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Sub-daily 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 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 water stable isotopes can provide valuable insights into how trees 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 (24h) patterns of water cycling in δ_v, δ_{xyl} and ecohydrological variables during a summer drought followed by a rewetting period 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 was characterized by a daytime depletion in heavy isotopes, driven by local evaporation and atmospheric factors (entrainment). Daytime enrichment in δ_{xyl}, with maximal enrichment in afternoons, was consistent with diurnal hydroclimatic cycles, limited sap flow sourced from enriched soil water and stomatal regulation of transpiration. 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 was precipitation driven, while potential evapotranspiration (PET) rates decreased. The systematic diurnal cycling of δ_v was mostly discontinued due to lower soil and canopy evaporation. Only δ_v just above the grassland surface (0.15 m) showed a significant daytime enrichment hinting for ET fluxes promoted by high moisture stored in soil and vegetation surfaces and transpiration of superficially enriched soil water. δ_{xyl} was still characterized by significant daytime enrichment, however, with sub-daily amplitudes more than halved compared to the drought period, when hydraulic conductance was restricted. Our continuous, sub-daily dataset of δ_v and δ_{xyl} have the potential to help constrain ecohydrological models towards prediction of climate change impacts on UGS. Urban planning should consider a "mosaic" of urban vegetation types together with resilient species composition to maximize cooling benefits throughout the 24-hour cycle.

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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, 2022), 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.

Stable water isotopes 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 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 with diffusion-tight bags (Herbstritt et al., 2023; Dahlmann et al., 2024).

More recently, field studies which measure stable water isotopes 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). Although, the fractionation of δ_{xyl} through plant physiological processes can be a confounding issue (Barbeta et al., 2020; Vega-Grau et al., 2021). Previous 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

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willow trees (Landgraf et al., 2022), 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). 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. 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 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 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 hottest summer in Europe since records began, according to Copernicus Climate Service, 2022. Thus, this research has the potential to gain novel high-frequency insights on sub-daily UGS water cycling in times of climate change.

Our specific research questions were:

- What are the sub-daily dynamics of xylem and vapor water stable isotopes over the growing season in different urban vegetation?
- Can we identify water limitations on tree function at a sub-daily basis for the investigated urban green vegetation?
- Do high-resolution 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 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 datasets.

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2 Study Site

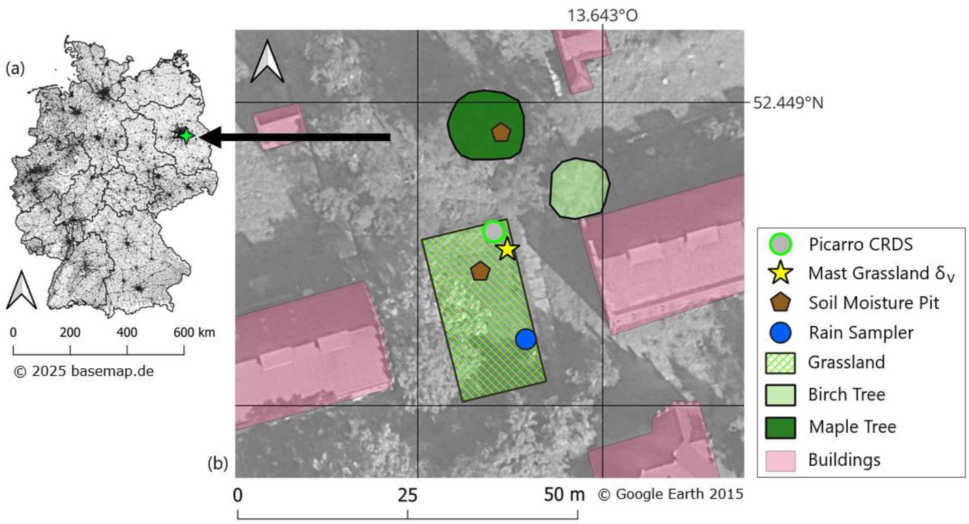

Figure 1: (a) Location of the study site in Germany (residential areas and borders of federal states in black - modified from basemap.de/open-data). (b) Study site in Berlin-Friedrichshagen with investigated grassland, Norway maple and Silver birch, including CRDS, flag mast for atmospheric vapor (δ_v) measurements, soil moisture pits (underneath canopy and at grassland) and precipitation sampler (basemap: © Google Earth 2015).

The study was conducted in a peri-urban area 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).

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, 2021). 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, 2024). 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.

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).

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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 tree (*Acer platanoides;* ~ 80 years old) with a height of ~16 m and a stem diameter of 560 mm and one dominant Silver birch tree (*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 1. Hourly potential evapotranspiration (PET; cf. Bliss Singer et al., 2021) was estimated by the FAO Penman–Monteith method (Allen, 1998) using data from a IGB rooftop station, 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 1). 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).

