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Coupled Hydro-Climatic Signals in the Radial Growth of Oaks Benefitting from Groundwater Availability

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Abstract: Lowland forests benefiting from groundwater availability are important ecosystems in Central Europe, both from ecological and economic perspectives. Besides a great reduction in their extent in the historical times and further shifts in the land use and water management regimes intensified during the industrial era, continuing changes in the groundwater and overall hydro-climatic conditions can pose significant challenges to them. Although tree-ring analyses serve as widely used tools to assess the climatic impact on tree growth and vitality, few studies have attempted to investigate the effects of subsurface hydrology on interannual fluctuations in xylem production. In this study, we compared the tree-ring width series of pedunculate oak (*Quercus robur* L.) from a forested area in southwestern Hungary with the time series of monthly groundwater depth and climatic variables over the period of 1920–2017 with a specific focus on 1961–2017. The radial growth of the studied trees showed the strongest relationship with late winter and early spring groundwater and drought conditions preceding the growing season, differing from the commonly reported climatic signals marked by early summer meteorological conditions of the vegetation season. The results suggest that the groundwater recharge during the dormant period preceding the vegetation season and the groundwater levels in early spring were among the key limiting factors on tree growth in the study area. In the growing years starting with a sufficiently high groundwater table, even scarce summer precipitation did not seem to limit radial growth drastically. However, unfavorable shifts in climatic conditions during the past few decades and the associated uncertainties in the future groundwater regime imply that additional active measures aimed at maintaining and restoring groundwater conditions may well be highly beneficial for sustaining groundwater-dependent forest ecosystems and their productivity.

Keywords: lowland forests; groundwater recharge; winter drought; tree rings; pedunculate oak

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1. Introduction

Oak forests dependent on groundwater availability represent ecologically and economically important types of lowland forest ecosystems in the temperate-continental climate zone, including several parts of Central Europe [1]. Historical and recent human activities, such as the regulation of watercourses and drainage of areas with excess water, including for industrial and agricultural purposes, as well as the recent climate-change-induced shifts in the precipitation and evaporation regimes, can adversely affect the hydrological conditions and groundwater availability in these areas [1–3]. These environmental changes can impose significant stress and challenges on the affected forest ecosystems, indicating the importance of dedicated forest ecosystem restoration efforts.

Over the course of the past few decades, tree-ring analysis has become a standard tool to link the variations in climatic conditions to tree growth [4], among others, to assess the impact of changing environmental conditions on forest productivity and ecophysiological stress factors on trees. Dendroecological tree-ring research has, however, mostly focused on those forests without sustained groundwater availability and thus dependent on balanced intra-annual precipitation. Fewer studies attempted to relate tree-ring formation to subsurface hydrological conditions, including studies aiming to use tree rings as proxies of past groundwater conditions [5,6]. Other works dealt with the ecophysiology and growth of oaks in groundwater-dependent environments of Central Europe [2,7–9], but only a few compared the measured time series of groundwater fluctuations to the radial growth of any tree species [10,11].

Most of the studies dealing with groundwater-dependent forests were conducted in riparian forests or with aquifers directly affected by riverine systems and their connections [2,7,8,11]. Some of their analysis found significant relationships between measured water-level fluctuations and radial tree growth [7,8,11]. Studies from the Rhine Valley in Germany compared sites with different ecohydrological conditions, without using an exact hydrological time series [2,3]. Yet, all of these studies are of the same mind that groundwater availability plays a crucial role in the vitality and productivity of trees and forests dependent on them. Studies on groundwater-dependent ecosystems without periodic flooding events and direct riverine connections are underrepresented in the literature. At the same time, the effect of groundwater availability was also found to potentially vary between individual trees and different tree species and to be dependent on different hydrological conditions (e.g., flooding) [7–10], calling also for further research on the different groundwater-dependent ecosystems of the region.

