 2023a; Bernhard et al., 2024). In the past, most samples of δ_v were obtained through discrete collection in the field via cryogenic trapping (e.g. Helliker et al., 2002). Also, a more novel method is trapping ~~δ_v~~ soil water vapor with diffusion-tight bags (Dahlmann et al., 2025; Herbstritt et al., 2023).

More recently, field studies which measure ~~stable water isotopes~~SWI in situ by cavity ring-down spectroscopy (CRDS) have provided more detailed insights into processes of water cycling (Beyer et al., 2020; Galewsky et al., 2016). For instance, original observations were made of the SWI dynamics in soil and transpiration water of mixed tree cultures as well as pore water in the subsurface of a vineyard terrace (Volkmann et al., 2016a; Volkmann and Weiler, 2014). ~~Although, the fractionation of δ_{xyl} through plant physiological processes can be a confounding issue (Barbeta et al., 2020; Vega-Grau et al., 2021).~~ After the pioneering approach for in situ monitoring of tree δ_{xyl} values by Volkmann et al. (2016b), ~~Previous~~ various in situ studies investigating δ_{xyl} at high temporal resolution were performed over several weeks or months, e.g. for beech trees in a mixed forest (Gessler et al., 2022) or riparian willow trees (Landgraf et al., 2022), and~~but~~ rarely at urban sites, ~~and~~ usually presented as daily mean values to account for the high methodological uncertainties (Kühnhammer et al., 2022; Landgraf et al., 2022). Wherein, the fractionation of δ_{xyl} values through plant physiological processes can be a confounding issue (Barbeta et al., 2020; Vega-Grau et al., 2021). The influence of time of the day on in situ monitored δ_{xyl} was first investigated in a tropical field location during the dry season for three months by Kühnhammer et al. (2022). They found clear diurnal differences of δ_{xyl}; although data analysis was restricted with < 1.2 measurements per day for each of around 3 boreholes of two trees and soil moisture measurements at different depths. Kübert et al. (2022) have analyzed the dynamics of sub-daily transpired water from an experiment in an enclosed rainforest using a δ^2H deep water pulse. They were able to capture quick responses (2 h resolution) in plant water transport showing the value of high resolution in situ measurements of plant water. Recent work by Tierney et al. (2025) on the influence of time of day on xylem SWI samples indicated clear differences between AM and PM samples of δ_{xyl} values of oak and maple in a temperate US forest. To our knowledge, no literature exists which combined prolonged in situ measurements of δ_{xyl} and δ_v in combination with high-resolution sub-daily environmental and plant physiological data.

Several in situ studies that have performed real-time analysis of δ_v provided insights on seasonal changes in partitioning of ET ~~evapotranspiration~~ above agricultural land (Wei et al., 2015) or diurnal variations in evaporative signals at different heights above the Greenland ice sheet (Steen-Larsen et al., 2013). A recent urban study from Berlin-Friedrichshagen, 2021, has shown contrasting (sub-)daily dynamics of δ_v above different urban green spaces~~UGS~~, that indicated evaporative fractionation after rainfall events just above an urban grassland surface (Ring et al., 2023). But in general, prolonged (several months) in situ measurements of δ_{xyl} and δ_v and that allow interpretation of sub-daily dynamics over a full growing period are rare. Reasons are that obtaining and quality-checking such datasets is time consuming and expensive. Previously reported methodological uncertainties can be overcome through rigorous maintenance and quality checking (cf. methods by Ring et al., 2024; Kühnhammer et al., 2022).

Here, we analyze a sub-daily dataset of ~~urban~~ in situ δ_{xyl} and δ_v together with environmental and plant physiological data from an urban tree stand and an urban grassland throughout the whole growing season in 2022, in Berlin, Germany. We compare diurnal (24h) patterns of water cycling at these different types of vegetation ~~in UGS~~ during a period of summer drought followed by autumn rewetting. The summer in 2022 was the 4th hottest summer in ~~Europe~~ Berlin since records began in 1881, according to DWD (2022c). ~~Copernicus Climate Service, 2022.~~ Thus, this research has the potential to gain novel high-frequency insights on sub-daily atmospheric vapor and plant ~~UGS~~ water cycling in times of climate change.

Our specific research questions were:

- What are the sub-daily dynamics of δ_{xyl} and δ_v values~~xylem and vapor water stable isotopes~~ over the growing season in different ~~urban~~ types of vegetation?
- Can we identify water limitations on tree function at a sub-daily basis~~ for the investigated urban green vegetation~~?
- Do high-resolution sub-daily~~hourly~~ water isotope data provide significant new insights, or are daily means sufficient for understanding ~~urban~~ moisture cycling at the plot scale?

The work was intended to give valuable insights into the mechanistic links of sub-daily water cycling at the SPAC during summer drought and autumn rewetting~~ for informing urban green space planning and maintenance strategies under future climate scenarios~~. It was also expected that the sub-daily signals help to explain previously unexplained short-term variations in daily ~~stable water isotopes~~SWI datasets.

2 Study Site

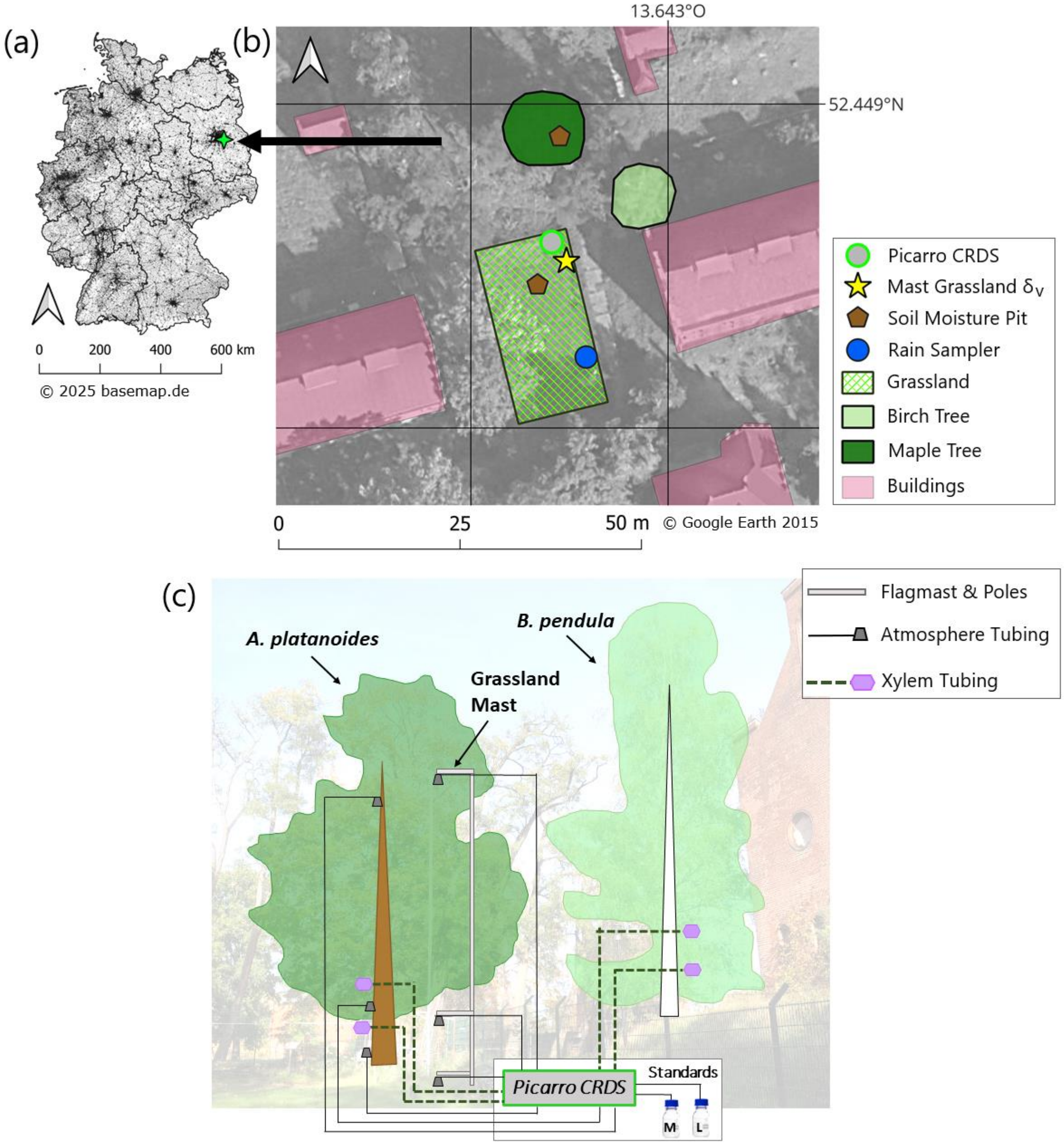

Figure 1: (a) Location of the study site in Germany (residential areas and borders of federal states in black - modified from basemap.de/open-data). (b) Study site in Berlin-Friedrichshagen with investigated grassland, ~~Norway maple~~*A. platanoides* and ~~Silver birch~~*B. pendula*, including cavity ring-down spectroscopy (CRDS), flag mast for atmospheric vapor (δ_v) measurements, soil moisture pits (underneath canopy and at grassland) and precipitation sampler (basemap: © Google Earth 2015). (c) Conceptual diagram of the general in situ measuring setup for stable water isotopes of atmospheric water vapor (δ_v) and plant xylem water (δ_{xyl}). All inlets were measured sequentially via tubing connected to the CRDS. δ_v was measured at 0.15 m, 2 m and 10 m height under the *A. platanoides* canopy and above grassland at a flag-pole (distance between *A. platanoides* and flag mast was 16 m; grey caps refer to rain and wind protection cover). δ_{xyl} was measured from boreholes at *A. platanoides* and *B. pendula* (1.5 m and 2.5 m height; violet hexagons refer to attached bottles filled with desiccant). Temperature probes were placed at each tubing inlet. Standards were connected via tubing for automated calibration with liquid values of δ^2H = -73.623 ‰ and $\delta^{18}O$ = -10.522 ‰ for the 'L' standard, and δ^2H = 16.74 ‰ and $\delta^{18}O$ = 1.53 ‰ for the 'M' standard.

The study was conducted in a peri-urban area southeast~~SE~~ of Berlin, Germany, on the grounds of the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB) (Fig. 1~~–~~a). Berlin is situated around the former Warszaw-Berlin ice marginal valley and its glacial spillway which were formed during the Weichselian glaciation (Lüthgens and Böse, 2011). From this emerged a flat topography filled with sand and gravel deposits (Limberg et al., 2007). 59.4 % of Berlin is residential areas, followed by 34 % with vegetation cover and 6.6 % surface waters (SenMVKU, 2023). The study site is located roughly 200 m north of Lake Müggelsee, 38 m.a.s.l. It is surrounded by buildings (on average 10 m distance) and vegetation is a mosaic of extensive grassland and mature trees (~30-100 years old). Groundwater levels directly at the site are ~4 m below the ground surface (Umweltatlas Berlin, 2020) with limited annual variability (< 0.15 m). Sandy regosols are the prevailing soil type (Geoportal Berlin, 2015) and anthropogenic impacts are reflected through existing debris, sandy materials and a shallow humus layer (roughly 8 cm deep).

Berlin's climate is a warm-summer humid continental climate (Köppen classification: Dfb; Beck et al., 2018). The long-term (1991–2020) mean annual precipitation and temperature are 579 mm and 10.2 °C, respectively (DWD, 2023). In comparison to the 1981–2010 reference period, the region has become warmer and drier in recent years, making it more susceptible to drought. In 2022, the study year, Berlin only received 403 mm of annual rainfall (DWD, 2024). Summer precipitation exhibits irregular, more intensive, convective rainfall (Environmental Atlas Berlin, 2025). This high-intensity precipitation during summer is often lost to urban drainage or high ET responses, and often does not fully replenish soil moisture or recharge groundwater.