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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 vapour)	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-vapour 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* (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

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3.2 In situ monitoring of δ_v and δ_{xyl}

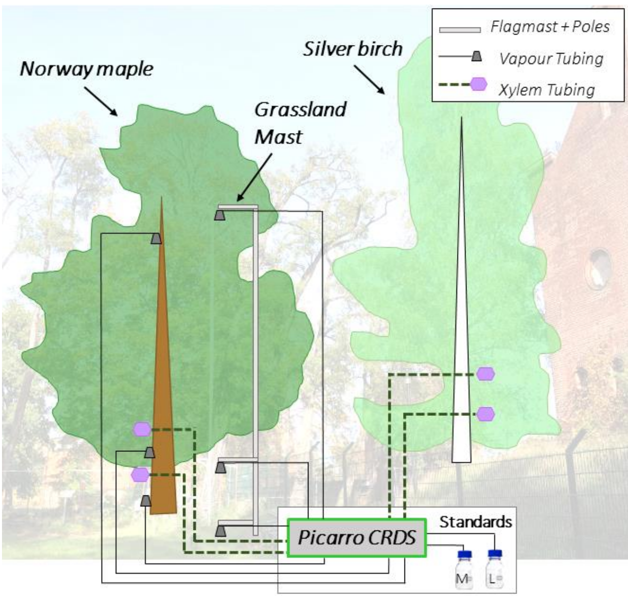

Figure 2: Conceptual diagram of the general in situ measuring setup for stable water isotopes of atmospheric water vapor (δ_v) and plant xylem water (δ_{xyl}). All inlets were measured sequentially via tubing connected to the CRDS. δ_v was measured at 0.15 m, 2 m and 10 m height under the maple canopy and above grassland at a flag-pole (distance between maple and flag mast was 16 m; grey caps refer to rain and wind protection cover). δ_{xyl} was measured from boreholes at Norway maple and Silver birch (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.

Stable water isotopes of atmospheric water vapour (δ_v) and plant xylem water (δ_{xyl}) were measured in situ real-time and sequentially (automatic switch of tube) via CRDS (Fig. 2). The CRDS 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 1. The plot-scale elevation profile above the two distinct UGS 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 (Fig. 2). Each δ_v tube inlet (Fig. 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 bottles covered with aluminum foil over each δ_v tube inlet.

δ_{xyl} of the Maple and the Birch tree was 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. 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

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$\delta^{18}O$). We could not use the δ_{xyl} data of the maple 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, 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):

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

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.

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 concentration dependencies, automated calibration of CRDS measurements was performed after every three loops of measuring δ_v and δ_{xyl} 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, we conducted monthly destructive soil sampling from April until October 2022 at the grassland site and underneath the Maple tree (Fig. 1) (see Table 1). 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 the SPAC of urban vegetation: including sap flow, stem growth, twig water potential, LAI, soil moisture and groundwater levels (see Table 1). 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 data we used

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non-parametric alternatives (assuming all observations were independent and random): the Wilcoxon signed-rank test for two groups (Wilcoxon, 1945) and the Kruskal-Wallis test by ranks for plus two groups (Kruskal and Wallis, 1952) 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, 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.

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.

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4 Results

4.1 Hydroclimatic conditions during 2022

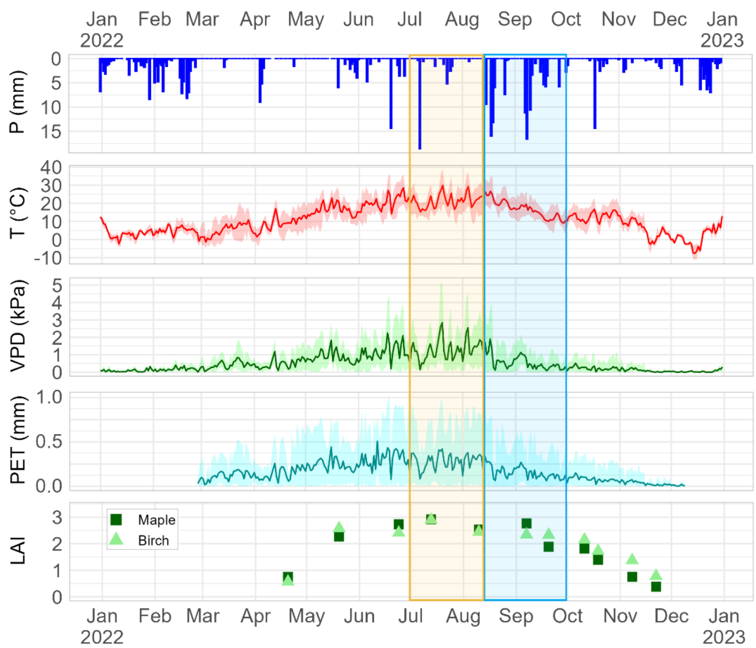

Figure 3: Hydroclimatic Context 2022: Precipitation [mm] is shown as daily sum. Temperature [°C], VPD [kPa] and PET [mm/h] are shown as daily mean values with daily min/max band. Leaf Area Index (LAI) is shown as daily mean values. Periods of interest are shown as an orange box (summer drought 01.07.-14.08.2022)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