The regional topography and groundwater regime of southwestern Hungary implies that groundwater availability plays an important ecological role by contributing to the water supply of various habitat types located in valleys and local topographical depressions. The extensive areas of forests oriented in the north–south direction and 5–10 km wide valleys of the region were previously associated with groundwater and were delineated as groundwater-dependent ecosystems in the framework of a national quantitative status assessment of groundwater bodies in Hungary [12]. Groundwater-dependent ecosystems require input from the groundwater supply [13], which, in most cases, means that the shallow groundwater table or the capillary fringe above it is permanently or temporarily within the reach of the vegetation root system [14]. Within this region, the Szenta Forest represents an iconic, ecologically and economically important block of forested area, where concerns of potentially decreasing groundwater levels affecting forest health and productivity brought melioration and monitoring efforts into action [15].

A tree-ring dataset with a smaller sample size was previously considered from this area in an evaluation of oak tree-ring growth in eastern Central Europe [16]. A correlation analysis using monthly climatic records over the 1935–1995 period revealed negative correlations with the temperature of the dormant period preceding the growing year (December and February–March) and, in contrast to most other sites from the region, a complete lack of significant correlation with the amount of precipitation [16]. A more recent study also analyzed the tree-ring series from nearby younger and middle-aged forest stands, aiming to identify the benefits of the above-mentioned melioration efforts to increase the groundwater level and maintain its balanced interannual course on tree growth [17]. This study found no clear significant correlations with the same climatic variables for the post-1982 period either and suggested that the annual growth of oaks may be more closely related to the groundwater level fluctuations [17]. This hypothesis, however, remained untested.

The present work aims to exploit the opportunity for analysis on an extended timescale by merging both tree-ring width datasets to clarify the (missing) common climatic signals in the radial growth of pedunculate oaks in the study area and to broaden our knowledge of how groundwater availability may interfere with them. The joint tree-ring width series, well-distributed within the study area by sampling design, were compared to the monthly historic time series of groundwater depth measurements and to the climatic variables considered important to the overall hydro-climatic conditions. The detailed research objectives were (i) to revisit and test the unique or missing climatic signals in the radial growth reported for the area by also considering the monthly groundwater data and an enhanced sample size of trees; (ii) to address the role of groundwater availability in a potential interplay with the common climatic signal of the greater region and the relative growth rates in more details; and (iii) to assess the long-term shifts in the climatic regime and their effects on growth limitation (i.e., the shifts in the climatic signal) beyond the availability of the groundwater time series. Finally, with these objectives, we also aimed to reflect on tree growth and vitality in similar forest ecosystems, where hydro-climatic conditions may change.

2. Materials and Methods

2.1. Study Area

The Szenta Forest, representing the study area, lies around the village of Kaszó (ca. 46.32° N 17.22° E) at a lower elevation part of the Transdanubian region in southwestern Hungary (Figure 1). The meridional sand ridges and valleys of the aeolian landscape were formed by northerly winds by reshaping fluvial landforms [18]. The analyzed forest stands lie in valleys and deflation hollows at a mean elevation of 154 m a.s.l., while the height of the surrounding ridges reaches 165–170 m a.s.l. A modeled groundwater level map [19] suggests that the water table is controlled by the topography. Due to the varied relief, local flow systems convey groundwater from the recharge areas of ridges to discharge areas at lower elevations. Site conditions are thus influenced by permanent or periodic high groundwater table, with deep (in periodically waterlogged depressions also organic-material-rich) soils formed on sand parent material.

An area comprising about two-thirds of the Szenta Forest, along with the enclosed lakes, wetlands, and grasslands, is considered a groundwater-dependent ecosystem [12,20], with a yearly average of 100–200 mm specific annual groundwater demand to maintain optimal ecohydrological conditions [20]. Forests are dominated by pedunculate oak (*Quercus robur* L.) in several parts of the study area, sometimes along with a smaller share (5–10%) of Turkey oak (*Quercus cerris* L.) and European hornbeam (*Carpinus betulus* L.) as admixing species. Depressions with mostly groundwater-maintained excess water and baseflow-dependent streams are dominated by black alder (*Alnus glutinosa* (L.) Gaertn.). The annual mean temperature and total precipitation were 10.4 °C and 770 mm, respectively, for the period of 1981–2010 [21].