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This study focused on two different types of ~~UGS~~ vegetation: a grassland and a tree-dominated area, both non-irrigated (Fig. 1 b). The grassland was managed at low intensity (mowed twice a year) and covered by grass (e.g. *Bromus sterilis, Lolium perenne*) and herb species (e.g. *Rumex acetosa, Trifolium pratense)* of up to 60 cm height. For the investigation of urban trees, we focused on one large ~~Norway maple~~*A. platanoides* tree (“norway maple”~~*Acer platanoides*~~*;* ~ 80 years old) with a height of ~16 m and a stem diameter of 560 mm and one dominant ~~Silver birch~~*B. pendula* tree (“silver birch”~~*Betula pendula*~~*;* ~ 60 years old) with a height of ~12 m and a stem diameter of 490 mm (stem diameters were measured in April 2022). Both tree genera are representative of temperate-zone city trees (Roloff, 2013). Previous isotope-based studies at the site have detected deep soil water and groundwater as the likely dominant sources of water to these trees (Ring et al., 2024) and an enrichment of atmospheric water vapor just above the grassland surface indicating evaporative enrichment (Ring et al., 2023).

3 Data and Methods

3.1 Climatic inputs and precipitation isotopes

This study focuses particularly on two sub-periods within the growing season in Berlin, 2022: a summer drought period from 01 July to 14 August and a rewetting period from 15 August to 30 September. Details of climate data are summarised in Table S1 and Fig. 2. Hourly potential evapotranspiration (PET [mm h^{-1}]; cf. Bliss Singer et al., 2021) was estimated by the FAO Penman–Monteith method (Allen, 1998) using data from a IGB rooftop station 315 m away from the study site, as this featured the most continuous timeseries. The transition point between the drought and the rewetting period was identified for the 15.08.2022 with the onset of late summer rain. This choice was based on a study outlined by Birkel et al. (2025b), which combined data from an associated field study at this site with parsimonious tracer-aided conceptual modelling. Their analysis showed that both hydrometeorology and stable water isotopic signatures rapidly changed from dry to wet on that day in 2022.

Precipitation amounts, as well as precipitation and groundwater isotopes were measured at the study site and on IGB grounds (see Table S1 in the supplementary). Details on handling of liquid water samples can be found in Ring et al. (2024). Expression of results was in δ-notation with Vienna Standard Mean Ocean Water (VSMOW).

~~**Table 1. Details of the monitored parameters with location, sampling intervals and logger, sensor and sampling details, respectively.**~~

~~**Parameter**~~	~~**Location**~~	~~**[∞]**~~	~~**Logger and Sampling Details**~~
~~T [C°]~~ ~~P [mm]~~ ~~WS [m/s]~~ ~~RH [%]~~ ~~GR_{net} [W/m²]~~	~~IGB Weather Stations 350 m distance to study site~~	~~5 min~~	~~Pt100, Thies GmbH; cup anemometer, Thies GmbH; hair tension dial hygrometer, Thies GmbH; Albedometer CMP6, Kipp&Zonen~~
~~P [mm]~~	~~Study site; open grassland~~	~~15 min~~	~~tipping bucket raingauge, 0.2 mm/tip, precision ±3% of total rainfall; AeroCone® Rain Collector, Davis Instruments, Hayward, USA; CR800 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~T [C°] δ_v~~	~~At δ_v tube inlets~~		~~CR300 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~T [C°] δ_{xyl}~~	~~Inside borehole membranes~~		~~fine PFA-sealed resistance thermometers (Pt100, HSRTD, Omega Engineering, Norwalk, USA; tolerance: ±0.15 to 0.35 C (over 0 to 100 °C); CR800 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~**Stable water isotopes [‰]**~~			~~cavity ring-down spectroscopy~~ ~~(CRDS; L2130-i, PICARRO, INC., Santa Clara, CA)~~
~~Precipitation~~	~~Study site~~	~~24 h – 72 h~~	~~sampled manually with HDPE deposition sampler (100 cm2 opening; Umwelt-Geräte-Technik GmbH, Müncheberg, Germany); analysed with CRDS~~
~~Precipitation~~	~~IGB grounds; 350 m distance to study site~~	~~24 h~~	~~autosampler (ISCO 3700, Teledyne Isco, Lincoln, USA); autosampler bottles were filled with a paraffin oil layer that was more than 0.5 cm thick (per IAEA/GNIP, 2014); analysed with CRDS~~
~~Groundwater~~	~~IGB grounds; 350 m distance to study site~~	~~7 d~~	~~submersible pump (COMET-Pumpen Systemtechnik GmbH & Co. KG, Pfaffschwende, Germany); analysed with CRDS~~
~~δ_v~~ ~~(ambient water vapourvaporvap or)~~	~~Study site; below *A. platanoides* canopy, above grassland~~	~~~ 3.5h~~	~~Measured in situ real time sequentially; connected to CRDS with polytetrafluoroethylene (PTFE) tubing (1.6 mm x 3.2 mm); sample flow rate 0.04 L min⁻¹ in 1 Hz resolution; calibration every 3rd monitoring sequence~~
~~δ_{xyl}~~ ~~(tree stem xylem water)~~	~~Study site;~~ ~~*Acer platanoides Betula pendula*~~		
~~Soil water~~	~~Below~~ ~~*A. platanoides* canopy & grassland;~~ ~~five depths (0-5, 5-10, 10-20, 20-40 and 40-70 cm)~~	~~30 d~~	~~Destructive sampling; sampling ring up to 10 cm depth, below 10 cm soil auger (diameter 4 cm); 3 replicates; stored in stable bags (CB400-420siZ, WEBER Packaging GmbH, Güglingen, Germany); Los Gatos off-axis integrated cavity output spectroscopy (OA-ICOS) triple water-vapourvapor isotope analyser (TWIA-45-EP, Los Gatos Research, Inc., San Jose, CA, USA)~~
~~**Ecohydrology**~~			
~~Sap flow [L/h]~~	~~Study site;~~ ~~"breast height"~~ ~~1.3 m at stem of~~ ~~*Acer platanoides Betula pendula*~~	~~15 min~~	• ~~SFM-4, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany; ±0.1 cm/hr heat velocity precision: *A. platanoides* north & south~~ • ~~SFM1 instrument, ICT International, Australia: *A. platanoides* (northwest) *B. pendula*B. pendulaB. pendulaB. pendulaB. pendula (north, northwest and south)~~ • ~~CR800 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~Stem growth [µm]~~			~~DR Radius Dendrometer, Ecomatik, Dachau, Ger170; accuracy max. ± 4.5% of the measured value (stable offset); CR800 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~Soil moisture; VWC [%]~~	~~Below~~ ~~*A. platanoides* canopy & grassland;~~ ~~5 depths~~ ~~(5-70 cm)~~		~~SMT-100, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany;~~ ~~CR800 Datalogger (Campbell Scientific, Inc. Logan, USA)~~
~~Twig water potential [MPa]~~	~~*Acer platanoides Betula pendula*~~	~~14 d~~	~~9 am and 12:30 pm; Scholander pressure chamber instrument (Model 1000, PMS Instrument Company, Albany, OR, USA; 0.5% accuracy)~~
~~LAI~~			~~Plant canopy analyser (LAI 2000, Li-cor, Inc., Lincoln, NE, USA); 3 replicates; constant point under canopy~~
~~Groundwater level [m]~~	~~IGB grounds~~	~~7 d~~	~~Water level meter~~

3.2 In situ monitoring of δ_v and δ_{xyl}

~~Stable water isotopes~~SWI of atmospheric water ~~vapour~~vapor (δ_v) and plant xylem water (δ_{xyl}) were measured in situ real-time and sequentially (automatic switch of tube) via a cavity ring-down spectroscopy (CRDS) laser (L2130-i, PICARRO, INC., Santa Clara, CA; Fig. 1 c~~2~~). The results were expressed in δ-notation as the ratio of heavy over light SWI with relation to Vienna Standard Mean Ocean Water (VSMOW). The CRDS laser was installed between the trees and the grassland in a shaded box to prevent from overheating during high radiation exposure. Measurement details are displayed in Table S1 in the supplementary. The plot-scale elevation profile above the two distinct ~~UGS~~ types of vegetation was monitored to assess possible effects of diverse urban vegetation and potential air turbulence. δ_v was measured at 0.15 m, 2 m and 10 m height at the urban grassland using a flag mast and under the canopy of the ~~Norway maple~~*A. platanoides* (Fig. 1 c~~2~~). Each δ_v tube inlet (Fig. 1 c~~2~~) was sampled for 20 min. The first 8 min after tube switching were always discarded to mitigate memory effects only data exhibiting stable isotope values were retained for analysis (defined as standard deviation of ≤2 ‰ for δ^2H and ≤0.5 ‰ for δ^{18}O). To prevent the δ_v inlets from rain and radiation exposure, we fitted PET plastic-bottles covered with aluminum foil over each δ_v tube inlet.

δ_{xyl} values of ~~the~~ *A. platanoides* ~~Maple~~ and the ~~*Birch*~~*B. pendula* ~~tree~~ were~~as~~ monitored in situ via the stem borehole equilibration method (Kühnhammer et al., 2022; Marshall et al., 2020; Beyer et al., 2020). At each tree, two stem boreholes (1.5 m and 2.5 m height) were drilled to record potential height variations or travel times within the tree stems. Details on the method are given in Ring et al. (2024). Each δ_{xyl} tube inlet (Fig. 1 c~~2~~) was sampled for 30 ~~–~~min. To mitigate memory effects, the first 15 min of δ_{xyl} measurements following a tube switch were consistently excluded, and only data exhibiting stable isotope values were retained for analysis (defined as standard deviation of ≤3 ‰ for δ^2H and ≤0.8 ‰ for δ^{18}O). We have checked the sub-daily water vapor concentration change and calculated the saturation point for the respective temperatures. Water vapor concentration was always close to full saturation during the measurements (e.g. 28000 ppm at 25 C° which has a saturation point at ~31400 ppm). Thus, we can rule out evaporation effects and kinetic fractionation of measurements. We could not use the δ_{xyl} data of the ~~maple~~*A. platanoides* borehole at 2.5 m height for further analysis due to unstable measurements, which simultaneously occurred with high CH_4 values detected by the CRDS (cf. Ring et al., 2024).

3.3 Liquid δ-values and calibration

For later conversion of δ_v and δ_{xyl} measurements into liquid water isotope values and to account for temperature dependencies, temperature probes were set up at all tube inlets (see Table 1). By combining the in situ stable water isotope data with associated temperature data we could correct the measured values of δ_v and δ_{xyl} to liquid values with the correction Eq. (1) formulated by Majoube (1971):

$$\alpha = exp\frac{a\left(\frac{10^6}{T_k^2}\right)+b\left(\frac{10^3}{T_k}\right)+c}{1000}, \qquad (1),$$

where α is the isotopic fractionation factor, Tk is the temperature (in K), and a, b, and c are empirical parameters that vary depending on the isotopologue (values in supplementary).

Therefore, all isotopic values in this study can be compared with each other, as they are all given for the liquid phase and relative to Vienna Standard Mean Ocean Water (VSMOW). To correct for isotopic offsets and ~~vapour~~vapor concentration dependencies, automated calibration of CRDS measurements was performed after every three loops of measuring δ_v and δ_{xyl} values using two standards, which had liquid isotope values of δ^2H = -73.623 ‰ and $\delta^{18}O$ = -10.522 ‰ for the 'light' standard, and δ^2H = 16.74 ‰ and $\delta^{18}O$ = 1.53 ‰ for the 'heavy' standard. Then, temperature-dependent slopes were incorporated using linear regression.