Hydroclimatic conditions surrounding the study period in 2022 are shown in Fig. 3. The spring of 2022 was very dry with very low precipitation input from March until May (~ 40 mm at study site in 3 months). The summer was also very dry and warm compared to the long-term average (1991-2020) at DWD station Berlin Marzahn (DWD, 2025). The Global Precipitation Climatology Centre drought index for July 2022 indicated a mild to moderate drought for southeast Berlin (DWD, 2022). Daily mean temperature during the drought period (01.07.-14.08.2022) was 21.6 °C (cf. long-term average: 19,7 °C; DWD, 2021), reaching a maximum of 38.5 °C. Daily maximum PET was mostly above 0.6 mm/h. Cumulative precipitation during the drought period was 32.4 mm (long-term average sum: 105 mm; DWD, 2021), with most events totaling less than 5 mm. The largest rainfall event was a convective event of 18.6 mm on July 7. Daily mean VPD exceeded 1 kPa throughout most of the drought period. Rewetting 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 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

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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

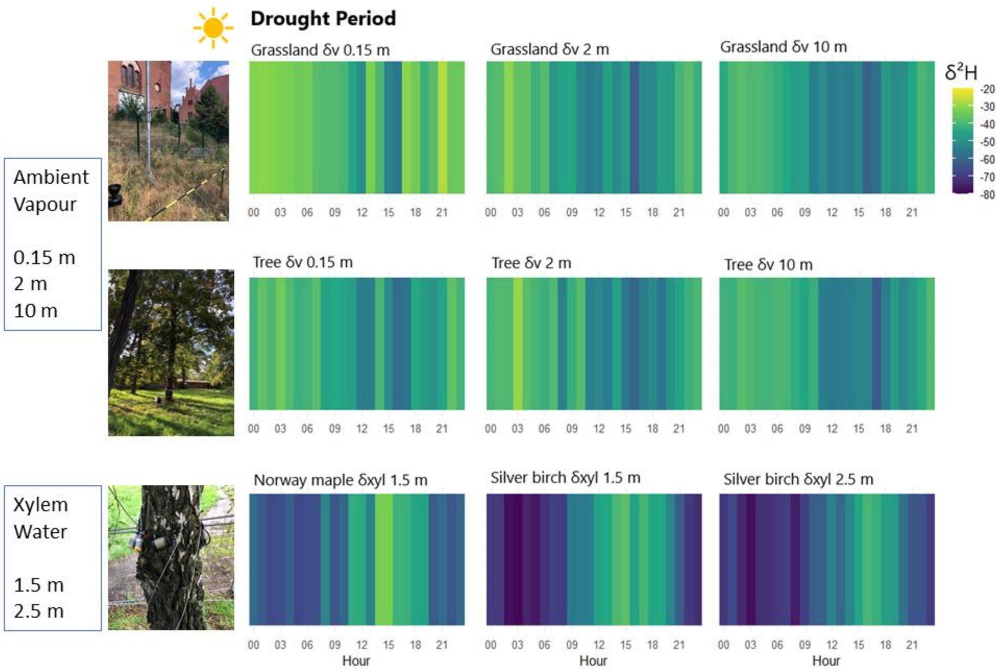

Figure 4: 24-h cycle heatmap of hourly median δ²H data of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) during summer drought period 01.07.-14.08.2022. One in situ measurement loop took ~3.5 h and unstable measurements were ruled out (cf. Method section). The hourly median shown for each hour of the day was calculated based on ~8.6 measurements.

For this analysis, we focus on δ²H, setting aside δ^{18}O which showed near-identical patterns. High-resolution in situ monitoring of δ_{xyl} and δ_v exhibited clear diurnal cycling during the entire drought period (01.07.-14.08.2022; Fig. 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. However, opposing systematic sub-daily dynamics in the isotope signatures of ambient vapor and plant xylem water were apparent: δ_v showed afternoon depletion and nighttime enrichment. δ_{xyl} showed clear afternoon enrichment in heavy isotopes in both trees indicating circadian cycle. Especially, δ_{xyl} of the birch became highly depleted (up to -80 ‰ δ²H) during nighttime. The mean amplitude between day- and night-time values of δ_{xyl} was 38 ‰.

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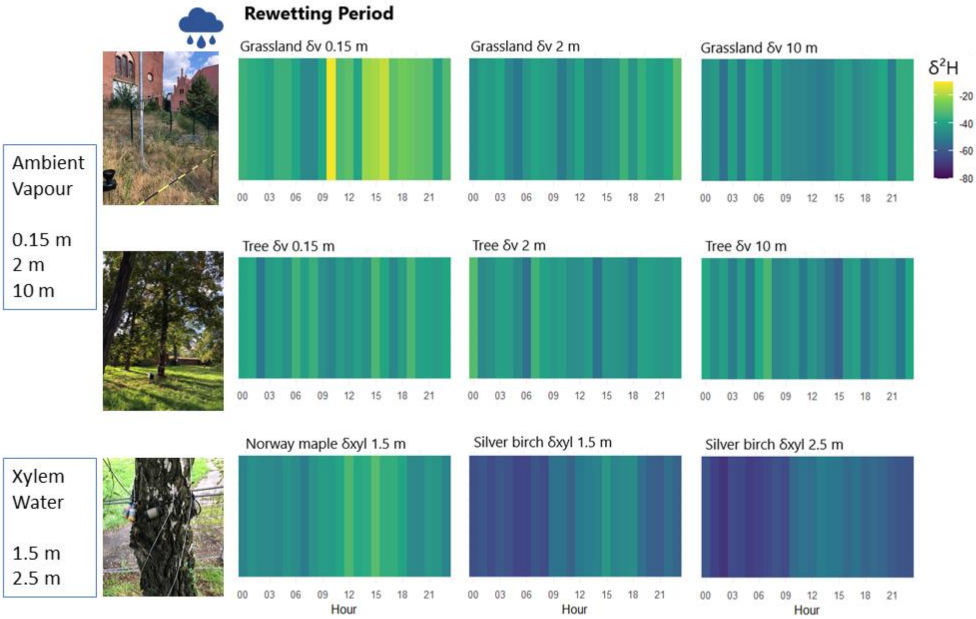

