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Impact of technical water retention on European beech (*Fagus sylvatica* L.) resilience and growth dynamics

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Abstract: Global climate change (GCC) is putting increasing pressure on forest ecosystems, leading to more frequent disturbances such as pest outbreaks and other climate-related stressors, all of which threaten forest stability. This study examines how different technical water retention measures (infiltration pits) can enhance the resilience of European beech (*Fagus sylvatica* L.) to these climatic challenges, focusing on their impact on radial growth, sap flow, and acclimatisation to moisture conditions at two sites in Czechia (430–440 m a.s.l.). Three treatments were compared: a water infiltration pit under a culvert mouth, an infiltration pit without a culvert and a control plot without a technical solution. Results showed that maximum daily transpiration rates of beech ranged between 90–120 L per day. Air temperature had a stronger influence on beech radial growth than precipitation, particularly at the waterlogged sites. The lowest radial growth occurred in the treatment involving a water infiltration pit under a culvert mouth, while treatments with an infiltration pit without a culvert demonstrated notable seasonal stem shrinkage and swelling (tree water deficit – *TWD*), especially in early spring. On the other hand, no differences were found between the three treatments including the control variant in the maximum growth or the context of minimum *TWD*. In conclusion, these technical measures had limited or short-term effects on the growth and physiological processes of European beech. Despite the high costs of implementation, sap flow and dendrochronological measurements do not support the construction of infiltration pits as a means of improving water retention in forest ecosystems.

Keywords: climate change; forest-water management; infiltration pits; radial growth; sap flow

Global climate change (GCC) significantly affects forest ecosystems, which face increasing pressure of more frequent wind disturbances, forest fires, pest outbreaks associated with irregular precipitation and extreme temperature fluctuations (Keenan 2015; Seidl et al. 2017; Venäläinen et al. 2020). These changes disrupt tree growth processes and endanger the stability of forest stands and biodiversity (Martinez del Castillo et al. 2022; Vacek et al. 2023). Long-lasting drought peri-

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ods and water scarcity hinder the ability of forests to absorb carbon and mitigate GCC (Seidl et al. 2014). In this context, implementing technical measures seems to be a key aspect in enhancing the resilience of forest ecosystems to climatic extremes (Seidl et al. 2014; Valtera, Schaetzl 2017). Landscape reconstruction through retention reservoirs, culverts, and drainage can, on the one hand, facilitate water flow regulation and minimise damages caused by floods and erosion (Chang et al. 2013; Kalantari, Folkeson 2013), on the other hand, water retention in forest ecosystems could be crucial for maintaining moisture, supporting tree growth, and increasing their resistance to drought and GCC (Ellison et al. 2017). This role increased in mixed stands, which are generally more resilient to drought. Such stands enhance water retention, thereby supporting critical ecosystem stability and promoting healthier, more vigorous tree growth. This synergy is key to increasing the forest's natural ability to adapt and thrive under varying environmental stresses, making water retention strategies and the promotion of biodiversity essential components of forest management and conservation efforts (Steckel et al. 2020; Vospernik et al. 2023). Furthermore, it is crucial to adapt forest management to the new climatic conditions and implement strategies that support forest adaptation to GCC (D'Amato et al. 2011; Brang et al. 2014; Pretzsch et al. 2020; Vacek et al. 2020; Del Río et al. 2022). Therefore, integrating technical measures including artificial infiltration pit with or without culvert building with silviculture-ecological principles can contribute to forest protection and reduce the negative impacts of GCC on forest ecosystems (Lindner et al. 2014).

Present research on technical measures focuses on European beech (*Fagus sylvatica* L.) forests because it is considered to be the most representative deciduous tree species in Europe, and plays a crucial role in the ecological stability of forest ecosystems (Leuschner, Ellenberg 2021; Sharma et al. 2019; Fuchs et al. 2024; Černý et al. 2024). Its growth at diverse site conditions makes it an essential component of both mixed and broadleaf forests across the continent (Jump et al. 2006; Vacek et al. 2021). Beech radial growth is strongly influenced by climatic factors, particularly water availability and air temperature, which shape its seasonal growth dynamics (Scharnweber et al. 2019; Šimůnek et al. 2019, 2021). GCC, including prolonged droughts and extreme air temperature events, adversely affects beech vitality, leading to reduced growth and lower radial increments (Pretzsch et al. 2014; Vacek et al. 2019b). Long-term drought stress can significantly decrease beech carbon assimilation capacity, impacting both the growth and the stability of entire forest ecosystems (Bouriaud et al. 2005). Given its sensitivity to water shortages, forest management adaptations that support water retention appear essential to increase beech resilience to GCC (Vacek et al. 2023).

Climate change-induced drought significantly impairs sap flow dynamics in forest tree species, triggering a cascade of physiological disruptions that threaten tree survival. The reduced soil water availability forces trees to decrease their hydraulic conductivity through stomatal closure and embolism formation, severely restricting water transport from roots to leaves (Chen et al. 2022). This compromised sap flow not only limits the trees' capacity to maintain optimal leaf temperatures through transpirational cooling but also impairs their ability to synthesise and transport essential osmolytes and defence compounds (Basile et al. 2024). Moreover, the diminished production of defensive compounds, such as terpenes and phenolics, further compromises the trees' immune responses, creating a dangerous feedback loop of declining health (Leuschner 2020). These physiological impairments have far-reaching consequences for forest ecosystem stability, potentially leading to widespread tree mortality, altered species composition, and, finally, reduced ecosystem services (Allen et al. 2010; Anderegg et al. 2013).

Many articles deal with the effect of climatic factors on the growth of European beech and/or the influence of technical measures on forest ecosystems, but there is no desired research focused precisely and currently in the given period on the effect of water retention measures on tree growth and sap flow. Therefore, the present research focused on: (*i*) the effect of modified soil moisture conditions on the stem radial growth increment of beech located at various physical and chemical soil compositions, (*ii*) the effect of various water retention treatments on the growth of beech, and (*iii*) the effect of the treatments on sap flow (i.e. the cooling ability of individual trees). The treatments also include a control plot to evaluate the effects of two artificial technical measures: infiltration pits with and without culverts.