3.4 Soil water isotopes

Further, to detect the variation in bulk soil water isotopic signatures over time and between the ~~green spaces~~grassland and the tree site, we conducted monthly destructive soil sampling from April until October 2022 at the grassland site and underneath *A. platanoides* ~~the Maple tree~~ (Fig. 1 b) at five depths (0-5, 5 10, 10-20, 20-40 and 40-70 cm) (see Table S1). For analysis in the lab, we used the direct equilibrium method outlined by Wassenaar et al. (2008). Further details on the method are displayed in Ring et al. (2024).

3.5 Ecohydrological parameters

To gain full insights into ecohydrological partitioning at our study site, we also implemented comprehensive monitoring of ecohydrological parameters, that reflect changes in water status ~~at~~ of the soil-plant-atmosphere-continuum (SPAC)~~ of urban vegetation~~: including sap flow, stem growth, twig water potential, LAI, soil moisture and groundwater levels (see Table S1). Sap flow rates were assessed via the monitored sap velocity (heat ratio method by Marshall (1958) with the softwares implexx (SFM-4 meters, UGT) and Sap Flow Tool (SFM1, ICT International) including data of sap wood, heart wood and bark depths from drilled tree cores. The soil moisture monitoring pits entirely consisted of sandy soils (over 94 % of fractions > 0.063 mm).

3.6 Data analysis

Data processing and analysis were conducted in R, Version 4.4.1 (R Core Team, 2024). We used the Shapiro-Wilk test (Shapiro and Wilk, 1965) to test the normality of all datasets. For the non-normally distributed isotopic data we used non-parametric alternatives (assuming ~~all~~ observations of SWI were paired~~independent~~ and random): the Wilcoxon signed-rank test for two groups of day and night values (Wilcoxon, 1945), ~~and~~ the ~~Kruskal-Wallis~~ Friedman test by ranks for plus two groups (Friedman, 1937) and post-hoc the pairwise Wilcoxon rank sum test with Bonferroni correction (Bonferroni, 1935; Mann and Whitney, 1947; Wilcoxon, 1945).

For the assessment of evaporation, the line-conditioned excess (short lc-excess) (Landwehr and Coplen, 2006) of the measured water isotopic signatures was calculated for local evaporative effects. Lc-excess represents the deviation of the sample from the local meteoric water line (LMWL):

$$lc - excess \ = \ \delta^2 H \ - a \ \times \ \delta^{18} O \ - b \ , \qquad (2),$$

where *a* is the slope and *b* the intercept of the weighted isotopic composition of the local precipitation. The LMWL was calculated by amount-weighted least square regression (Hughes and Crawford, 2012) from daily precipitation isotopes measured at the study site during the whole year of 2022, where *a* = 7.37 and *b* = 4.249.

To assess potential time-dependent relationships between the monitored ecohydrological variables and high-resolution in situ isotope data of δ_{xyl} and δ_v, we performed a cross-correlation analysis at hourly resolution. This method is commonly used in hydrology to identify connections and trends between hydrological and meteorological timeseries (Khaliq et al., 2009; Rahmani and Fattahi, 2021). It computes the relationship between two univariate (time-) series as a function of the (time-) lag between them (cf. Chambers et al., 2002). The in situ measured isotopes were aggregated to hourly data via linear interpolation for cross-correlations.

4 Results

4.1 Hydroclimatic conditions during 2022

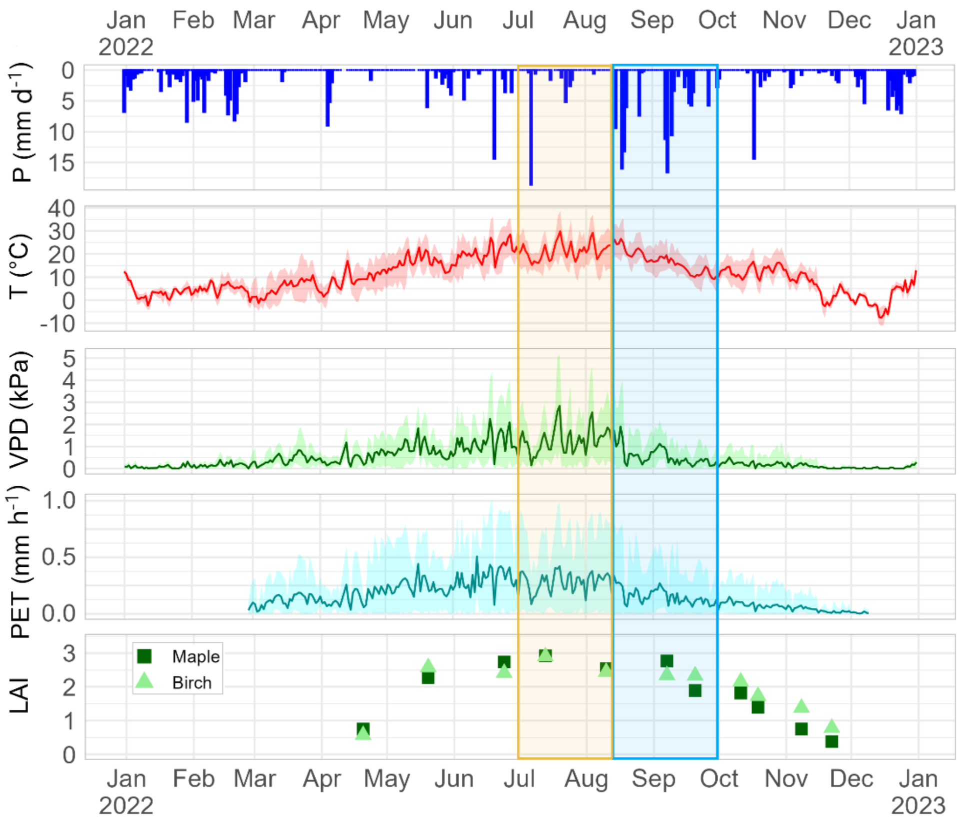


Figure 2~~3~~: Hydroclimatic Context 2022: Precipitation [mm d^{-1}] is shown as daily sum. Temperature [°C], VPD [kPa] and PET [mm/h] are shown as daily mean values with daily min/max band. Leaf Area Index (LAI) is shown as daily mean values. Periods of interest are shown as an orange box (summer drought 01.07.-14.08.2022) and blue box (rewetting 15.08.-30.09.2022). Figure adapted from Ring et al. (2024).

Hydroclimatic conditions surrounding the study period in 2022 are shown in Fig. 2~~3~~. Compared to the international reference period 1961-1990 t~~T~~he spring of 2022 was very dry with very low precipitation input from March until May with~~(~~~ 40 mm at study site ~~in~~ within these 3 months compared to a long-term average of 132 mm for Berlin (DWD, 2022b). The summer 2022 was also very dry and warm in the area of Berlin with 20,6 °C and 120 mm compared to 17,8 °C and 182 mm between 1961-1991. ~~compared to the long-term average (1991-2020) at DWD station Berlin Marzahn~~ (DWD, 2022c)~~(DWD, 2025)~~.

~~The Global Precipitation Climatology Centre drought index for July 2022 indicated a mild to moderate drought for southeast Berlin (DWD, 2022).~~ With regard to the identified summer drought period (01.07.-14.08.2022) the d~~D~~aily mean temperature ~~during the drought period (01.07.-14.08.2022)~~ was 21.6 °C (cf. long-term average 1991-2020: 19,7 °C; DWD, 2023), reaching a maximum of 38.5 °C. ~~Daily maximum PET was mostly above 0.6 mm/h.~~ Cumulative precipitation at the study site during ~~the drought~~that period was 32.4 mm~~-~~(long-term average sum Berlin 1991-2020: 105 mm; DWD, 2023), with most events totaling less than 5 mm. The largest rainfall event was a convective event of 18.6 mm on July 7. Daily maximum PET during the summer drought was mostly above 0.6 mm h^{-1}. Daily mean VPD exceeded 1 kPa throughout most of the drought period. The identified r~~R~~ewetting period started from August 15 with recurrent summer rain events of > 10 mm and continued with frequent rainfall in September. Daily mean PET was mostly < 0.25 mm ~~/~~h^{-1} during rewetting.

LAI depicted rapid leaf-burst between April and May and showed highest values between June and early September. From late September until November the advancing leaf senescence was represented in LAI. Twig water potential of both trees (Fig. S1, supplementary material) was most negative in July and August, compared to spring and autumn months. Additionally, it was more negative during midday compared to morning measurements during the drought period (Fig. S1, supplementary material).

4.2 Sub-daily Dynamics of Stable Isotopes

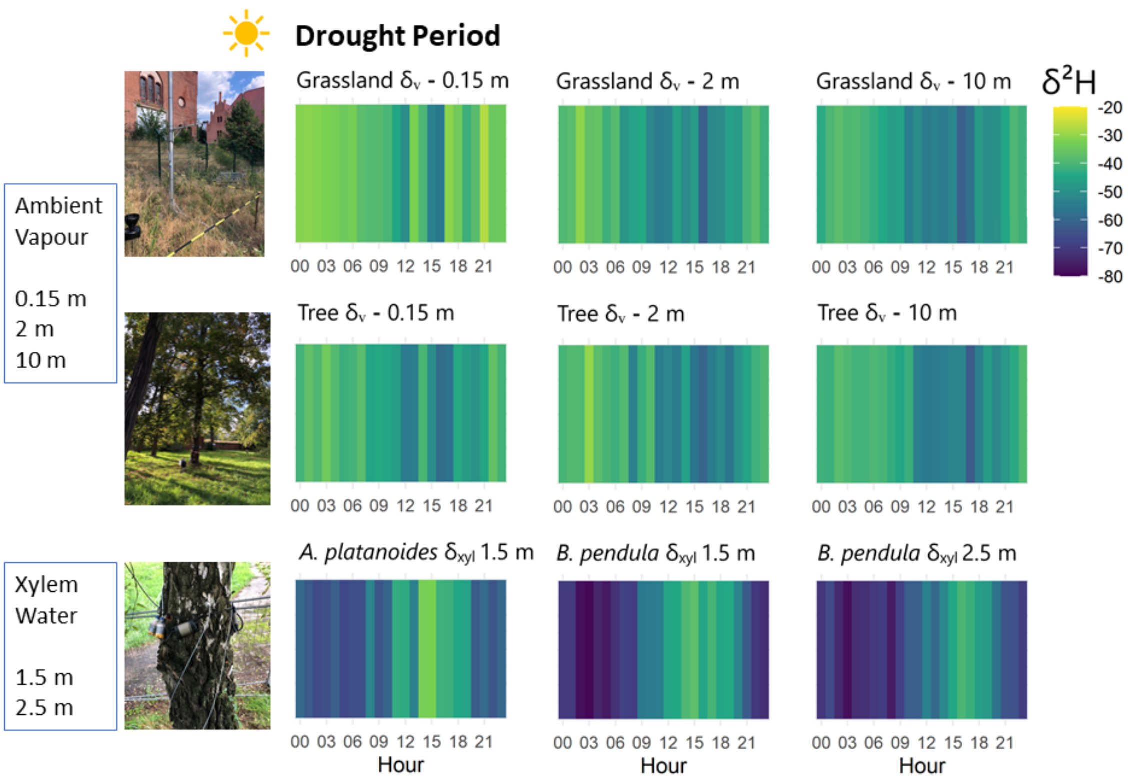


Figure ~~3~~4: 24-h cycle heatmap of hourly median δ^2H data of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) during summer drought period 01.07.-14.08.2022. One in situ measurement loop took ~3.5 h and unstable measurements were ruled out (cf. Method section). The hourly median shown for each hour of the day was calculated based on ~8.6 measurements.