A key hydrographical feature of the study area is Lake Baláta (Figure 1). The water level fluctuation of the lake, which depends on rainfall and groundwater, is considered to be associated with a strong limiting factor on the productivity of the surrounding vegetation [22,23]. Lake Baláta and the surrounding Szenta Forest have been relatively protected from drastic human influence over the past few centuries [24], and the area became protected in 1942 [23]. A part of the Szenta Forest received a higher level of protection in 2008 when it was declared as a forest reserve [25]. The entire Szenta Forest is also part of the Natura 2000 network. Within the framework of the KASZÓ-LIFE project running between 2013 and 2018, interventions were carried out to restore and maintain its forest ecosystems by retaining water and mitigating the decrease in the groundwater levels [15].

The water availability of the Szenta Forest is characterized by annual fluctuations. The interannual fluctuation of the mid-summer groundwater level exceeds 1 m, and remarkable differences can also be seen in the extent of the water-covered surface. As observed in aerial images, the open water area of Lake Baláta has increased since 2015. This may be interpreted as a positive effect of the interventions aiming to ameliorate groundwater conditions (e.g., construction of reservoirs and bottom thresholds in streams), which were reported to result in ca. 0.4–0.5 m groundwater level rise in the vicinity of the constructed lakes [26].

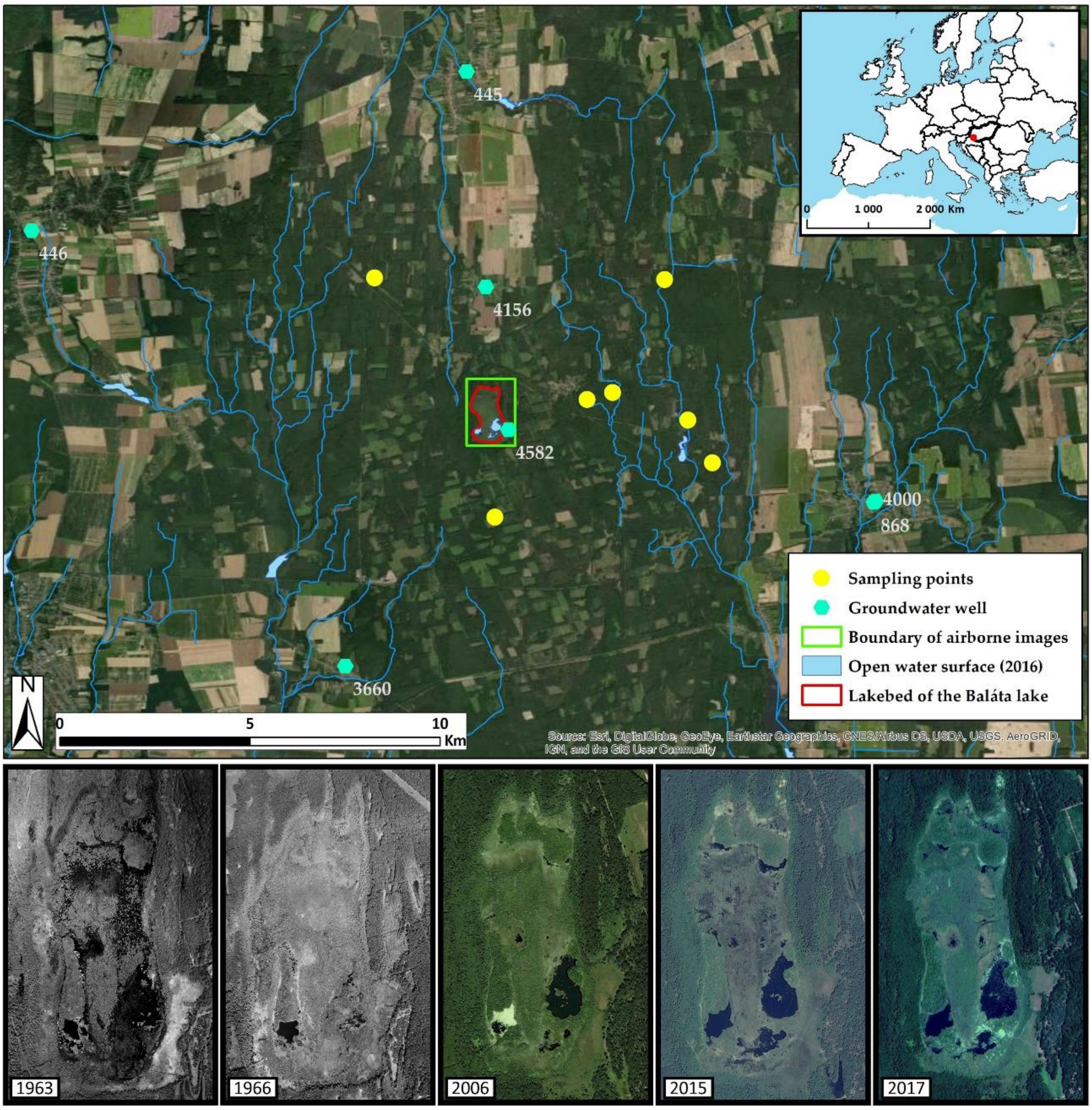

Figure 1. Aerial overview of the study area with its land-cover and hydrographical properties, tree-ring sampling sites, and groundwater wells with available data (main panel), and historical aerial images of the Lake Baláta and its changing open water surface, a key hydrographic and conservational feature of the Szenta Forest (below). Source of imagery: [27,28].

2.2. Tree-Ring Sampling and Measurement

Tree-ring samples were collected from pedunculate oaks in two distinct sampling campaigns. Each campaign was performed using a Pressler increment borer to collect two cores per sample tree at breast height. The first campaign in 2001 targeted old dominant individual trees around the village of Kaszó, with 13 trees sampled (covering the dated period of 1903–2001), out of which 9 were analyzed (site ID U05) in the previous work of [16]. The second sampling campaign in 2018 was oriented toward selected forest compartments as part of the monitoring tasks of the KASZÓ-LIFE project [17] when a total of 60 codominant oak trees were sampled from the intermediate and younger age classes (covering the dated period of 1948–2017).