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MATERIAL AND METHODS

Site characteristics. The study site A [Lesy ČZU (Forests of the Czech University of Life Sciences Prague); 49°57'49.44'N, 14°47'37.44'E] is situated at an altitude of 440 m a.s.l. The study site is characterised by significant soil heterogeneity with exclusively semi-hydromorphic and hydromorphic soil types (pseudogley, stagnogley, gley, and their subtypes). The geological bedrock consists of Říčany-type Moldanubian granite with varying thicknesses, slopes, depositions and polygenetic clays content, with a distinctly boulder-covered soil surface. There are two springs in the study area. The significant soil saturation with water results in soil moisture with values exceeding the retention water capacity, with gravitational water movement but without runoff. It is leading to predominantly or periodically anoxic conditions ('wet variant' in the project design). From a typological point of view, this is a habitat nutrient-medium Beech category (*Fagetum oligo-mesotrophicum*) (Viewegh et al. 2003). For more details about the natural site conditions, forest stand history and monitoring research, see Bílek et al. (2009, 2014).

The study site B (Forest Training Enterprise of Mendel University; 49°18'29.54'N, 16°41'55.76'E) is situated at an altitude of 430 m a.s.l. and is characterised by significant soil homogeneity, with a single soil type, cambisol, dominated by its modal subtype. The complex geological structure is primarily composed of siliceous sediments of the Rudice layers, with an admixture of loess clays, in contact with the limestone bedrock of the Moravian Karst, which emerges at varying depths but always outside the soil body zone. The site also exhibits consistently low soil moisture levels throughout the entire season, especially during the growing season ('dry variant' in the project design). Typologically, this habitat is classified within the nutrient-medium Oak-Beech category (*Querceto-Fagetum oligo-mesotrophicum*), as described by Viewegh et al. (2003). For a description of the climatic data, see an overview in Table 1.

In each of the two study sites, three treatments were established in the forest stands dominated by European beech (*Fagus sylvatica* L.) with admixed (a proportion of less than 5%) European hornbeam (*Carpinus betulus* L.). These were (*i*) a water infiltration pit under a culvert mouth, (*ii*) an infiltration pit without a culvert and (*iii*) a control plot without a technical solution. On each site, two infiltration pits were constructed in a paired design with a uniform retention volume. One of the pits is always located beneath the outlet of a culvert, directing its flow into the pit. The second control pit is situated approximately 30 m away under the same pedological and stand conditions, in a location without connection to the culvert and without concentrated inflow. The control plot without a technical solution is again located at the same distance (approx. 30 m) from the next treatment. Considering the possibilities of the research project and the requirements for the installation of measuring equipment, infiltration pits with the following dimensions were chosen: length at the base 3.5 m, width at the base 2.0 m, wall slope 2:1, and retention depth 1.5 m. The volume of the pits without filling is approximately 18 m^3. The banks of the infiltration pits were lined with separation geotextile with a surface weight of 350 $g \cdot m^{-2}$ (about 40 m^2). The pits were filled with riprap stone with an assumed porosity of 35%. The expected retention volume of the infiltration pits (with the voids between the stones filled) is approximately 6.5 m^3. For more details on locality characteristics and experimental design including treatment plan and photos, see Kupec et al. (2023).

Data collection. All trees within the research plots representing particular treatments with a minimum stem diameter at breast height of ≥ 7 cm were registered. Using the FieldMap technology (IFER, Czech Republic), positions of trees and crown projections were mapped, stem diameters at breast height (*DBH*) were measured using the Mantax Blue metal calliper (Haglöf, Sweden) with a 1 mm accuracy, and tree heights and crown base heights were assessed using the laser Vertex height gauge (Haglöf, Sweden) with a precision of 0.1 m. The canopy layer was categorised into the upper layer (comprising dominant and co-dominant trees) and lower layer (consisting of suppressed trees) based on Kraft's classification (Kraft 1884).

For long-term dendrochronological analysis, increment cores were taken from European beech trees using a Pressler borer (Haglöf, Sweden) at 1.3 m above ground level, perpendicular to the trunk axis (Steckel et al. 2020). In both study sites, 30 healthy dominant and co-dominant trees were randomly selected based on the Kraft classification (Kraft 1884), using Excel's RNG function, to com-

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Table 1. Basic site climatic characteristics of study sites averaged for the period 1961–2023

Study site	Meteo. station name	GPS of meteo. station	Station altitude (m a.s.l.)	Growing season	Annual temp. (°C)	Seasonal temp. (°C)	Annual precip. (mm)	Seasonal precip. (mm)
A	Ondřejov	49°54'24.7'N 14°46'48.0'E	491	May to September	8.0	15.4	629	378
B	Brno, Tuřany	49°9'10.8'N 16°41'19.7'E	241		10.3	17.3	473	303

Meteo. – meteorological; growing season – month range; temp. – mean annual air temperatures in 1961–2023; precip. – annual sum precipitation in 1961–2023
Source: CHMI (2024)

pare the differences between sites. This focus was intended to capture significant growth responses in dominant trees compared to sub-dominant or suppressed classes (Remeš et al. 2015). The trees sampled had a minimum *DBH* over 20 cm.

Tree-ring width was measured on all the increment cores using a LINTAB measuring table (Rinntech, Germany) equipped with an Olympus microscope (Olympus, China). The measuring table has a precision of 0.01 mm, and the TSAP-Win software (Version 4.6, 2012) was utilised to record the chronologies of each tree-ring width. Subsequent cross-dating of the measured tree-ring cores was carried out using Cdendro software (Version 9.6, 2020). The cross-correlation index (*CC*) for the measured tree-ring sample was greater than *CC* > 25 compared to the other samples. Monthly air temperature and precipitation data for Czechia were obtained for meteorological stations mentioned in Table 1 from the Czech Hydrometeorological Institute, Prague (CHMI 2024).