In this section~~For this analysis~~, we focus on δ^2H values, setting aside $\delta^{18}O$ values which showed near-identical patterns (displayed in supplementary as Figs. S2, S3 & S4). High-resolution in situ monitoring of δ_{xyl} and δ_v values exhibited clear diurnal cycling during the entire drought period (01.07.-14.08.2022; Fig. 3~~4~~). Wilcoxon-tests on differences between day (8 am – 8 pm) and night (8 pm – 8 am) isotopic signatures indicated significant ($p < 0.01$) statistical difference for δ_{xyl} and δ_v values. However, opposing systematic sub-daily dynamics in the isotope signatures of ambient vapor and plant xylem water were apparent: δ_v values showed afternoon depletion and nighttime enrichment. δ_{xyl} values showed clear afternoon enrichment in heavy isotopes in both trees indicating circadian cycle. Especially, δ_{xyl} values of the ~~birch~~*B. pendula* became highly depleted (up to -80 ‰ δ^2H) during nighttime. The mean amplitude between day- and night-time values of δ_{xyl}, averaged over all trees, was 38 ‰ δ^2H (Fig. 6).

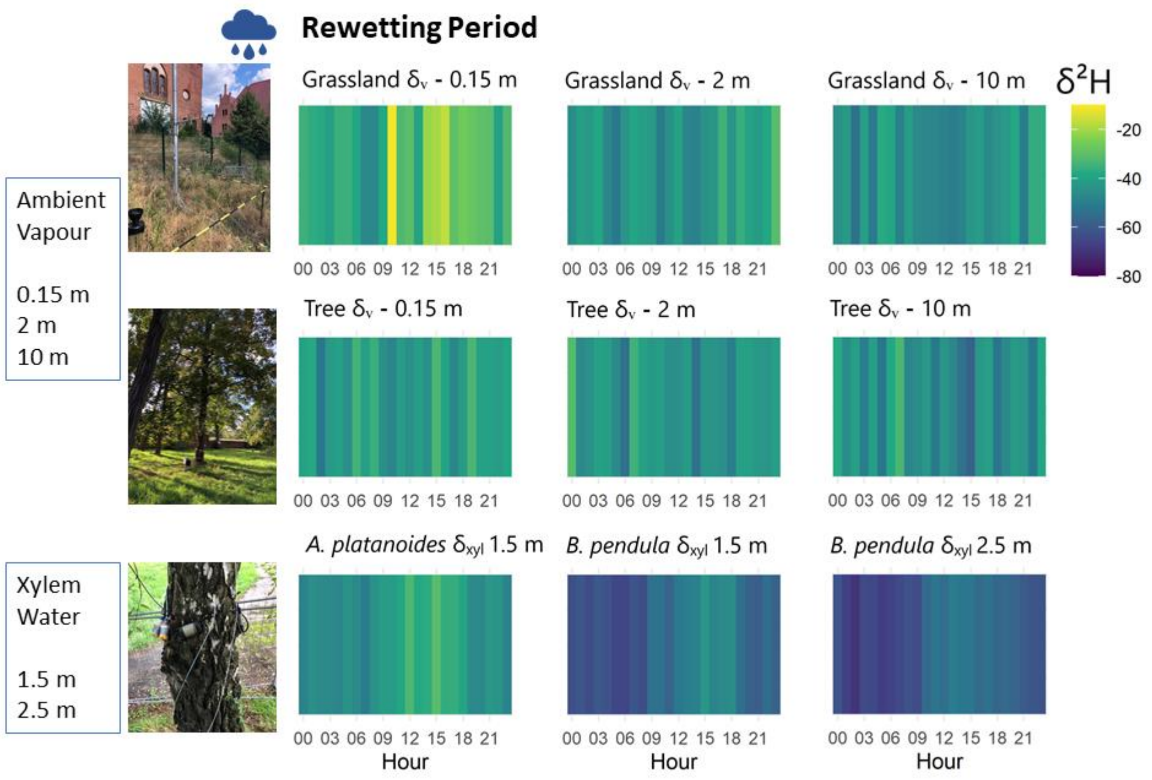


Figure 4~~5~~: 24-h cycle heatmap of hourly median δ^2H data of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) during rewetting period 15.08.-30.09.2022. One in situ measurement loop took ~3.5h and unstable measurements were ruled out (cf. Method section). The hourly median shown for each hour of the day was calculated based on ~9.2 measurements).

Diurnal cycling of ~~water stable isotopes~~SWI became less distinct during the rewetting period (15.08.-30.09.2022) (Fig. 4~~5~~). Wilcoxon-tests no longer indicated significant sub-daily differences of δ_v values ($p > 0.05$) during rewetting. Only δ_v values of grassland at 0.15 m (measured within higher grass) showed significant daytime enrichment ($p = 0.031$). The sub-daily range of δ_{xyl} values averaged between all trees was smaller during rewetting (~20 ‰ δ^2H; Fig. 6), but an afternoon enrichment was still evident and differences statistically significant ($p < 0.05$) revealed by Wilcoxon-tests.

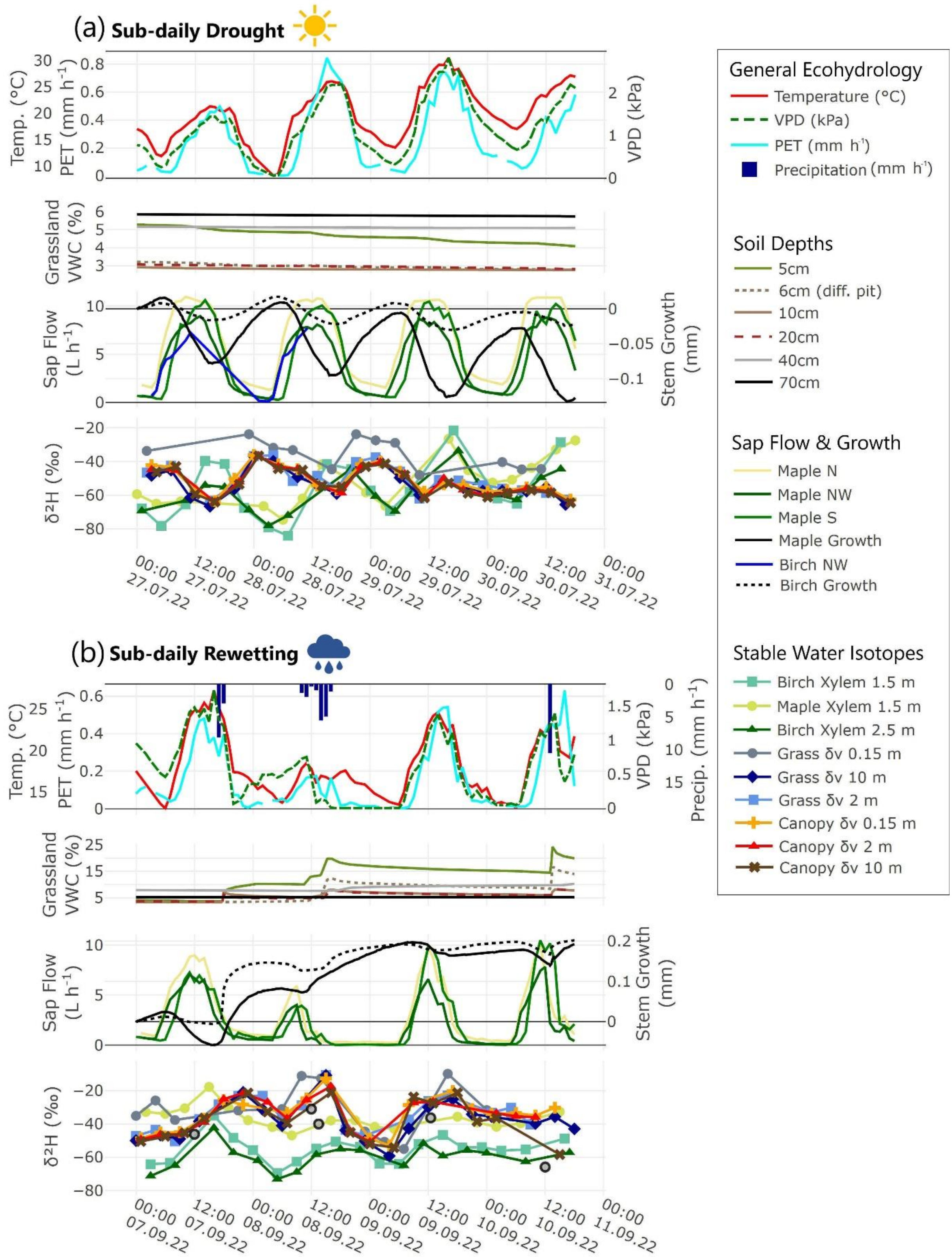


Figure 5:~~6: Drought conditions:~~ Sub-daily timeseries displaying diurnal variation of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) and measured ecohydrological variables during (a) drought conditions and (b) rewetting. ~~The top left box shows antecedent conditions 30 days prior the timeseries: hourly data of temperature and PET, precipitation as 30-day sum and mean LAI of each tree.~~

In Fig. 5 (a)~~6~~ we zoom into a typical 4-day long sub-daily timeseries (27.07.-31.07.2022) of the monitored ~~stable water isotopes~~SWI and ecohydrological data during the drought period. Meteorological conditions 30 days prior to July 27 2022 (Fig. S4 a) were characterized by a daily mean temperature of 20.5 °C, a mean PET of 0.19 mm ~~/~~h^{-1} and accumulated precipitation of 33.4 mm (with 18.6 mm from a single storm event on July 7). During the 4 days, sub-daily dynamics of temperature, VPD and PET were clearly radiation driven (daily maxima between 500-900 W m^{-2}) with no precipitation. Soil moisture remained relatively constant over the 4-day period; only the upper soil layer (5 cm) became drier. Sap flow rates of both trees rose from morning hours until noon (up to 12 L ~~/~~h^{-1}) and then decreased, dropping below 2.5 L ~~/~~h^{-1} during nighttime. Stem growth of both trees showed a similar temporal trend in a circadian cycle of daytime shrinking and nighttime swelling. The timeseries during drought showed clear opposite sub-daily cycling of δ_{xyl} and δ_v in δ^2H values similar to the averages presented in Fig. 3~~4~~. δ_{xyl} values became enriched in heavy isotopes during afternoons and depleted during nighttime (large sub-daily variation of ~40 ‰ δ^2H). The amplitudes in δ_{xyl} were greater in the lower borehole of *B. pendula* at 1.5 m compared to 2.5 m, which might be a dilution effect with height. δ_v values became enriched during nighttime hours (sub-daily variation of ~20 ‰ δ^2H). Lc-excess values are displayed in the supplementary Fig. S4. Lc-excess of δ_v values was mostly above zero (~ 5 ‰), with a single change to negative values during night on July 28th. δ_{xyl} value lc-excess was strongly negative with ~~birch~~*B. pendula* lc-excess becoming more negative (around -20 ‰) than ~~maple~~*A. platanoides* lc- excess (around ~~-~~– 8 ‰). The drop in the lc-excess values after 28.7. at 00:00 can be explained by stronger entrainment processes during that night, meaning an intensified turbulent flux of water vapor that occurred between the relatively dry air in the free troposphere above and the moister air within the surface boundary layer (cf. Lai and Ehleringer, 2011; Lee et al., 2006).

~~**Figure 7: Rewetting conditions: Sub-daily timeseries displaying diurnal variation of tree xylem water (δ_{xyl}), atmospheric vapor (δ_v), precipitation water isotopes and measured ecohydrological variables. The top-left box shows antecedent conditions 30 days prior the timeseries: hourly data of temperature and PET, precipitation as 30-day sum and mean LAI of each tree.**~~

In Fig. 5 (b)~~7~~ we additionally zoom into a typical 4-day long sub-daily timeseries (07.09.-11.09.2022) during the rewetting period. Meteorological conditions 30 days prior Sep 7 2022 (Fig. S4 b) were characterized by a daily mean temperature of 21 °C, a mean PET of 0.1 mm ~~/~~h^{-1} and a precipitation sum of 51.6 mm. During the 4 days, daily maxima of temperature, VPD and PET were dampened during the 7 h precipitation event on Sep 8, but not during the shorter convectional events. Soil moisture rates indicated infiltration of precipitation to a depth of 5 – 20 cm in the sandy soil, especially after the longer 7 h rainfall. Soil moisture in depths below 30 cm was unaffected. Sap flow rates of the ~~maple~~*A. platanoides* rose up to 10 L ~~/~~h^{-1} by noon. But also here, rates were dampened on the colder, rainy day of Sep 8. Stem increments of both trees were picking up the precipitation signals consistent with a swelling of the bark.