Sample surfaces were processed by using machine-operated abrasive belts until the tree-ring structure became clearly visible [29], using progressively finer grain sizes from FEPA 80 grits (~200 µm) to FEPA 400 grits (33 to 36 µm) [30]. Ring-width measurements were made at a resolution of 0.01 mm, using a LINTAB measuring table with TSAP-Win 4.67 software [31] and WinDENDRO software [32] on scanned images at 1200 dpi, for the samples from the first and second campaign, respectively. The ring-width series from both measurements were merged and cross-dated, first through visual comparison and then checked using the COFECHA program through the analysis of the correlation in successive 50-year segments with 25-year overlaps between the log-transformed ring-width series of the individual records and the mean of the remaining dataset [33,34]. By omitting very short series and samples with potential growth bias compared with the entire population, a final number of 61 samples was used in the analyses.

Tree-ring width series were detrended [35], choosing a flexible 30-year cubic smoothing spline method, in order to remove age-related trends and the effects of other longer-term biotic and abiotic factors and to enhance the hydro-climatic signal by retaining interannual–subdecadal variations in growth. Detrending was performed using the ARSTAN software [36], by subsequently deriving individual tree-ring width indices as the ratios between the raw measurements and modeled growth. The standard versions of the detrended series were further checked for autocorrelation, as reported previously in the radial growth of oaks [37,38]. Autoregressive models were fit to the primary index series by using the ARSTAN software, calculating the Akaike information criterion (AIC) for each autoregressive order. However, the procedure did not suggest the need for further processing and the use of pre-whitened data, associating the zero-order autoregressive model with the lowest AIC value.

The final tree-ring width index (TRWI) chronology was calculated as the biweight mean of the individual series solved iteratively using the arithmetic mean as the initial estimate [39]. Biweight mean effectively eliminates the bias of the arithmetic mean in the presence of outliers and provides a nearly unbiased estimate of the central values of the distribution of tree-ring indices, discounting those values representing extreme growth disturbances [35].