270 **Figure 5: 24-h cycle heatmap of hourly median δ^2H data of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) during rewetting period 15.08.-30.09.2022. One in situ measurement loop took ~3.5h and unstable measurements were ruled out (cf. Method section). The hourly median shown for each hour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

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

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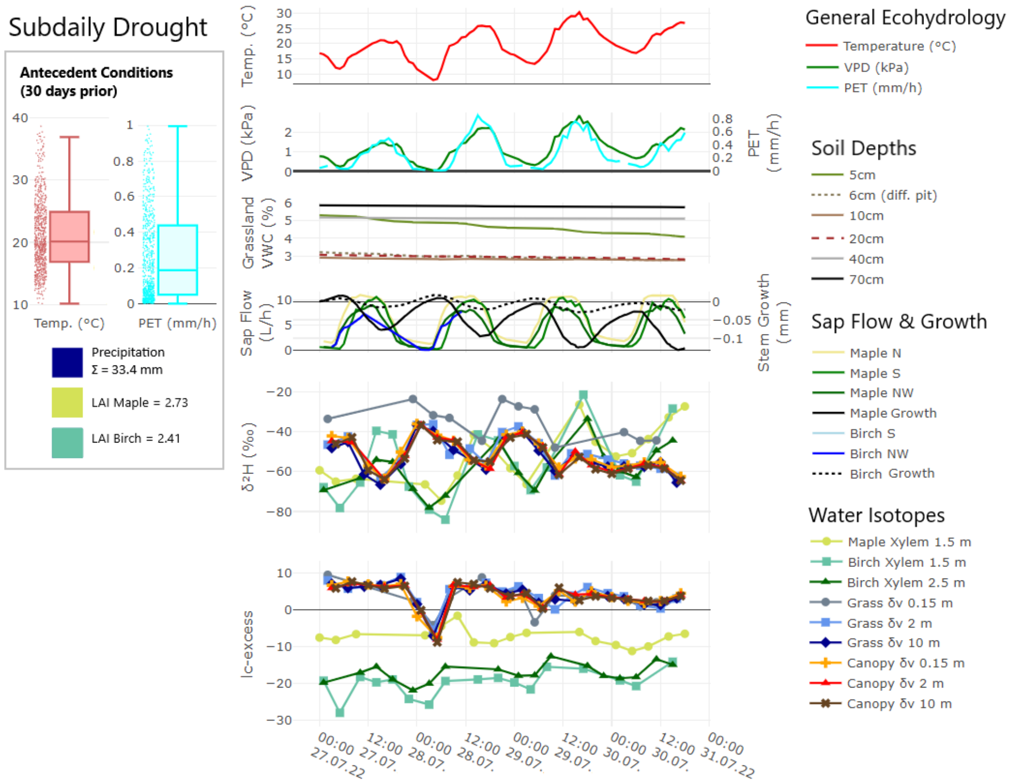

Figure 6: Drought conditions: Sub-daily timeseries displaying diurnal variation of tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v) and measured ecohydrological variables. The top-left box shows antecedent conditions 30 days prior the timeseries: hourly data of temperature and PET, precipitation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

In Fig. 6 we zoom into a typical 4-day long sub-daily timeseries (27.07.-31.07.2022) of the monitored stable water isotopes and ecohydrological data during the drought period. Meteorological conditions 30 days prior to July 27 2022 were characterized by a daily mean temperature of 20.5 °C, a mean PET of 0.19 mm/h 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 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) and then decreased, dropping below 2.5 L/h 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 similar to the averages presented in Fig. 4. δ_{xyl} became enriched in heavy isotopes during afternoons and depleted during nighttime (large sub-daily variation of ~40 ‰ δ^2H). δ_v became enriched during nighttime hours (sub-daily variation of ~20 ‰ δ^2H). Lc-excess of δ_v was mostly above zero (~ 5), with a single change to negative values during night on July 28th. δ_{xyl} lc-excess was strongly negative with birch lc-excess becoming more negative (around -20) than maple lc- excess (around - 8).