The timeseries after two medium precipitation events showed smaller sub-daily variation of δ_{xyl} values (~20 ‰ δ^2H) compared to the presented drought timeseries which had no precipitation input. The two boreholes of birch showed similar amplitudes of δ_{xyl} values, implying no axial dampening during these days. δ_v signatures showed a drop in δ^2H values after the rainfall events and stable values form the next morning onwards as indicated by the average rewetting period values from Fig. 4~~5~~. Lc-excess values of δ_{xyl} and δ_v became higher compared to drought

The sub-daily timeseries during wet conditions (= after rewetting; 01.10.-05.10.2022) (Fig. S5~~2~~, supplementary material) showed lower maximum sap flow rates of ~~maple~~*A. platanoides*. Soils were (re)wetted: Upper soils retained water from precipitation inputs for several days after a rain event. Lc-excess values of δ_v and δ_{xyl} during wet conditions showed overall positive values indicating lower influence of evaporative fractionation. Sub-daily variation of δ_{xyl} values was lowered compared to drought and rewetting (~10 ‰ δ^2H). δ_v signatures were influenced by the precipitation event.

Dual isotopes of all measured waters (Fig. S6~~3~~, summary statistics in Table S2 & S3, supplementary material) revealed that deeper soil water and groundwater had isotopic signatures close to those of δ_v and δ_{xyl}. In contrast, dual isotopes of upper soil water and precipitation were more distinct from δ_v and δ_{xyl} dual isotope values. However, δ_v values of grassland at 0.15 m had similar signatures to upper soil waters. A comparison of the dual isotopes between the drought and rewetting period showed that δ_v (mean -44.79 ‰ δ^2H and -7.45 ‰ δ^{18}O) and δ_{xyl} (mean -55.02 ‰ δ^2H and -7.09 ‰ δ^{18}O) values corresponded more closely to the precipitation signatures (mean -43.37 ‰ δ^2H and -6.72 ‰ δ^{18}O) during the rewetting phase. Notably, δ_{xyl} values of *B. pendula* ~~birch~~ did not reflect the precipitation signal during rewetting. As the location of *B. pendula* was closer to a building and growing on a slope, we assume precipitation did not percolate as quick and soil replenishment was potentially composed of more fractionated waters.

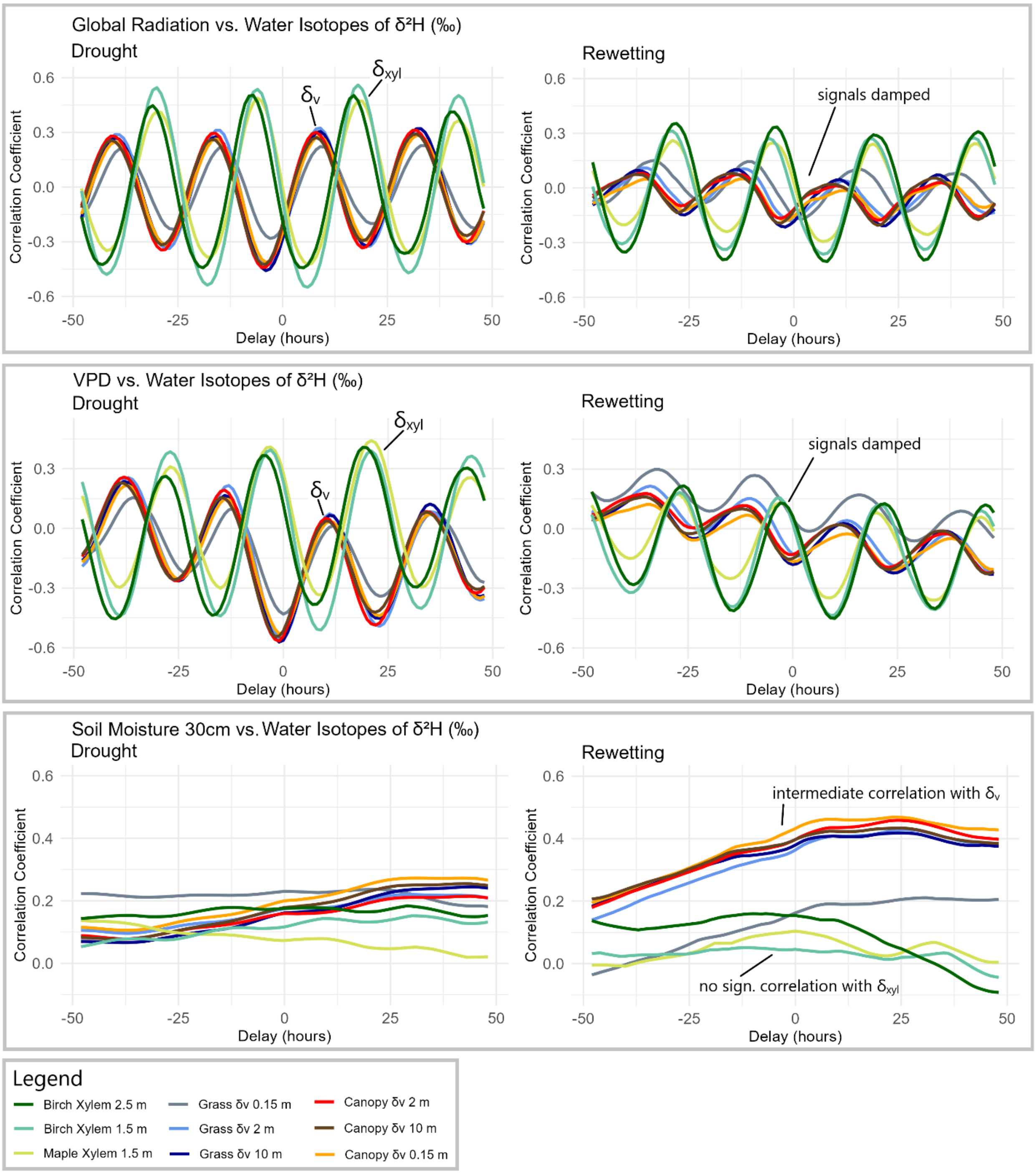
4.3 Cross-Correlation Analysis of Sub-daily Isotopes and Ecohydrological Variables

A cross-correlation analysis between the monitored ecohydrological variables and in situ SWI~~δ^2H~~ values revealed some inversions of the sub-daily patterns between the drought and the rewetting period (supplementary Figs. S7, S8~~8~~). Both δ^2H and δ^{18}O showed analogous patterns. During the summer drought, a high correlation of radiation (> (-)0.5) and an intermediate correlation of VPD (> (-)0.3) with δ_{xyl} and δ_v values was detected. It followed the diurnal radiation cycle with the inverse behavior of δ_{xyl} and δ_v signatures; δ_{xyl} had a positive correlation with solar radiation and VPD at lag 0 hours. In contrast, δ_v values showed a negative correlation with solar radiation and VPD at lag 0 hours. VPD maxima were lagged 2 h behind global radiation for both δ_{xyl} and δ_v values. This indicates that VPD had a delayed temporal influence on the isotope signatures than global radiation.

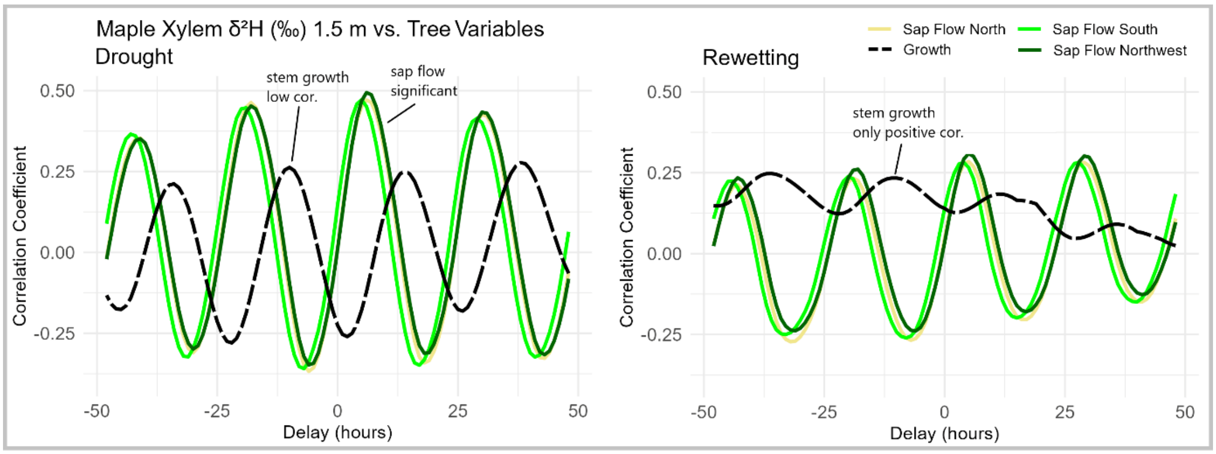
During rewetting, correlation signals of solar radiation and VPD with δ_{xyl} and δ_v values were damped: correlation coefficients were usually below (-)0.3. Lags of δ_v values above the grassland at 0.15 cm were intermediate between other heights of ambient vapor and tree xylem values during rewetting. Soil moisture at 30 cm depth below canopy showed only a low positive correlation (< 0.3) with δ_{xyl} and δ_v values during drought. During rewetting, the correlation of soil moisture below the canopy with δ_{xyl} values stayed low but rose above 0.4 after a lag 0 hours for δ_v values.

The cross-correlation between δ_{xyl} values of the ~~maple~~*A. platanoides* borehole at 1.5 m and sap flow data of the ~~maple~~*A. platanoides* (supplementary Figs. S9, S10) showed a positive correlation of 0.5 at a delay of ~6 hours during drought and a general radiation-driven sinusoidal curve. Stem growth and δ_{xyl} values of the ~~maple~~*A. platanoides* (supplementary Figs. S9, S10~~Fig. 9~~) were only weakly correlated (< (-) 0.3) during drought and showed the radiation driven sinusoidal curve. During rewetting, the correlation between δ_{xyl} values of ~~maple~~*A. platanoides* and its sap flow was weaker. In addition, the correlation of δ_{xyl} values with stem growth stayed low but became positive indicating less radiation influence.

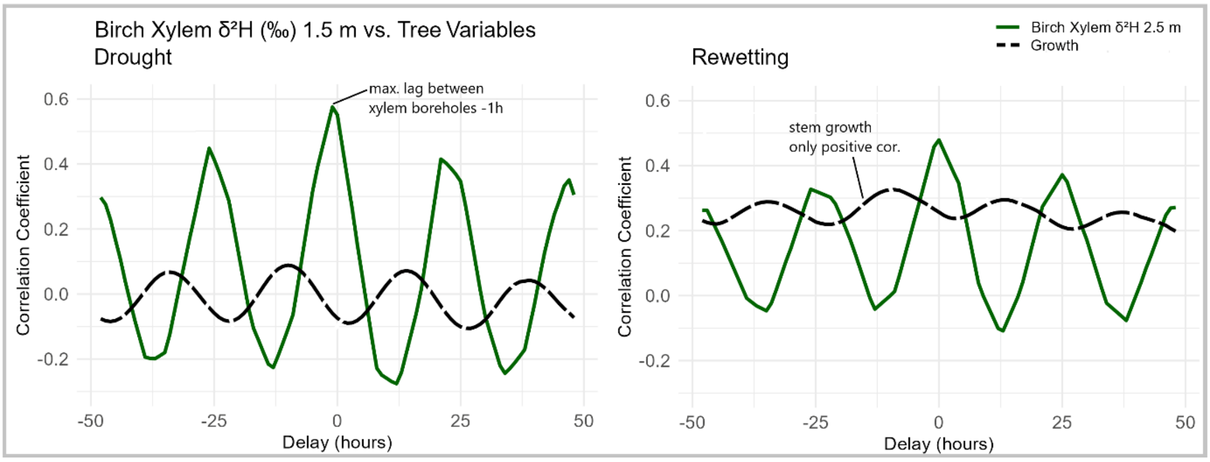
Cross-correlation analysis between δ_{xyl} values of the two ~~birch~~*B. pendula* boreholes (1.5 m and 2.5 m height; supplementary Figs . S9, S10~~Fig. 10~~) showed a high positive correlation (> 0.5) at lag 0 hours during both drought and rewetting with a sinusoidal radiation driven pattern. During drought, the maximum lag of the cross correlation between both boreholes of ~~birch~~*B. pendula* had a delay of -1 hour, which could hint at a travel time between both boreholes. During rewetting, there was a general shift to an overall positive correlation between the ~~birch~~*B. pendula* boreholes and its stem growth. There was no significant correlation of ~~birch~~*B. pendula* δ_{xyl} values with stem growth during drought, but an intermediate positive correlation of 0.33 at delay of -10 hours during rewetting.