The signal strength of the detrended chronology was checked using the expressed population signal (EPS) statistic [40,41]. The mean inter-series correlation (Rbar) and EPS were calculated within 50-year running windows. The final effective chronology length was selected with a minimum replication of 7 sample trees and with the running EPS statistic exceeding the traditional 0.85 acceptance level [40]. This resulted in the selection of the period of 1920–2017 (Figure 2a), represented by a mean EPS of 0.92 and Rbar of 0.27.

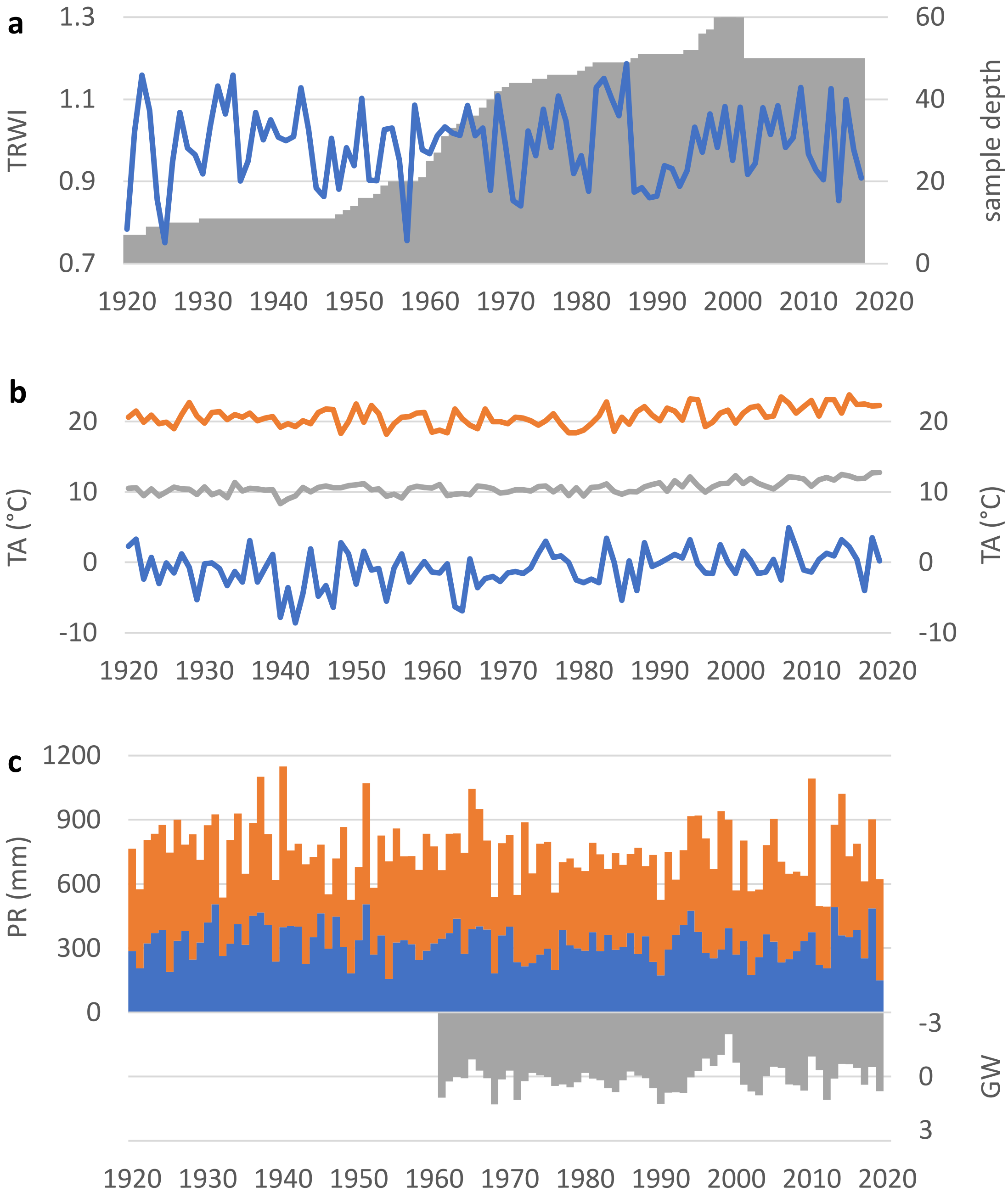

Figure 2. Mean detrended tree-ring width index chronology (TRWI) and its sample depth (**a**); January (blue), July (orange), and annual (gray) mean temperature (TA; CRU TS4.05) (**b**), and cumulated October–March (blue) and April–September (orange) precipitation sums (PR; GPCC V2020 analysis), as well as, normalized mean annual groundwater depth (GW; grey) (**c**), for the period of 1920–2019, with respect to data availability.

2.3. Groundwater and Climate Data

Groundwater depth measurements were available from a monitoring well in Kaszó (well ID 4582) with daily resolution since 31 August 2006 and a coarser temporal resolution (median sampling cycle of 8 days) dating back to 12 January 2005. The surrounding monitoring wells (well IDs 445, 4000, and 4156) situated closer than 6.5 km to the Szenta Forest and characterized by high cross-correlations (r = 0.57 to 0.88) were used for gap-filling and extending the time series of groundwater levels (Figures 1 and 2). The data from the same months were averaged for each well, and the time series with overlapping records were normalized to well 4582 by subtracting the mean and dividing by the standard deviation of the period of January 2006 to December 2019. The normalized series were averaged to a preliminary composite record. In the next step, additional overlapping groundwater level time series from the surrounding wells (well IDs: 868 and 446) were scaled to this preliminary composite over the period from January 1982 to December 1992 and averaged. The final composite groundwater depth (GW) time series spanned from 1961 to 2019 (Figure 2c). Representing groundwater depth, higher GW values indicate lower groundwater levels. Negative values are principally due to the normalized composite nature of the derived time series. Therefore, their interpretation should be limited to the interannual variability, rather than the actual quantification of the groundwater depth.