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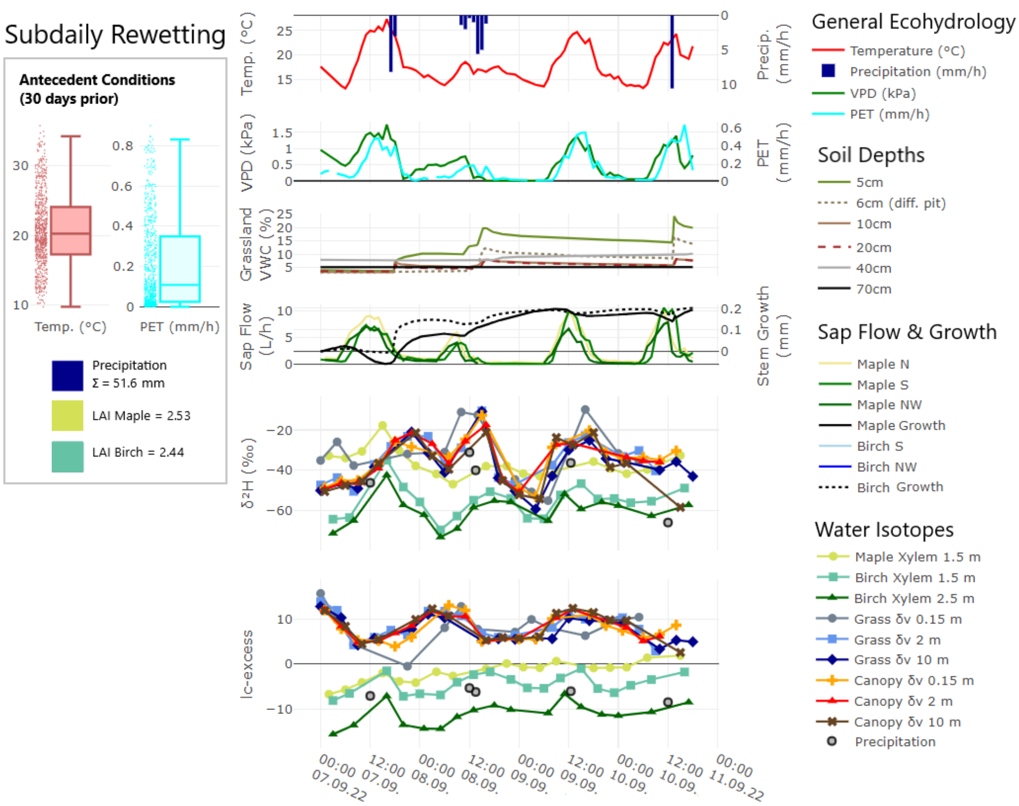

Figure 7: Rewetting conditions: Sub-daily timeseries displaying diurnal variation of tree xylem water (δ_{xyl}), atmospheric vapor (δ_v), precipitation water isotopes and measured ecohydrological variables. The top-left box shows antecedent conditions 30 days prior the timeseries: hourly data of temperature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

In Fig. 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 were characterized by a daily mean temperature of 21 °C, a mean PET of 0.1 mm/h 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 rose up to 10 L/h 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} (~20 ‰ δ^2H) compared to the presented drought timeseries which had no precipitation input. 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. 5. Lc-excess values of δ_{xyl} and δ_v became higher compared to drought

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The sub-daily timeseries during wet conditions (= after rewetting; 01.10.-05.10.2022) (Fig. S2, supplementary material) showed lower maximum sap flow rates of maple. Soils were (re)wetted: Upper soils retained water from precipitation inputs for several days after a rain event. Lc-excess 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} 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. 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}. However, δ_v 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 and δ_{xyl} corresponded more closely to the precipitation signatures during the rewetting phase. Notably, δ_{xyl} of birch did not reflect the precipitation signal during rewetting.

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

A cross-correlation analysis between the monitored ecohydrological variables and in situ δ^2H revealed some inversions sub-daily patterns between the drought and the rewetting period (Fig. 8). 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 was detected. It followed the diurnal radiation cycle with the inverse behavior of δ_{xyl} and δ_v; δ_{xyl} had a positive correlation with solar radiation and VPD at lag 0 hours. In contrast, δ_v 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. 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 were damped: correlation coefficients were usually below (-)0.3. Lags of δ_v 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 during drought. During rewetting, the correlation of soil moisture below the canopy with δ_{xyl} stayed low but rose above 0.4 after a lag 0 hours for δ_v.

The cross-correlation between δ_{xyl} of the maple borehole at 1.5 m and sap flow data of the maple (Fig. 9) 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} of the maple (Fig. 9) were only weakly correlated (< (-) 0.3) during drought and showed the radiation driven sinusoidal curve. During rewetting, the correlation between δ_{xyl} of maple and its sap flow was weaker. In addition, the correlation of δ_{xyl} with stem growth stayed low but became positive indicating less radiation influence.

Cross-correlation analysis between δ_{xyl} of the two birch boreholes (1.5 m and 2.5 m height; 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 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 boreholes and its stem growth. There was no significant correlation of birch δ_{xyl} with stem growth during drought, but an intermediate positive correlation of 0.33 at delay of -10 hours during rewetting.