~~**Figure 8: Cross correlation analysis between in situ measured δ^2H data (tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v)) and global radiation, VPD and soil moisture at 30 cm depth underneath canopy comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022 - 30.09.2022).**~~



~~Figure 9: Cross correlation analysis between δ^2H of Maple~~*A. platanoides* ~~xylem water (1.5 m borehole) and measured sap flow and stem growth comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022 - 30.09.2022).~~



~~**Figure 10: Cross correlation analysis between δ^2H of Birch xylem water (1.5 m borehole) and δ^2H of Birch xylem water (2.5 m borehole) plus stem increments comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022 - 30.09.2022).**~~

5 Discussion

5.1 Diurnal water cycling in urban green spaces over the growing season

The combination of ecohydrological measurements and in situ monitoring of δ_v and δ_{xyl} signatures provided valuable long-term insights on diurnal water cycling processes in different urban vegetation over the growing season including summer drought conditions in 2022. We found significant sub-daily differences displayed in key Fig. 6 for both δ_v (amplitude ~26 ‰ δ^2H with daytime depletion) and δ_{xyl} (amplitude ~38 ‰ δ^2H with daytime enrichment) values during the drought.~~,~~ B~~b~~ut during rewetting δ_v values showed constant signatures over the day.~~,~~

U~~u~~niquely δ_v values just above grassland (0.15 m) exhibited sub-daily ~~but subdued~~ cycling (amplitude ~ 36 ‰ δ^2H with significant daytime enrichment) ~~(key figure: Fig. 11)~~. Daytime enrichment of ~~-~~δ_{xyl} values was still significant during rewetting, but with reduced sub-daily amplitudes of ~20 ‰ δ^2H.

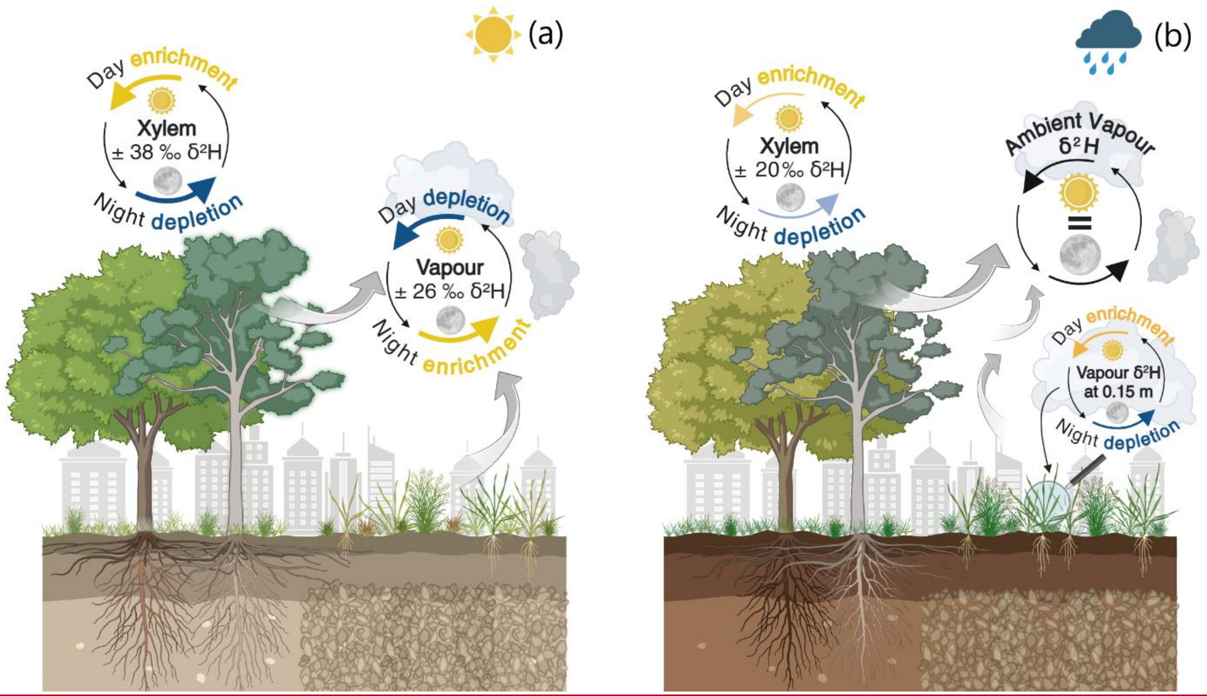


Figure 6~~11~~: Key figure summarizing the sub-daily change in signatures of ~~water~~ stable water isotopes in urban tree xylem water (δ_{xyl}) and atmospheric water vapor (δ_v) (over grassland and under canopy). Day-night change defined as: day (8 am – 8 pm) and night (8 pm – 8 am). We compare summer drought (a) and autumn rewetting (b) in Berlin, Germany, 2022. Displayed amplitudes of the stable hydrogen isotope deuterium (δ^2H [‰]) were calculated from hourly medians from the 24-h cycle of each period averaged over all δ_{xyl} and δv, respectively. Created in BioRender (CC BY-NC-ND). Ring, A. (2025) https://BioRender.com/s1f2bm9

5.1.1 Ecohydrological fluxes

Through the integrated ecohydrological monitoring of urban trees (sap flow, LAI, stem growth, twig water potential), soil moisture and climate data we could identify drivers of distinct sub-daily variations in isotopic signatures of δ_v and δ_{xyl} ~~the response~~ of ~~urban~~ different green spaces to summer drought and autumn rewetting (Stevenson et al., 2023; Marx et al., 2022; Ring et al., 2024). During the drought period (01.07.-14.08.2022), water cycling was predominantly radiation driven showing clear sub-daily variation (Fig. 5a~~6~~). ~~with mid-day values of twig water potential (Fig. S1) being always more negative than in the morning, hinting at water limitation under high radiation (Charrier, 2020).~~ While sap flow rates peaked at noon, VPD reached the highest values in the afternoon for *A. platanoides*, hinting at stomatal control with increasing VPD or a radiation-VPD lag (O'Brien et al., 2004; Zhang et al., 2014). Peak sap flow rates were around 10 L h^{-1} suggesting no drought stress due to water supply by deeper water sources (cf. Ring et al., 2024). ~~; hinting at reinforced drought patterns reducing UGS cooling effects to a minimum in the afternoon~~ (Kraemer and Kabisch, 2022)~~.~~ Mid-day values of twig water potential at the lower shaded canopy (Fig. S1) was most negative at -1.35 mPa, indicating no drop below the critical species-specific water potential value "P_{50}" at which the plant experiences a 50% loss of hydraulic conductivity at least for the lower canopy (Petruzzellis et al., 2022)~~. Also,~~ A natural swelling of the tree stems was observed between midnight and morning hours, when VPD was low, followed by a shrinking during daytime as tree stems shrink and swell in relation to their water status (Steppe et al., 2015). Despite the precipitation input of 18.6 mm from a convectional event on July 7 – the water did not infiltrate into deeper soils (> 30 cm depths), only replenishing upper soils for about a week until it was lost to ET fluxes. This persistence of dry soils further reduced ET processes enhancing moisture stress (cf. Kleine et al., 2020).

During the autumn rewetting period (15.08.-30.09.2022), radiation inputs decreased and precipitation became the dominant factor influencing the ~~UGS~~ water cycling within the SPAC~~e~~. Higher twig water potential and swelling of the tree stems during rewetting revealed improved water supply (Herrmann et al., 2016; Schweiger et al., 2023). At the same time, PET rates (Fig. 2~~3~~) decreased due to lowered radiation in autumn. Especially during precipitation events, temperature, VPD and PET rates were reduced (Fig. 5b~~6~~). In parallel, we observed decreasing LAI and sap flow rates.

5.1.2 Atmospheric ~~vapour~~vapor isotopes below urban canopy and above urban grassland

The sub-daily isotopic signatures of in situ monitored δ_v values suggest systematic behaviour of diurnal water cycling in vegetated areas ~~UGS~~ during summer drought. We detected clear daytime (8 am - 8 pm) depletion in heavy isotopes of δ_v and vice versa and a night time enrichment at all heights under canopy and above grassland (Figs. 3~~4~~, 6~~11~~). As δ_v values were~~as~~ not correlated in time with soil moisture and also showed low coefficients in the cross-correlation with radiation and VPD (Figs. S7, S8~~8~~) – we argue that during drought, not only ET processes were controlling δ_v values at daytime, but also atmospheric circulations of the larger urban surface boundary layer. A similar trend of diurnal ~~δ_v~~ cycling δ_v values during summer was found by in situ eddy covariance measurements of δ_v in the surface boundary layer of a forest in Germany (Braden-Behrens et al., 2019; 2020). They identified entrainment effects that were stronger than local ET as the main aspect for the daytime enrichment of δ_v in heavy isotopes. Also, Zannoni et al., 2025, identified that at sub-daily scales, vertical mixing is the dominant process affecting isotopic variability of δ_v values, which was high during drought in our study, when radiation was main influencing factor (Figs. S7, S8). This effect is related to mixing with dryer isotopically lighter δ_v values in the atmosphere surrounding the vegetation during daytime. This daytime entrainment results from the rapid molecular exchange of water isotopes between the moist surfaces and atmospheric water vapor~~δ_v~~, which can outweigh the impact of evaporation (Craig et al., 1963). At night time, the effect is reduced and local ET processes dominate, driving the isotopic enrichment. However, we argue that evaporation cannot be ruled out as a significant moisture source in the afternoon when the local convective boundary layer is stabilized (Lai and Ehleringer, 2011). At night, δ_v values partially exhibited negative lc-excess during the drought (Fig. S4 a~~6~~), emphasizing that the isotopic nocturnal enrichment of δ_v values is due to evaporative signals.

During the rewetting, we found no significant sub-daily differences (similar to Braden-Behrens et al., 2020) and an intermediate positive correlation with soil moisture for most of the measured heights of δ_v values (Figs. 4~~5~~, S8). This indicates that δ_v values become~~s~~ more evaporation driven from the re-saturated upper soils (< 30 cm depth), while entrainment is reduced with lower radiation (cf. Lai and Ehleringer, 2011). Only δ_v values monitored at a low height above the grass (0.15 m) showed significant daytime enrichment during rewetting (amplitude ~ 36 ‰ δ^2H with daytime enrichment). This suggests that ET fluxes were stronger just above the grass, likely promoted by higher moisture in the (enriched) upper soil water and at vegetation surfaces (cf. Ring et al., 2023). But it needs to be considered that for this valve, only 6.5 measurements were available on average to calculate the hourly median for each hour of the day during the rewetting period: we had to discard several measurements, which were probably due to increasing problems with condensation of cooler air in situ monitoring during autumn (cf. Landgraf et al., 2022). The overall positive lc-excess in δ_v values during rewetting (Fig. 5 b~~7~~) implies weaker evaporation signals occurred here, indicating that the re-wetted soils and the increasing number of precipitation events did not lead to higher E during autumn because of reduced radiation inputs. Angert et al. (2022) found that seasonal variations in near-surface δ_v values are driven by rainout effects, temperature and relative humidity controlling the initial ~~vapour~~vapor and variations in vertical mixing.