For the analysis of intra-annual growth dynamics of the target tree species European beech, data were collected using 90 point dendrometers (TOMST, Czech Republic). Specifically, 15 dendrometers were set up for each variant at each site (2) to compare differences between treatments (3). Dendrometers monitor changes in stem radius at a sub-micrometer scale (< 1 μm) with a range of 8.89 μm, resolution of 0.27 μm, and linearity within 5%. Air temperatures were recorded continuously using the same device. The dendrometers were installed on trees (1.3 m above the soil surface) with stem diameters ranging from 20 cm to 37 cm at both study sites, positioned within 12 m distance from the centre of infiltration basins (or the centre of control plots). Stem radius changes were monitored only on healthy (fully foliated), dominant and co-dominant trees. Regular checks were conducted to assess potential damage or malfunctions, and data retrieval was processed at the end of each growing season. Dendrometers were installed in May 2022 and the final data retrieval was done in November 2023.

In total, 12 sample trees from both study sites were chosen for sap flow measurements. Sap-flow sensors (EMS 81 – EMS Brno, Czech Republic) were installed at a height of 2 m in 2022 on the sample trees, two sensors for every treatment, i.e. 6 sap flow sensors per study site. The measurement was done every 10 minutes from April to October. The false data (e.g. electricity failure) were removed from the dataset. The final data were gained as a mean of ten-minute intervals, and hourly means and daily sums were calculated. The night-time fluxes were removed using EMS 81 software.

Data analysis. European beech dendrochronological data were analysed in R software (Version 4.4, 2024) using the 'dplR' package (Bunn 2010). Each tree-ring series was detrended by fitting a negative exponential curve with interval splines, which removed age-related trends and preserved low-frequency climate signals according to Cook et al. (1990). An expressed population signal (*EPS*) of > 0.85 was set as a threshold to ensure reliability in climate analyses (Bunn et al. 2018a). Additional indices such as signal-to-noise ratio (*SNR*) and inter-series correlation (*R*-bar) were calculated to assess chronology quality following 'dplR' package guidelines (Bunn et al. 2018b).

Raw measurements of stem radius changes (Rad_{stem}) downloaded from dendrometers were checked and fixed from erroneous measurements and artefacts (e.g. jumps resulting from dendrometer adjustments) and then aggregated into daily means using 'PLOTeR' R package (Matula

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et al. 2023). Daily stem growth (*GRO*) was calculated from the Rad_{stem} data using the zero growth concept (Zweifel 2016). The *GRO* indicates the irreversible stem expansion of growing cells, namely, the radial increase because of dividing and enlarging wood and bark cells in the cambium. On the other hand, there is the reversible, tree water deficit (*TWD*)-induced shrinking and swelling of the stem, caused by imbalances between transpiration and root water uptake, which was also calculated according to Zweifel et al. (2005).

Sap-flow measurement is based on the trunk-heat-balance (THB) method consisting of four electrodes heating the small volume of the sapwood (Čermák et al. 2004). The heat balance of a defined heated space according to Equation (1):

$$Q = \frac{P}{c_w} \times d \times \Delta T - \frac{Z}{c_w} \qquad (1)$$

where:

Q – sap-flow rate ($kg \cdot s^{-1} \cdot cm^{-1}$);
P – power of heat input (W);
c_w – specific heat of water ($J \cdot kg^{-1} \cdot K^{-1}$);
d – circumferential distance covered by the electrodes (cm);
ΔT – temperature difference in the measuring points (K);
Z – coefficient of heat losses from the measuring point ($W \cdot K^{-1}$).

The Q of the measured area was multiplied by the length of the circumference of the xylem at the height of installation to calculate total tree water use.

RESULTS

Climate factors and radial growth of beech. Dendrochronological characteristics are described in Table 2 and include the mean tree ring increment for the plot (mean *RW*), mean ring width range from the smallest to the largest tree (mean *RW* min-max), mean age of the sample trees (age), standard deviation from ring width (SD *RW*), inter-series correlations (*R*-bar), expressed population signal (*EPS*), and signal-to-noise ratio (*SNR*). Treatments at site A, influenced by groundwater, show a larger mean increment (2.59 mm), on average 15% greater than that of the acidic site B (2.25 mm). Similarly, greater variability in radial growth was observed at site A (Figure 1). The most significant decrease in diameter increment was detected at site A in 1990; at site B, it occurred in 2023, a year marked by prolonged drought. Conversely, standard dendrochronological indices indicated higher reliability at site B. The age of the examined beech trees differed by only one year (68–69 years).

From the perspective of climatic factors, air temperature had a more significant effect on radial growth than precipitation, particularly at the waterlogged site A (Figure 2), i.e. when water is not a limiting factor. Specifically, air temperature in September of the previous year ($P < 0.05$, $r = -0.22$) and in June of the current year ($P < 0.05$, $r = -0.21$) harmed radial growth, while temperature in November of the previous year ($P < 0.05$, $r = 0.31$) had a positive effect at site A. No significant influence ($P > 0.05$) of monthly temperature on beech growth was observed at site B. Regarding the monthly precipitation amount, only a positive effect on beech growth in the current year was found. Specifically, precipitation in February of the current year ($P < 0.05$, $r = 0.30$) had a positive effect on growth at site A, while precipitation in May of the current year ($P < 0.05$, $r = 0.28$) showed a positive effect at site B.