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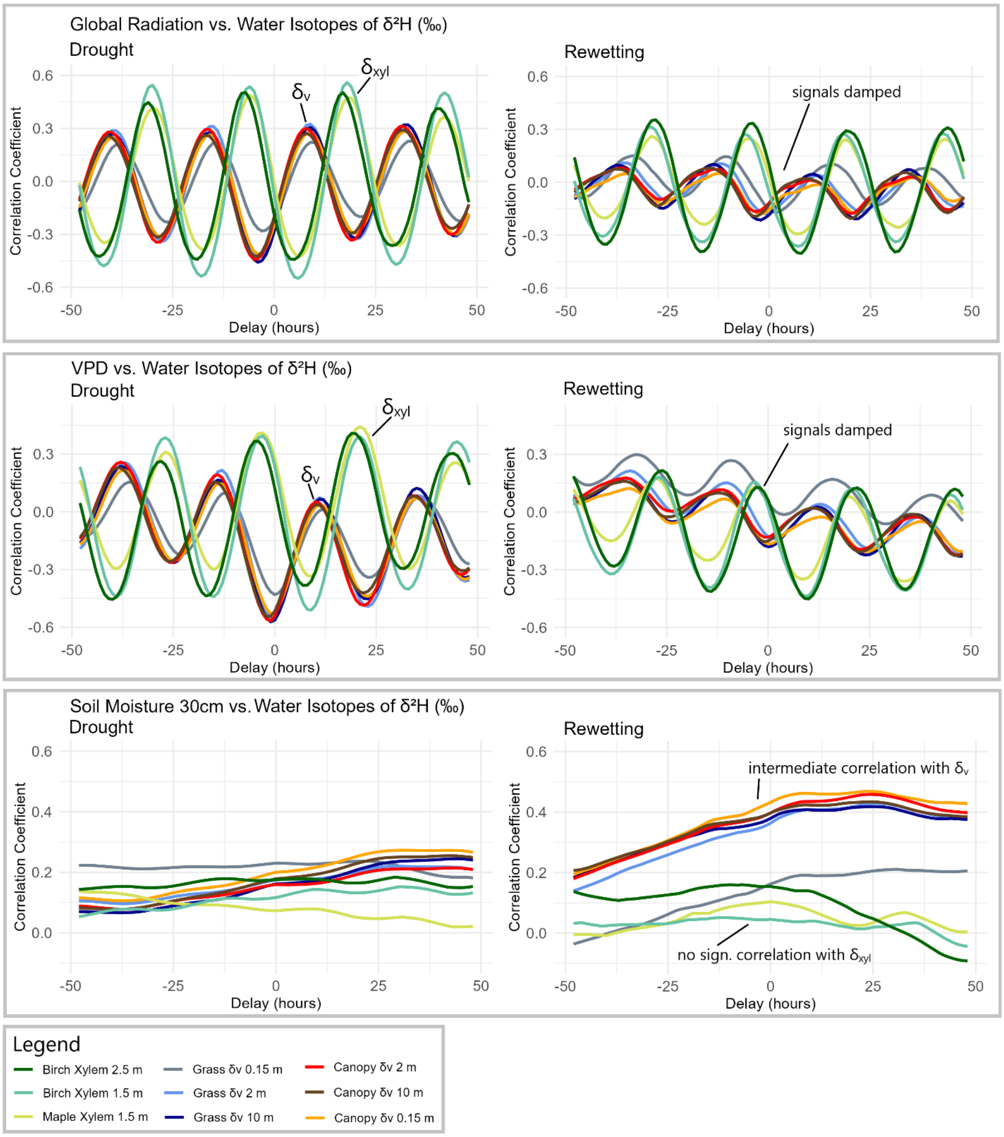

355 **Figure 8: Cross correlation analysis between in situ measured δ^2H data (tree xylem water (δ_{xyl}) and atmospheric vapor (δ_v)) and global radiation, VPD and soil moisture at 30 cm depth underneath canopy comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022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

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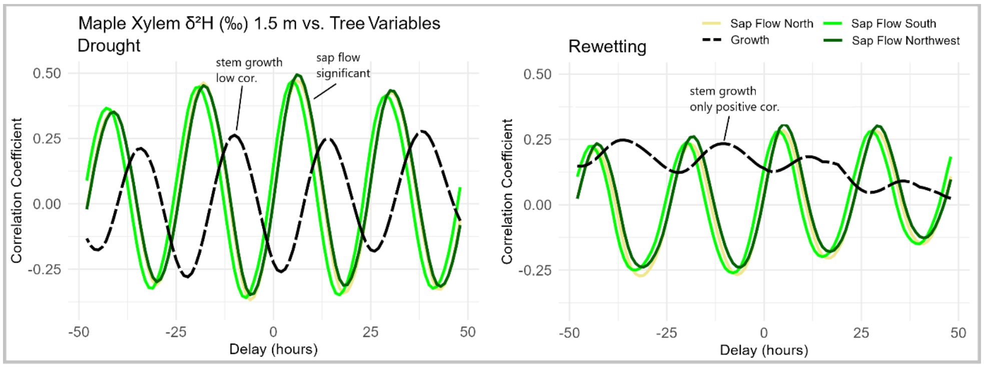

Figure 9: Cross correlation analysis between δ²H of Maple xylem water (1.5 m borehole) and measured sap flow and stem growth comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022 - 30.09.2022).