Thus, we assume that diurnal cycling of δ_v values over the growing season is driven by climatic and entrainment effects, while local ET does not fully dominate δ_v values during daytime, but also atmospheric factors within the footprint of the larger urban surface boundary layer. We identified an influence of local ET on δ_v values only at daytime just above grassland (0.15 m) during rewetting, when surfaces were very moist. Simple conceptual tracer-aided models, which integrated the high-resolution δ_v data from our study site, previously revealed that small-scale variations in interception and soil evaporation sources can subtly influence the composition of δ_v values (Birkel et al., 2025b). Considering that, sub-daily signals of δ_v have great potential to reveal previously unexplained short-term variances in ~~stable water isotopes~~SWI in daily resolved datasets to constrain conceptual models investigating the urban SPAC (cf. Birkel et al., 2025b).

5.1.3 ~~Urban t~~Tree xylem waters

The relatively small sample size of two trees reflects the trade-off between measurement depth and spatial replication inherent to high-resolution in situ monitoring of δ_{xyl} values. Despite this, the temporal dynamics this study captured offer valuable perspectives on tree internal water cycling. The sub-daily isotopic signatures of in situ monitored δ_{xyl} values suggest systematic behaviour of sub-daily water cycling in urban trees. During summer drought, we detected strong differences between day- and night-time (8 pm - 8 am) signatures of δ_{xyl} (amplitude ~38 ‰ δ^2H; Figs. 3~~4~~, 6~~11~~). In contrast to δ_v values, we identified an afternoon enrichment in heavy isotopes of δ_{xyl} when VPD and sap flow rates reached their maxima. The cross-correlation analysis revealed a dominant temporal connection between the diurnal hydroclimatic cycles of radiation and VPD with δ_{xyl} values during drought (Figs. S7, S8). While sap flow rates were highest at noon, maximum δ_{xyl} enrichment in heavy isotopes was ~3 pm (Fig. 3~~4~~), like VPD maxima. Cross-correlation analysis also revealed a 1 h lag between the two boreholes of ~~Silver birch~~*B. pendula* during drought (Figs. S9, S10). ~~But a~~As sap velocities were quite high, this seems less likely to indicate a 1 h travel time between boreholes, but rather an artefact of the sequential in situ measurements. But the amplitudes in δ_{xyl} day-time enrichment were occasionally larger in the lower borehole of *B. pendula* at 1.5 m compared to 2.5 m height, which might be a dilution effect with height. A recent in situ study by Minick et al. (2025) on internal water movement in oak tree xylem, saw slow axial advection and a loss of applied tracers in the shallow sap wood and with stem height, indicative of dilution and dampening with height. Likewise, De Deurwaerder et al. (2020) revealed such dynamic temporal fluctuations in measured δ_{xyl} values dependent on sampling height, which needs to be considered in sampling protocols.

While radiation inputs and PET were greatly reduced during rewetting, we still found significant day-time enrichment and night-time depletion in heavy isotopes of δ_{xyl} consistent with diurnal hydroclimatic cycling (Figs. 4~~5~~, S7~~8~~). But the sub-daily δ_{xyl} amplitudes of ~20~~15~~ ‰ δ^2H were ~~smaller by more than~~almost half smaller compared to the drought period (Fig. 6). Lc-excess of δ_{xyl} values became positive during the rewetting period, indicating a lowered evaporation signal in the xylem. Kühnhammer et al. (2022) likewise observed a clear daytime enrichment in heavy isotopes of δ_{xyl} in tropical rainforest trees with maxima around noon, and depleted δ_{xyl} values after sunset (sub-daily amplitude approx. 30 ‰ δ^2H). ~~In a lab experiment, Martín-Gómez et al. (2017) found short-term dynamics of δ_{xyl} in response to drought, reflected in a xylem evaporative enrichment under limited sap flow. This is similar to our finding that max. enrichment of δ_{xyl} (~3 pm) does not follow max. sap flow (noon) in time.~~

It exist various potential plant physiological processes driving daytime enrichment of δ_{xyl} values: During daytime, water demand in the tree canopy exceeds water absorption through the roots (Herzog et al., 1995; Cermák et al., 2007), which was reflected~~revealed~~ in our study by the more negative twig water potential at noon compared to morning (Fig. S1). King et al. (2013) also reported a daily cycling of water uptake and loss in stem diameters of conifers in Switzerland, with the smallest diameters, occurring in the late evening and a diurnal amplitude that increased with temperature. In a 24-h field experiment including manual sampling of *Eucalyptus globulus* leaves, Cernusak et al. (2005) found the strongest enrichment of leaf water in the afternoon, while photosynthetic rates were highest in morning indicating that photosynthesis is not a dominant driver of diurnal tree SWI ~~δ_{xyl}~~values. Most importantly, De Deurwaerder et al. (2020) list that the regulation of plant transpiration by stomata and root water uptake, which involves typical diurnal patterns linked to VPD, can have a sub-daily impact on δ_{xyl} values. In a lab experiment, Martín-Gómez et al. (2017) found short-term dynamics of δ_{xyl} signatures in response to drought, reflected in a xylem evaporative enrichment under limited sap flow. This is similar to our finding that maximum enrichment of δ_{xyl} values (~3 pm) does not follow maximum sap flow (noon) in time. Also, water loss and evaporation through the tree bark could be a driver for day-time δ_{xyl} enrichment, but is is dependent on tree species and reduced with bark thickness (Dawson and Ehleringer, 1993; Lintunen et al., 2021; Zhou et al., 2024). ~~This was further underlined by the findings of~~ Kübert et al. (2022)~~:~~ ~~in situ~~ monitored δ-values of tree transpiration (δ_T) in situ ~~as we~~ and found ~~as well for~~ that sub-daily cycling of δ_T~~xyl~~ values was~~ere~~ closely related to the diurnal variation of stomatal conductance. However, they discovered differences between in situ derived δ_T values and cryogenically extracted δ_{xyl} values, which hints for a possible deviation between δ_T and δ_{xyl} values. Earlier investigations indicate stomatal conductance as a driver of δ_T values but simultaneous non-steady-state effects within SWI fluxes of plants and isotopic fractionation leading to a variation between δ_T and δ_{xyl} values (Dubbert et al., 2017; Simonin et al., 2013). Additionally, it was found that δ^2H and $\delta^{18}O$ values in leaf water respond differently to environmental drivers (Cernusak et al., 2022). ~~Thus, limited sap flow, changes in stomatal conductance, negative water potential in the tree canopy along with high VPD drive the diurnal variances of δ_{xyl}.~~ Finally, w~~W~~e argue that trees actively react and adapt to environmental conditions to moderate their water use throughout the day, which in turn influences δ_{xyl} values. Still, δ_{xyl} values likely differ from δ_T values due to complex physiological and environmental interactions. Key influencing factors include changes in radiation and VPD, as well as resulting shifts in sap flow dynamics, plant water potential, stomatal conductance and bark transpiration.

~~Nevertheless,~~ O~~o~~ur observations were made for ~~(~~deciduous~~)~~ species in temperate regions, but there is evidence that sub-daily cycling of δ_{xyl} is alternating within tree species and climate. A 24 h monitoring of rainforest tree species suggested that diurnal variation of δ_{xyl} is species-specific – some trees showed clear sub-daily differences, some not (Sohel et al., 2023b). This could be explained by sub-daily variations in leaf hydraulic conductance within species (Lo Gullo et al., 2005). Zhao et al. (2016) found overall stable diurnal δ_{xyl} values, but an afternoon depletion in twig water as well as a general fractionation between stem and twig δ_{xyl} waters in *Populus euphratica*. Bernhard et al. (2024) found no significant sub-daily fluctuations of manually sampled xylem water and its δ_{xyl} values in spruce, oak and beech of a temperate forest, but variations for different stem heights. Still, a daytime enrichment in heavy isotopes of δ_{xyl} is plausible for various tree species, as evaporative influence resulting from higher gas exchange rates and high gradients of water potential from roots to canopy have an impact on δ_{xyl} values.

Before implementing δ_{xyl} data into modelling, the validation and quantification of vegetative processes influencing variations in δ_{xyl} values is essential (De Deurwaerder et al., 2020). Biases in δ_{xyl} data from isotopic fractionation as a natural process are ambiguous for use of such data in models and can exacerbate isotopic discrimination of root water uptake depths (Birkel et al., 2025b).

5.2 Effects of summer drought on urban green spaces

5.2.1 ~~Urban green space~~ Atmospheric moisture cycling during drought

Periods of drought are expected to not only become more frequent but also have greater longevity (Petrova et al., 2024), potentially impacting urban vegetation. Wei et al. (2015) found that the diurnal amplitude of δ_v values is larger during periods of lower transpiration, emphasizing that significant differences of δ_v values between daytime and night time occur during periods of water stress and limited transpiration. These diurnal cycling patterns of δ_v values during drought can be further impacted by the effects of climate change, when humidity differences between the surface boundary layer and atmosphere above are magnified by dry-air entrainment (van Heerwaarden et al., 2009). Although isolated high-intensity rainfall events can occur during summer droughts~~–~~ and their frequency and intensity are projected to increase (Sobaga et al., 2024),~~–~~ they often bring limited soil moisture replenishment. When rainfall intensity exceeds the soil infiltration capacity, water is rapidly lost through surface runoff to nearby water bodies or ponded water may increase evaporation. This effect can also be pronounced in urban areas where soils can be compacted by human footfall and sandy soils may have low water storage capacity and drain rapidly (Drastig et al., 2011; Ferreira et al., 2021). Further, drought periods can alter water transport in grasslands by restricted soil water mixing and reduced transpiration (Radolinski et al., 2025).~~, possibly also reducing the positive impacts of urban grasslands through evaporative cooling in times of climate change. Still, the more unsealed, green surfaces are present in UGS, generally the higher is vegetation growth, gas exchange and cooling effects in a city (Konarska et al., 2023) - which emphasizes the importance of resilient UGS.~~

5.2.2 Tree ~~W~~water cycling during drought~~of urban trees~~

The insights from in situ monitoring of δ_{xyl} values revealed significant impact of summer drought, indicated by large amplitudes δ_{xyl} values in~~on~~ the sub-daily water cycling and linked ~~consequent~~ responses in plant physiological processes (see Sect. 5.1 & 5.1.3). During drought conditions, both ~~maple~~*A. platanoides* and ~~birch~~*B. pendula* exhibited no significant positive correlation of δ_{xyl} values with stem growth (as a proxy for sap flow) over the course of the day (Figs. S9, S10) indicating water limitation also at night.

Previous isotopic studies revealed that during drought tree canopies exhibit signs of stress, affecting their overall health and cooling capacity (Kuhlemann et al., 2021). Stevenson et al. (2025) further highlighted a strong sensitivity of ~~UGS~~ urban green space hydrological functioning to seasonal hydroclimatic changes and high suppression of ET fluxes in urban trees in SW-Berlin during the 2022 drought. Gessler et al. (2022) showed that drought reduces water uptake in beech from the drying topsoil, but also with no compensatory uptake from deeper soil layers.~~-~~ Such limitation can especially impair tree functioning when temperatures are high during daytime. Kupper et al. (2017) found that elevated daytime atmospheric humidity increases the potential for night time water flux in *B.~~etula~~ pendula*. This effect is reduced under drought conditions, so that night-time recharge may also have been more constrained in the ~~birch~~*B. pendula* ~~analyzed~~analyzed.