For the meteorological variables and representation of longer-term climatic variability and trends, the monthly CRU TS4.05 temperature [42] and the GPCC V2020 analysis precipitation [43] data products (at a spatial resolution of 0.5°) were used (Figure 2b,c), by selecting the closest grid point to the study area. Combining these two climate data sources, the standardized precipitation and evapotranspiration index (SPEI) series [44] were also computed using the SPEI package [45] under the R statistical programming environment [46], where potential evapotranspiration was computed using the Thornthwaite equation [47]. In the calculated SPEI series, negative values indicate drier conditions. Conforming to the monthly resolution of groundwater and climate variables, the SPEI series were calculated in relatively short 3-month running windows, ending with the target month (SPEI3) but also incorporating some lagged effects of the previous months. Furthermore, SPEI3 is sometimes the finest resolution SPEI indicator that is available in regional databases [21] and is effectively used in previous dendroecological studies e.g., [48]. Hereafter, the monthly mean temperature (TA) and precipitation sum (PR) and the SPEI3 data, together with the monthly GW series, are referred to as monthly hydro-climatic variables.

Any issues of representativeness due to the use of coarse resolution climate datasets were also checked by comparing the descriptive statistics of their time series for common periods with the CARPATCLIM database, considered a highly representative homogenized gridded monthly meteorological data source at a resolution of 10 km over the period of 1961–2010 (Szalai et al., 2013). Although the annual mean temperature was 0.6 °C higher for the CRU, and the annual precipitation sum 29 mm (3.8%) lower for the GPCC databases than the climatology based on the CARPATCLIM data for the period of 1981–2010, the high correlation ($r > 0.9$) between their time series, including for those months of specific interest, demonstrated their suitability for the present analysis, in addition to the benefit of providing a longer period of data availability.