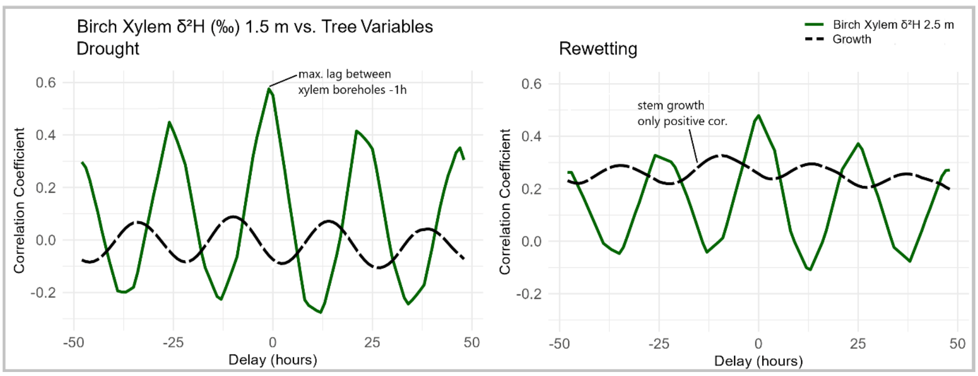

Figure 10: Cross correlation analysis between δ²H of Birch xylem water (1.5 m borehole) and δ²H of Birch xylem water (2.5 m borehole) plus stem increments comparing the two focus periods of drought (01.07. - 14.08.2022) and rewetting (15.08.2022 - 30.09.2022).

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} 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 for both δ_v and δ_{xyl} during the drought, but during rewetting δ_v showed constant signatures over the day, uniquely δ_v just above grassland (0.15 m) exhibited sub-daily but subdued cycling (key figure: Fig. 11).

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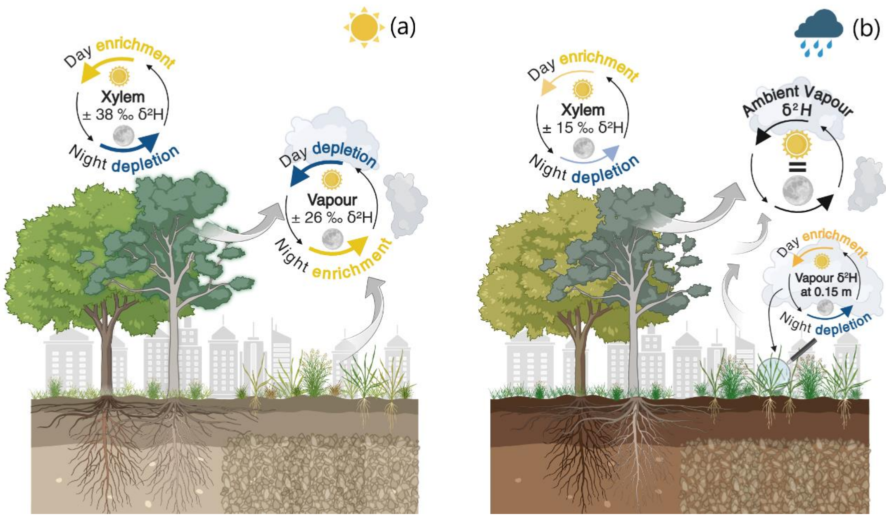

Figure 11: Key figure summarizing the sub-daily change in signatures of water stable isotopes in urban δ_{xyl} and δ_v (over grassland and under canopy). We compare summer drought (a) and autumn rewetting (b) in Berlin, Germany, 2022. Displayed amplitudes of δ^2H [‰] were calculated from hourly medians from the 24-h cycle of each period. 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 the response of urban 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. 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; hinting at reinforced drought patterns reducing UGS cooling effects to a minimum in the afternoon (Kraemer and Kabisch, 2022). Also, 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 cycle. 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. 3) decreased due to lowered radiation in autumn. Especially during precipitation events, temperature, VPD and PET rates were reduced (Fig. 6). In parallel, we observed decreasing LAI and sap flow rates.

5.1.2 Atmospheric vapour isotopes below urban canopy and above urban grassland

The sub-daily isotopic signatures of in situ monitored δ_v suggest systematic behaviour of diurnal water cycling in 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. 4, 11). As δ_v was not correlated in time with soil moisture and also showed low coefficients in the cross-correlation with radiation and VPD (Fig. 8) – we argue that during drought, not only ET processes were controlling δ_v at daytime, but also atmospheric circulations of the larger urban surface boundary layer. A similar trend of diurnal δ_v cycling 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., 2020, 2019). They identified entrainment effects that were stronger than local ET as the main aspect for the daytime enrichment of δ_v. Also, Zannoni et al., 2025, identified that at sub-daily scales, vertical mixing is the dominant process affecting isotopic variability of δ_v, which was high during drought in our study, when radiation was main influencing factor (Fig. 8). This effect is related to mixing with dryer isotopically lighter δ_v 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 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 partially exhibited negative lc-excess during the drought (Fig. 6), emphasizing that the isotopic nocturnal enrichment of δ_v 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 (Figs. 5, 8). This indicates that δ_v becomes 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 monitored at a low height above the grass (0.15 m) showed significant daytime enrichment during rewetting. 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., 2021). The overall positive lc-excess in δ_v during rewetting (Fig. 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 are driven by rainout effects, temperature and relative humidity controlling the initial vapour and variations in vertical mixing.

Thus, we assume that diurnal cycling of δ_v over the growing season is driven by climatic and entrainment effects, while local ET does not fully dominate δ_v 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 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 (Birkel et al., 2025b).