Drought severity and antecedent climatic conditions have been shown to be major factors influencing the magnitude of sub-daily drought stress on vegetation. Kübert et al. (2022) found similar sub-daily cycling with daytime enrichment in δ_T -values ~~of transpired waters~~ in trees of an enclosed rainforest, but here the amplitude of the diurnal variation strongly declined with increasing drought severity. In our study, the drought conditions during summer were less pronounced compared to their study: as the preceding 2021/22 winter was wet and some precipitation inputs were recorded during summer (Fig. 2~~3~~). Possibly with more severe drought conditions less distinct diurnal cycling would be evident. Further, the effects of droughts on ~~urban~~ tree functioning depend~~s~~ on species composition and their adaptation to drought. It was previously reported that trees can be in competition for water with neighbouring species (Kinzinger et al., 2024; Magh et al., 2020).

To conclude, long summer droughts affect the sub-daily water cycling in ~~urban~~ tree xylem~~s~~, which results in limited ET fluxes and reduced sap flow rates relative to high VPD rates during day time as well as a stagnation of night-time stem swelling. The magnitude of these effects is likely to be highly variable and dependent on the ecohydrological status of ~~the UGS and its~~ tree species composition within green spaces.

5.3 Wider implications

This study provided the opportunity to better understand the sub-daily dynamics of water cycling ~~during drought~~ in different types of ~~urban~~ vegetation over the growing season. The insights of our high-resolution SWI dataset on plant physiology and hydrological functioning, including atmospheric responses are of high relevance for studying ecohydrological partitioning (Birkel et al., 2025b). SWI of plant xylem and the surrounding atmosphere revealed clear diurnal cycling patterns, reflecting changes in radiation and VPD. State of the art SWI isotope assessment should transition towards in situ sampling to better catch complex sub-daily root water uptake and plant internal water cycling patterns. Moreover, investigating species-specific responses of trees across diverse biomes is essential (Sohel et al., 2023b). As we only measured δ_{xyl} values, we suggest to include measurements of SWI covering the whole tree from root to stem and branches to twigs, including direct measurements of transpiration for future in situ studies on sub-daily tree water cycling (Sohel et al., 2023a). Nevertheless, in situ monitoring providing sub-daily datasets is not always possible due to difficult sampling locations, high maintenance requirements or cost of instruments. We suggest more appropriate δ_{xyl} sampling protocols (Tierney et al., 2025), that include sampling at the same time of day, preferably in morning hours after sunrise which mostly reflect a daily mean value. Mid-day and afternoon sampling of plant water might very likely reflect daytime enrichment and further fractionation in SWI. Finally, we join others in calling for an exhaustive evaluation of in situ methods vs extracted waters to close the questioning about the validity of in situ methods towards a common methodological framework of studies of the SPAC (cf. Ceperley et al., 2024).

~~, at a time when increasing drought is a problem all over the world (van Loon, 2015). During summer droughts, altered day-time highs and night-time cooling patterns can negatively impact the wellbeing of urban residents. The cooling potential of urban trees can be reversed during extreme heat when stomatal regulation of leaf transpiration is strained by high VPD values (Meili et al., 2021). High temperatures can override the positive effects of trees, especially in highly urbanized areas, when transpiration is reduced during the day and heat stored under canopies at night (Wilkening and Feng, 2025). Kraemer and Kabisch (2022) highlight that tree dominated UGS preserve a certain level of ET cooling throughout the whole day, while urban grasslands lose their cooling characteristics more rapidly at daytime, but provide even stronger cooling during nights. Thus, city planners might best consider a mix or "mosaic" of urban vegetation types to maximize cooling benefits throughout the 24-hour cycle (Gillefalk et al., 2021; Kuhlemann et al., 2021).~~

~~Our findings support the integration of targeted vegetation planning and management into urban climate policy. The choice of climate resilient tree species that can sustain their natural water supply under drought (Roloff et al., 2009), to provide cooling during strongly heated afternoons, helps cities adapt to climate change (Pataki et al., 2021). Especially street trees can have positive impacts, as they can hold high rates of carbon cycling but also higher mortality rates compared to forest trees (Smith et al., 2019). Recently, *Robinia pseudoacacia* and *Platanus x acerifolia* were found to be little influenced by drought and degree of urbanisation in Munich, Germany, while *A. platanoides* and *T. cordata* showed accumulated stress during drought (Franceschi et al., 2023). The trees investigated in our study were mature, deep-rooted maple and birch individuals that accessed deeper soil water and groundwater for sustenance, ensuring sufficient sap flow rates and maintaining overall tree functioning (cf. Ring et al., 2024). However, in urban environments, smaller, younger trees as well as street trees with restricted rooting space and high surface sealing face additional challenges and are more vulnerable to drought stress (Kluge and Kirmaier, 2024; Anys and Weiler, 2025). Therefore, urban vegetation management that prioritises plant physiological functioning is essential. Furthermore, our results underline the need to store water from high intensity rainfall to sustain water availability for urban vegetation during periods of drought, by improving soil water storage and retention (Lin et al., 2018), or by implementing artificial water storage in cities (Suleiman et al., 2020).~~

Our high-resolution dataset also convenes a more quantitative understanding of ~~urban~~ ecohydrological fluxes and partitioning within green spaces, since~~:~~ the continuous, sub-daily (3-hourly) dataset of δ_v and δ_{xyl} values is highly valuable to constrain ecohydrological models which help predicting impacts of climate change on ~~UGS~~vegetation mediated water fluxes. The application of continuous water isotope data reduces parameter uncertainties in SPAC modelling (Smith et al., 2021). Birkel et al. (2025a) have just further emphasised the importance of including SWI ~~isotopes~~ in modelling to advance climate change prediction. Additionally, our ecohydrological dataset has the potential to upgrade the assumptions of remote sensing-based modelling of sub-daily water fluxes within vegetation (cf. Vermunt et al., 2022). ~~As we only measured δ_{xyl}, we suggest to include measurements of stable water isotopes covering the whole tree from root to stem and branches to twigs for future in situ studies on sub-daily urban tree water cycling (Sohel et al., 2023a). Finally, we join others in calling for an exhaustive evaluation~~

~~of in situ methods vs extracted waters to close the questioning about the validity of in situ methods towards a common methodological framework of studies of the SPAC (cf. Ceperley et al., 2024).~~

This study was able to capture vegetation water cycling during a summer drought, at a time when increasing drought and heatwaves with complex land-atmosphere feedbacks is a problem all over the world (van Loon, 2015; Miralles et al., 2019). Drier soils contribute to the intensification of heatwaves through reduced evaporative cooling and increased sensible heat fluxes, but at the same time ET processes can amplify the effects of negative precipitation anomalies (Teuling et al., 2013; Dirmeyer et al., 2021). These effects are further modulated by the type of land-use and soil: In European grasslands heating is on short-term suppressed be ET cooling, but at long term soil moisture depletion is accelerated underneath grasslands, whereas forests mitigate the impact of extreme heat more at long-term even though they have higher interception and transpiration losses (Teuling et al., 2010; Kleine et al., 2020). Our findings support vegetation management that prioritises plant physiological functioning and water storage within the landscape (Luo et al., 2024). Vegetation worldwide responds to drying surface soils by shifting water uptake to deeper layers, thereby sustaining transpiration and ensuring hydraulic safety during seasonal droughts (Bachofen et al., 2024). The trees investigated in our study were mature, deep-rooted *A. platanoides* and *B. pendula* individuals that accessed deeper soil water and groundwater for sustenance, ensuring sufficient sap flow rates and maintaining overall tree functioning (cf. Ring et al., 2024). However, smaller, younger trees with restricted rooting space and high surface sealing in cities face additional challenges and are more vulnerable to drought stress (Kluge and Kirmaier, 2024; Anys and Weiler, 2025). Therefore, it is important to choose climate resilient tree species that can sustain their natural water supply under drought (Roloff et al., 2009).

6 Conclusion

During the growing season of 2022, we combined in situ monitoring via CRDS and ecohydrological monitoring in different urban vegetation in Berlin, Germany. ~~Stable water isotopes~~SWI of atmospheric water ~~vapour~~vapor (δ_v) were monitored at different heights above a grassland and under the canopy of a mature ~~maple~~*A. platanoides* tree. ~~Stable water isotopes~~SWI of the xylem water within tree stems (δ_{xyl}) was monitored at different heights in an ~~maple~~ A. *platanoides* and ~~a *birch*~~*B. pendula* tree.

The summer period from July until mid-August was characterised by drought conditions, including occasional convective rainfall events, which did~~o~~ not infiltrate into deeper soils, and was followed by a rewetting period with frequent rainfalls starting in mid-August. We identified distinct sub-daily ecohydrological dynamics over drought and rewetting. Throughout the drought period, water cycling was predominantly radiation driven, with highest VPD rates in the afternoons and persisting dry soils. During rewetting, precipitation became the dominant driver of the ~~UGS~~ water cycling within the SPAC~~e~~, while at the same time PET rates decreased.

The analysis of sub-daily isotopes suggests systematic behaviour of both δ_v and δ_{xyl} values during summer drought. δ_v values were ~~was~~ characterized by a daytime depletion in heavy isotopes, driven by entrainment effects and evaporation. We found daytime enrichment in δ_{xyl} signatures, with maximum~~.~~ enrichment in afternoons, which was driven by VPD ~~limited sap flow and~~, stomatal regulation of transpiration and possibly bark transpiration. For the rewetting, we revealed that the systematic diurnal cycling of δ_v values was discontinued for most heights. It became more evaporation driven from the re-saturated soils, while the influence of entrainment from the larger urban surface boundary layer was reduced. Only δ_v values just above the grassland surface (0.15 m) showed a significant daytime enrichment (amplitude ~ 36 ‰ δ^2H), hinting for ET fluxes from vegetation surfaces and superficially enriched soil water. While radiation inputs were greatly reduced during rewetting, we still found significant daytime enrichment and night-time depletion of δ_{xyl} values with sub-daily amplitudes almost ~~more than~~ halved compared to the drought period. Our results suggest that the monitored urban vegetation experienced high water demand ~~sub-daily water limitations, particularly~~ during summer drought. Constrained ET fluxes were indicated by reduced precipitation and soil moisture. In the trees, this was reflected in lowered ~~twig water potential and~~ sap flux relative to VPD in the afternoons, as well as stagnated night-time trunk swelling, but the mature trees could overall sustain their physiological functioning.

Our findings provide novel insights on plant physiology and hydrological functioning by demonstrating the relevance of high-resolution SWI data and emphasizing the need for in situ SWI assessment to capture sub-daily plant water uptake and internal water cycling. ~~the cooling potential of urban vegetation. We assume that increasing droughts will reduce the cooling effects especially during the afternoons, parallel to accumulated heat storage under trees at night. Urban planning could usefully consider a "mosaic" of urban vegetation types together with resilient species composition to maximize cooling benefits throughout the 24-hour cycle.~~ Such continuous, sub-daily datasets of δ_v and δ_{xyl} values have the potential to better constrain ecohydrological models which help predicting impacts of climate change on plant mediated water fluxes ~~UGS~~. However, more research is needed to extend our findings on sub-daily water cycling within vegetated areas~~in UGS~~, covering different types of planting, higher sample size and varying tree species from root to twig, including leaf transpiration.

Code and data availiability

The isotope data are available with a password (to be received from the corresponding author upon request) from the open-access database FRED at IGB.

Competing Interests

The authors have no conflicts of interest to declare.

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Authors contribution

AMR: Conceptualization, Data curation, Data analysis and plotting, Methodology, Field activities, Writing – original draft preparation. DT: Investigation, Funding acquisition, Data curation, Methodology, Formal analysis, Writing – review & editing. CB: Investigation, Methodology, Formal analysis, Writing – review & editing. CS: Conceptualization, Investigation, Methodology, Formal analysis, Writing – review & editing.

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