Growth differences between treatments. In terms of current stem radial growth measured by point dendrometers, the three specific variants were compared (Figure 3). The lowest radial growth throughout 2022 and 2023 was found in the treat-

Table 2. Characteristics of tree-ring chronologies for European beech on the study sites A and B for the time period 1956–2024

Site	No.	Mean *RW* (mm)	SD *RW* (mm)	Mean *RW* min-max (mm)	Age sample (years)	*R*-bar	*EPS*	*SNR*
A	30	2.59	0.91	1.28–4.67	69	0.27	0.90	9.36
B	30	2.25	0.81	0.30–3.74	68	0.30	0.92	10.93

No. – number of trees; mean *RW* – mean ring width; SD *RW* – standard deviation from ring width; mean *RW* min-max – mean ring width range from the smallest to the largest tree; age sample – age range of sampled tree-ring time series; *R*-bar – inter-series correlation; *EPS* – expressed population signal; *SNR* – signal-to-noise ratio

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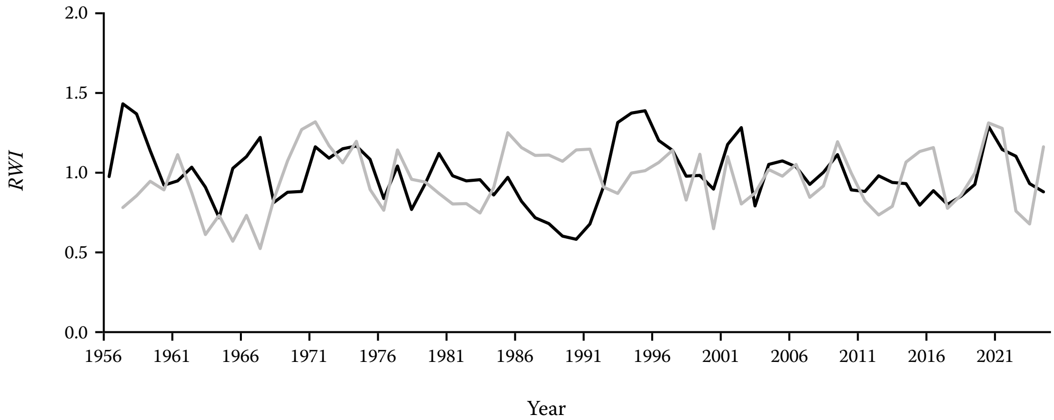

Figure 1. Standardised ring-width index (*RWI*) of European beech after age detrending on the study site A (black) and B (grey)

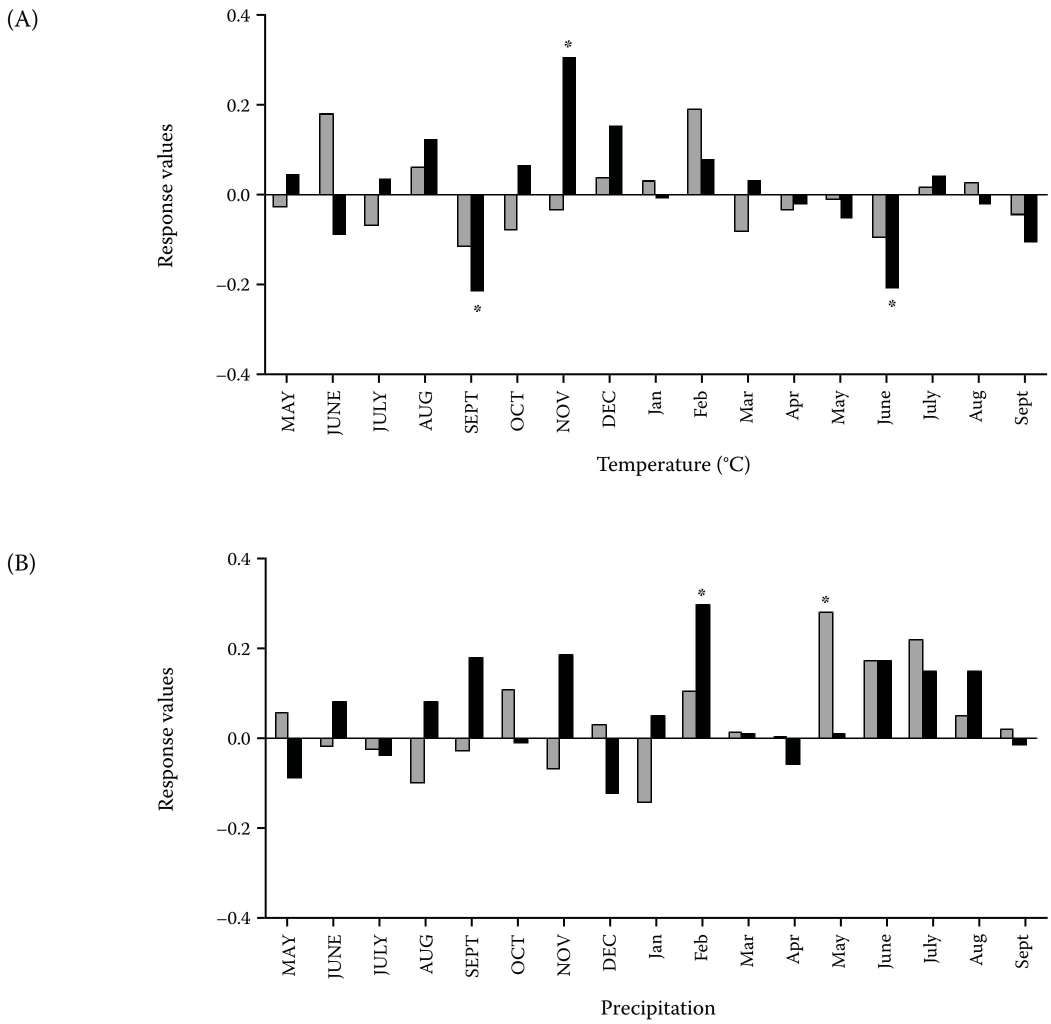

Figure 2. The values of response coefficients for European beech *RWI* chronology with (A) the monthly temperature and (B) monthly precipitation from May of the relative preceding year (in capitals) to September of the current relative year for the period of 1961–2023 on the study site A (black) and B (grey)