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Considering that, sub-daily signals of δ_v have great potential to reveal previously unexplained short-term variances in stable water isotopes in daily resolved datasets to constrain conceptual models investigating the urban SPAC (cf. Birkel et al., 2025b).

5.1.3 Urban tree xylem waters

The sub-daily isotopic signatures of in situ monitored δ_{xyl} 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 ‰; Figs. 4, 11). In contrast to δ_v, 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} during drought (Fig. 8). While sap flow rates were highest at noon, maximum δ_{xyl} enrichment was ~3 pm (Fig. 4). Cross-correlation analysis also revealed a 1h lag between the two boreholes of Silver birch during drought (Fig. 10). But 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.

While radiation inputs and PET were greatly reduced during rewetting, we still found significant day-time enrichment and night-time depletion of δ_{xyl} consistent with diurnal hydroclimatic cycling (Figs. 5, 8). But the sub-daily δ_{xyl} amplitudes of ~15 ‰ were smaller by more than half compared to the drought period. Lc-excess of δ_{xyl} became positive during the rewetting period, indicating a lowered evaporation signal in the xylem. Kühnhammer et al. (2022) likewise observed a clear daytime enrichment of δ_{xyl} in tropical rainforest trees with maxima around noon, and depleted δ_{xyl} after sunset (sub-daily amplitude approx. 30‰). 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}: During daytime, water demand in the tree canopy exceeds water absorption through the roots (Herzog et al., 1995; Cermák et al., 2007), which was revealed in our study by the more negative twig water potential at noon compared to morning. 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 δ_{xyl}. Most importantly, 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}. This was further underlined by the findings of Kübert et al. (2022): in situ monitored δ-values of tree transpiration as we found as well for δ_{xyl} were closely related to the diurnal variation of stomatal conductance. 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}. We argue that trees actively react and adapt to environmental conditions to moderate their water use.

Nevertheless, our 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

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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}, but an afternoon depletion in twig water as well as a general fractionation between stem and twig waters in *Populus euphratica*. Bernhard et al. (2024) found no significant sub-daily fluctuations of δ_{xyl} 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}.

Before implementing δ_{xyl} into modelling, the validation and quantification of vegetative processes influencing δ_{xyl} is essential (Deurwaerder et al., 2020). Biases in δ_{xyl} 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 moisture cycling

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 is larger during periods of lower transpiration, emphasizing that significant differences of δ_v between daytime and night time occur during periods of water stress and limited transpiration. These diurnal cycling patterns of δ_v during drought can be further impacted by the effects of climate change. 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 Water cycling of urban trees

The insights from in situ monitoring of δ_{xyl} revealed significant impact of summer drought on the sub-daily water cycling and consequent responses in plant physiological processes (see Sect. 5.1.3). During drought conditions, both maple and birch exhibited no significant positive correlation of δ_{xyl} with stem growth (as a proxy for sap flow) over the course of the day (Figs. 9,10) 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

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sensitivity of UGS 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 *Betula pendula*. This effect is reduced under drought conditions, so that night-time recharge may also have been more constrained in the birch 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-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. 3). Possibly with more severe drought conditions less distinct diurnal cycling would be evident. Further, the effects of droughts on urban tree functioning depends 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 trees, which results in limited ET fluxes and reduced sap flow rates relative to 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.

5.3 Wider implications

This study provided the opportunity to better understand the sub-daily dynamics of water cycling during drought in different urban vegetation, 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

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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: the continuous, sub-daily (3-hourly) dataset of δ_v and δ_{xyl} is highly valuable to constrain ecohydrological models which help predicting impacts of climate change on UGS. 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 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).

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 of atmospheric water vapour (δ_v) were monitored at different heights above a grassland and under the canopy of a mature maple tree. Stable water isotopes of the xylem water within tree stems (δ_{xyl}) was monitored at different heights in a maple and a birch tree.

The summer period from July until mid-August was characterised by drought conditions, including occasional convective rainfall events, which do 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 cycle, while at the same time PET rates decreased.

The analysis of sub-daily isotopes suggests systematic behaviour of both δ_v and δ_{xyl} during summer drought. δ_v was characterized by a daytime depletion in heavy isotopes, driven by entrainment effects and evaporation. We found daytime enrichment in δ_{xyl}, with max. enrichment in afternoons, which was driven by limited sap flow and stomatal regulation of transpiration. For the rewetting, we revealed that the systematic diurnal cycling of δ_v was discontinued for most heights. It became more evaporation driven from the re-saturated soils, while the influence

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of entrainment from the larger urban surface boundary layer was reduced. Only δ_v just above the grassland surface (0.15 m) showed a significant daytime enrichment, 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} with sub-daily amplitudes more than halved compared to the drought period. Our results suggest that the monitored urban vegetation experienced 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 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} have the potential to better constrain ecohydrological models which help predicting impacts of climate change on UGS. However, more research is needed to extend our findings on sub-daily water cycling in UGS, covering different types of planting and varying tree species from root to twig.

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,

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Writing – review & editing. CB: Investigation, Methodology, Formal analysis, Writing – review & editing. CS: Conceptualization, Investigation, Methodology, Formal analysis, Writing – review & editing.

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