*statistical significance ($P < 0.05$)

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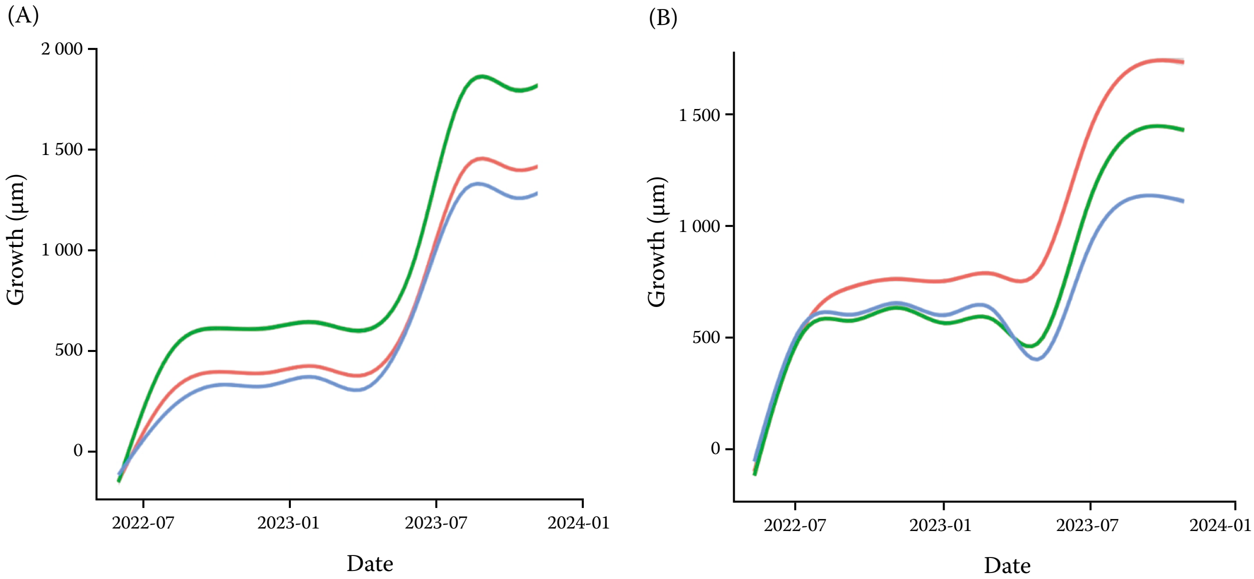

Figure 3. The stem radial growth ('growth') of European beech on the study sites A and B according to three treatments: A water infiltration pit under a culvert mouth (blue), an infiltration pit without a culvert (red) and a control plot without a technical solution (green)

ment involving a water infiltration pit located under a culvert mouth (blue line). In contrast, the highest stem radial growth was observed in the control plot without any technical intervention (green line) at site A, and in the treatment with an infiltration pit without a culvert (red line) at site B. The greatest radial increment occurred in the second week of June, whereas the beech growth typically stagnated between the third and fourth week of September. In terms of *TWD*-induced stem shrinkage and swelling, the largest declines at both sites were observed in the treatment with an infiltration pit without a culvert (red line), particularly in March and April (Figure 4). Conversely, there were no differences between the other two variants (the water infiltration pit under a culvert mouth and the control plot without technical intervention), with the curves overlapping during the monitored period.

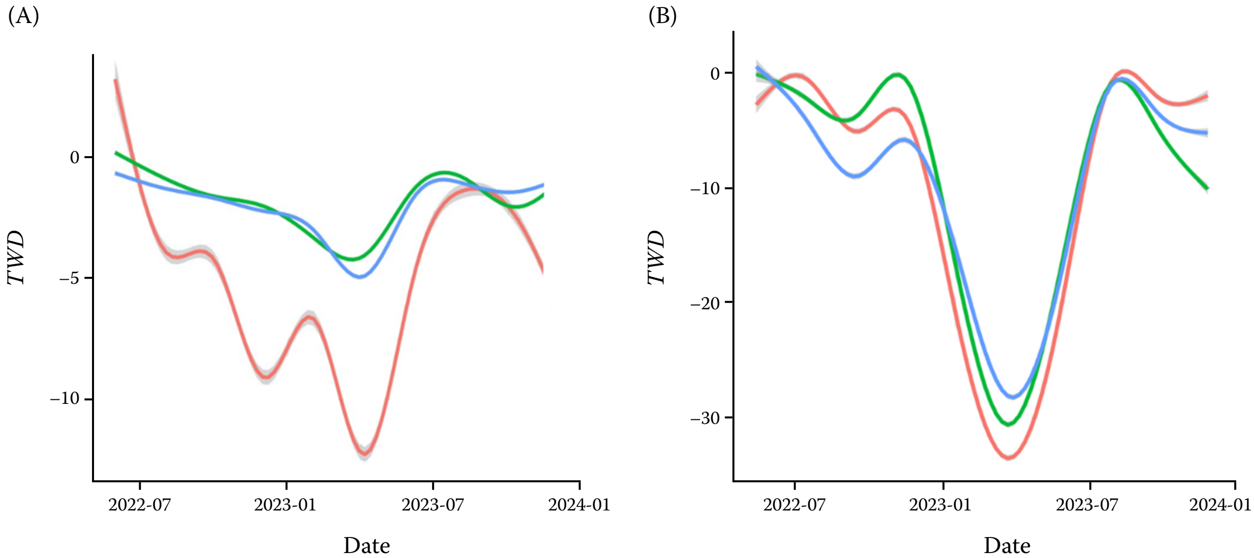

Figure 4. The *TWD* (tree water deficit)-induced shrinking and swelling of the stem of European beech on the study sites A and B according to three treatments: A water infiltration pit under a culvert mouth (blue), an infiltration pit without a culvert (red) and a control plot without a technical solution (green)

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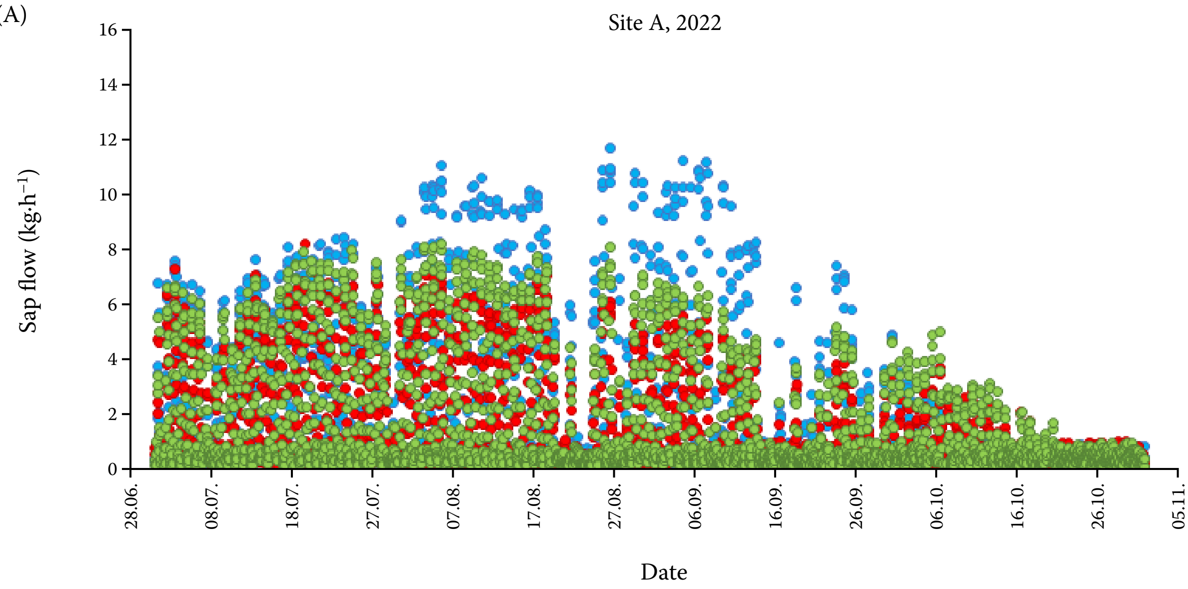
Sap flow course in infiltration pit with and without culvert mouth. In this experiment with sap flux monitoring across two sites, when each site was subjected to the treatments: (*i*) an infiltration pit with a culvert mount, (*ii*) an infiltration pit within a culvert mount, and (*iii*) a control treatment maximum daily transpiration amount reached up to 120 L per day at site A, whereas a maximum of 90 L per day were reached at site B. Across both sites, the treatment with an infiltration pit within a culvert mount consistently demonstrated lower transpiration rates throughout the entire growing season (Figures 5 and 6). In contrast, the treatment with an infiltration pit and a culvert mount showed varying results, with initially lower transpiration rates during the first half of the growing season, followed by higher transpiration compared to the control in the second half. This increase in transpiration was particularly noticeable in August and September; however, it did not manifest into significant changes in the stem increment, aligning with the findings from dendrometer measurements.

(A)



(B)

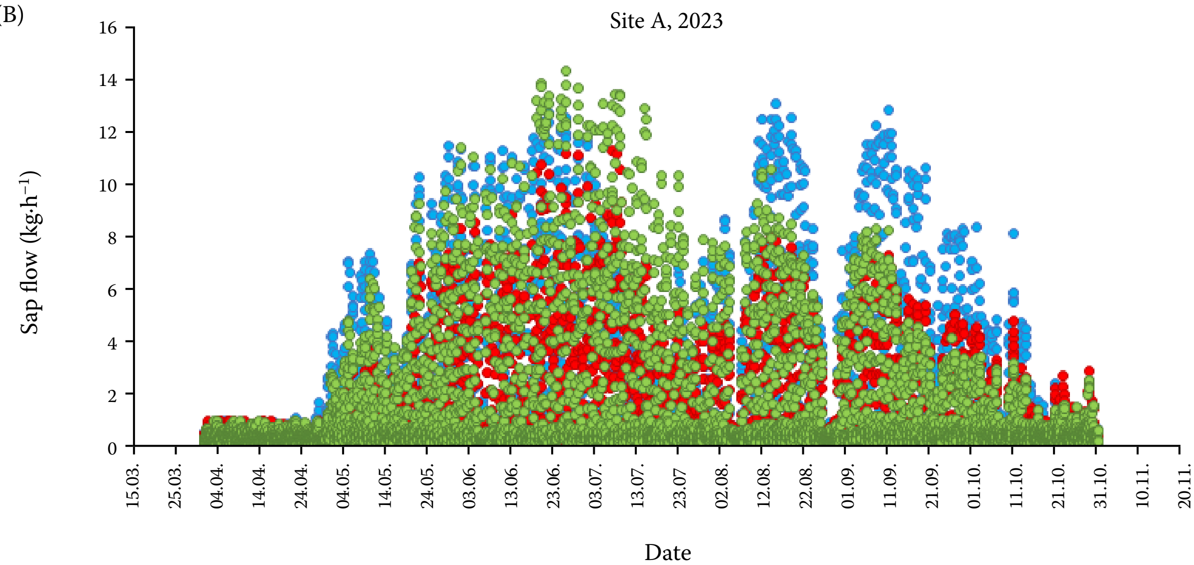


Figure 5. Course of sap flow over 2022 and 2023 at study site A in the proximity of infiltration pits (blue), in the proximity of infiltration pits without culvert mount (red) and control (green); dots represent the hourly means from April to October (delayed start in 2022)

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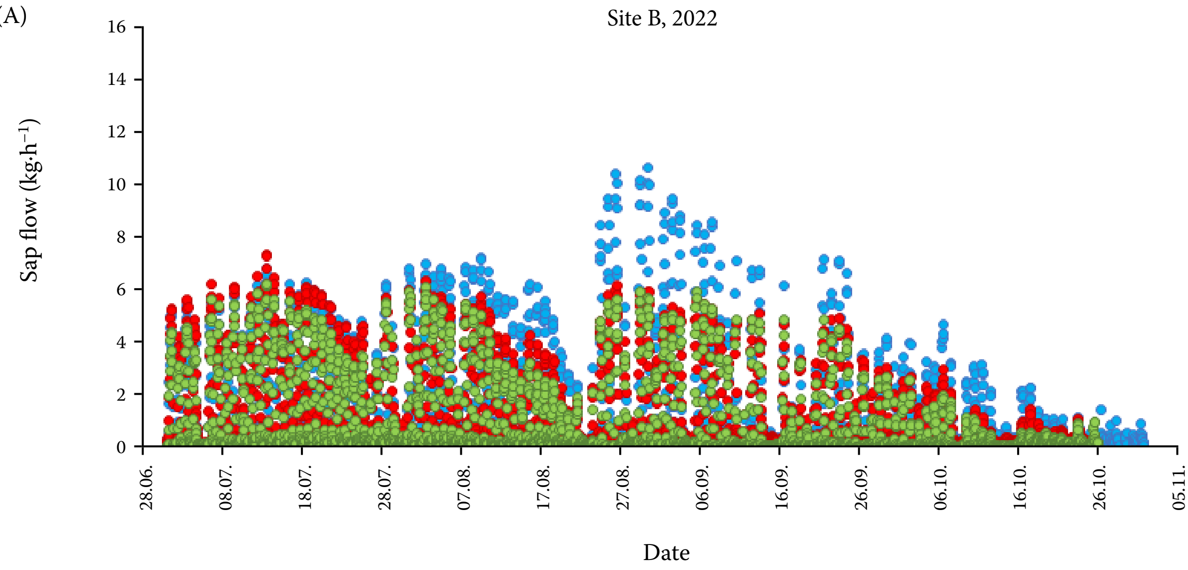
(A)



(B)

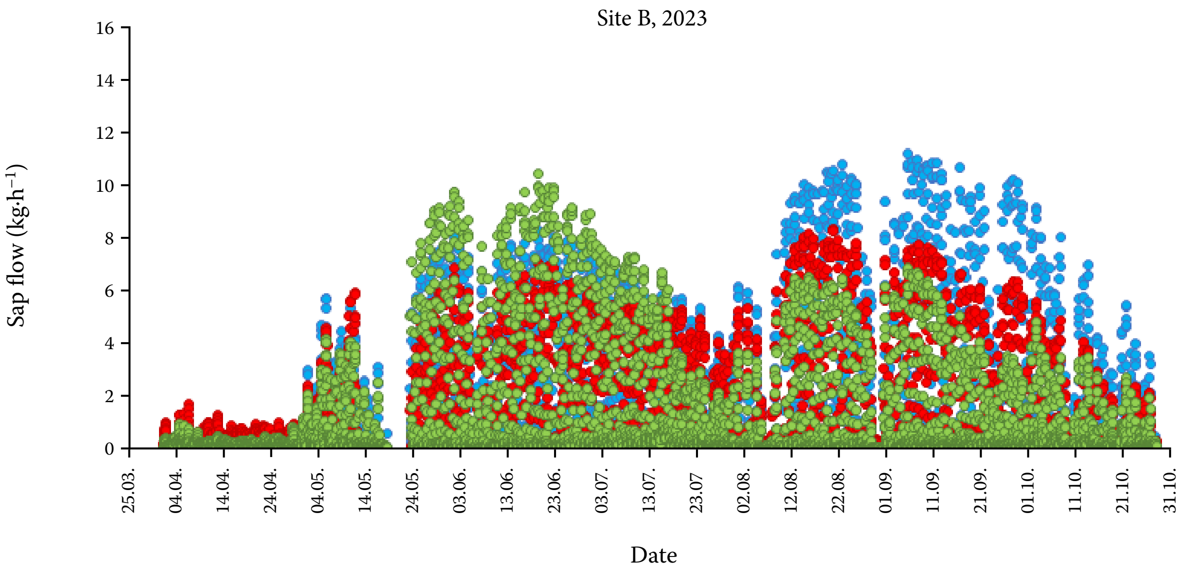


Figure 6. Course of sap flow over 2022 and 2023 at study site B in the proximity of infiltration pits (blue), in the proximity of infiltration pits without culvert mount (red) and control (green); dots represent the hourly means from April to October (delayed start in 2022)

These observations suggest that while late-season transpiration increased, it did not enhance growth, likely due to other limiting factors.

DISCUSSION

The main objective of the study was to determine the effect of three technical water retention treatments (an infiltration pit with a culvert mount, an infiltration pit within a culvert mount, and a control treatment) on the stem radial growth and sap flow rate of European beech in two different sites. In terms of growth, the stem radial increment is affected by many factors, such as silviculture practices and site conditions, and out of these especially altitude, climatic factors and air pollution (Remeš et al. 2015; Bosela et al. 2018; Šimůnek et al. 2020). In our case, the monthly air temperatures strongly affected beech radial growth compared to the sum of precipitation, particularly at the waterlogged

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site A. Specifically, September air temperatures from the previous year and June temperatures from the current year both negatively affected radial stem growth, whereas November temperatures from the previous year positively influenced growth at site A. Similarly, Vacek et al. (2019a) documented, that climatic factors in September of the previous year and from July to August of the current year had a significant effect on radial growth at similar elevations. In contrast, no significant relationship between monthly temperatures and beech growth was observed at acid site B. As for precipitation, a positive effect on beech growth was detected only in the current year. At site A, February precipitation increased growth, while at site B, May precipitation had a similar positive effect. In Germany, drought in the period June–August is the most prominent factor limiting growth in middle altitude (Van der Maaten 2012). In general, the limiting factor in the lowlands is drought (lack of precipitations), and with increasing altitude, the positive effect of air temperatures increases, not only for beech (Mäkinen et al. 2002; Králíček et al. 2017; Vacek et al. 2022).

This study evaluated the influence of various water management treatments on beech tree radial growth and water-induced stem changes over two years. Results show that the control plot, which had no interventions, demonstrated the highest radial growth of beech trees at site A. This aligns with findings that minimal disturbance often promotes natural moisture dynamics and root health (Tegel et al. 2014; Scharnweber et al. 2019). Conversely, the lowest growth occurred in the plot with a water infiltration pit beneath a culvert, suggesting possible disruption of soil and root zones that may limit effective water uptake. Radial growth peaked in early June and typically ceased by late September, consistent with the seasonal growth patterns of deciduous species driven by temperature and photoperiod changes. The months most critical for cambium formation and annual ring growth, influenced by climatic factors, are generally June and July (Mäkinen et al. 2003; Van der Maaten 2012; Giagli et al. 2023). It also fully coincides with the leaf area index (LAI) development, which reaches its maximum values in mid-June and persists until mid-September. After this period, the LAI begins to decrease because of the beginning of leaf fall (Černý et al. 2019, 2020). Interestingly, substantial stem shrinkage, particularly in March and April, was observed mainly in the treatment with an infiltration pit without a culvert, indicating early-season water availability but heightened stress during dry periods. This effect echoes findings by Brunner et al. (2015) on how soil moisture interventions can both benefit and challenge trees under varying conditions. Minimal differences in shrinkage between the control and culvert treatments, with overlapping growth curves, suggest similar moisture conditions throughout the season. These findings underscore the complex effects that water management techniques can have on forest growth dynamics, highlighting the need for further research into their ecological implications. However, no significant differences in growth or *TWD* were found between the variants.

The relationship between precipitation and sap flow is complex, yet the response of sap flow to precipitation is notably rapid. As Weithmann et al. (2022) observed, beech transpiration adjusts to available precipitation. The increased transpiration observed in treatments with culvert mounts at both sites during August likely resulted from enhanced soil water availability following elevated precipitation events at the end of July, particularly in site B where rainfall was almost double the long-term mean. However, treatments within culvert mounts consistently showed lower transpiration rates across both sites throughout the study period, indicating that this infrastructure configuration may harm plant water use. This pattern aligns with findings by Pretzsch et al. (2018), who highlighted that altered soil water distribution can lead to significant changes in tree water uptake dynamics and forest growth. Nevertheless, the increase in transpiration during August and September might suggest root growth into the infiltration space, which could be beneficial for trees adjacent to this facility. This adaptive response could also indicate long-term advantages in terms of access to deeper water reserves. Studies emphasise the importance of sustained soil water availability for maximising forest ecosystem resilience under changing climatic conditions (Leuschner, Ellenberg 2021). This suppressed transpiration in within-culvert treatments suggests possible root zone limitations or altered soil moisture dynamics created by the infiltration pit that inhibit optimal plant water uptake, despite the presence of adequate soil moisture as evidenced by the precipitation patterns.

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This study is limited to two forest sites within Czechia and focuses on only one tree species, European beech, which constrains the generalizability of the findings. Additionally, a longer-term study would be necessary to capture the full impacts of technical water retention measures on radial growth, vitality, sap flow, and photosynthesis or respiration processes over varying climate conditions (Lindenmayer et al. 2012). Future research should expand to multiple species and sites, and assess broader physiological responses beyond radial growth, examining stand- and ecosystem-level changes in response to water retention measures and their interaction with climate stressors.

CONCLUSION

This experiment compared radial growth and sap flow rates of sampled trees at two different sites with three different technical measure treatments: (*i*) infiltration pit with culvert mouth, (*ii*) infiltration pit without culvert, and (*iii*) control. The maximum daily transpiration rates were 120 L and 90 L per day for sites with higher and lower precipitation, respectively. Treatments with infiltration pits under a culvert mouth consistently showed lower transpiration rates throughout the growing season, while treatments with infiltration pits without a culvert demonstrated notable seasonal stem shrinkage and swelling, especially in early spring. The variable transpiration rates observed in treatments with a culvert mouth showed increased values in August and September, yet this did not correspond with increased radial growth. In the context of radial growth, no significant differences were found between the treatments. However, it is important to note that due to the low number of sampled trees per treatment for transpiration measurements, these results should be considered preliminary. Moreover, the study's findings highlight differences in water availability between the two sites: Site A, characterised by high annual precipitation and heterogeneous soil with hydromorphic soil types, contrasts with site B, which has approximately 25% less annual precipitation and 20% less precipitation during the growing season, coupled with a homogeneous cambisol soil type with lower clay content. While the study observed limited or short-term effects of the treatments on radial growth and physiological processes, the effectiveness of these costly technical measures for improving water infiltration or soil moisture conditions remains inconclusive, particularly when comparing water-limited (site B) to water-unlimited (site A) environments. The high costs of implementing water retention measures were noted; however, the specific costs of individual technical measures were not provided in this study, leaving room for speculation about their economic feasibility. Despite these limitations, the findings suggest that infiltration pits may offer localised benefits but do not substantially enhance the resilience of European beech forests to climatic challenges in the observed settings. As resilience to drought or water limitation was not directly evaluated, conclusions regarding this aspect should be treated with caution. Further research with a larger sample size and a detailed cost-benefit analysis is recommended to determine whether such measures can effectively support water-limited beech forests.

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