2.4. Statistical Analysis

The applied statistical analyses consisted of three steps, each partly building on the others. These included the final TRWI chronology and the hydro-climatic variables of GW, PR, TA, and SPEI3. In the first two steps, we focused on 1961–2017 as a common period of GW and TRWI series, while in the third step, the analysis was limited to 1920–2017, the common period of TRWI and climatic variables.

First, a Pearson correlation analysis was performed between the TRWI series and the monthly hydro-climatic variables for the 1961–2017 period, in order to define the most important hydro-climatic signals in radial growth [49]. The analysis was carried out for an extended period from April of the preceding year to September representing the end of the actual growing year of tree-ring formation [50]. Comparing the correlation coefficients, a smaller group of the most significant hydro-climatic variables were selected for later analyses.

In the second step, the TRWI values of the period of 1961–2017 were sorted according to the selected hydro-climatic variables, in order to assess the strength of their relationship with the hydro-climatic variables along the sorted gradient range of the hydro-climatic variables themselves. The correlation coefficients with TRWI were calculated in 30-element moving windows along the sorted series of hydro-climatic variables. At the same time, the 30-element moving average trends (MA30) of the relationships facilitated a visual interpretation of how the relative growth rates depend on the limitation of the selected hydro-climatic factors. To assess the significant shifts in the moving average trends, the first and last MA30 values along the sorted gradient ranges were tested for significant differences using Welch's two-sample *t*-test [51]. Given the variable GW of special interest, the upper moving correlation analysis based on the sorted GW series also included the other climatic variables in this case, in order to assess how subsurface hydrology might interfere with the pure climatic signal in growth.

As the final step, the longer-term moving average trends of the climatic variables and their changing correlation with the TRWI series were assessed in chronological 30-year moving windows from 1920 to 2017, as another frequently used method in dendrochronology, e.g., [8]. The changing correlations between TRWI and the hydro-climatic variables were then also compared and addressed with a view to their trends and the coupled hydro-climatic effects on growth revealed in the second part of the analyses.

Since most of our statistical analyses were based on the Pearson correlation analysis, the normality of the data used lies at the core of our work. Monthly hydro-climatic variables and detrended annual radial tree growth variations are widely (and indirectly) assumed to follow normal distribution within dendrochronological research. In this regard, only precipitation is problematic, which is not normally distributed on a short timescale. However, its normality at and above the monthly scale can be usually assumed at and above the monthly scale for practical applications [52]. Nevertheless, all the data used in our work were also tested for normality with the Shapiro–Wilk test [53] at a significance level of $p < 0.05$, with its outcomes briefly reported in the respective subsections under the Results section.

The associated significance levels with the Pearson correlation analyses were determined through a test statistic following a *t*-distribution with degrees of freedom n–2, where n is the length of the analyzed period. Since significance levels depend on the temporal window of analyses, we used the significance level of $p < 0.05$ for the first part of the analyses and the significance level of $p < 0.1$ for the moving window analyses. However, it can be noted that a correlation coefficient of $|r| > 0.5$ generally indicates a strong correlation and (hydro-)climatic signal within the dendrochronological literature [8,16,50,54].

3. Results

3.1. General Hydro-Climatic Signals in Radial Growth

The Pearson correlation analysis revealed a clear relationship between interannual variations in the radial tree growth and groundwater conditions, highlighting its relevance among the monthly hydro-climatic variables analyzed (Figure 3). A period during late winter and early spring, including the months of February–April, was when most of the significant correlations of the TRWI chronology with individual monthly hydro-climatic variables occurred. Besides the significant negative correlations with GW, SPEI3 also showed a strong correlation with TRWI for February and March. TA of February also had a significant negative relationship with radial growth, the only month for which this variable was significant. During summer, PR was only significant for the single month of June, while the correlations with GW stayed above the significance level of $p < 0.05$ until July.

The monthly variables exhibiting the three most significant correlation coefficients to the TRWI chronology were, in order, SPEI3 in February (SPEI3(Feb); r = 0.45) and March (r = 0.43), and GW in April (GW(Apr); r = −0.42), followed by winter and early spring precipitation (January and March), and GW and SPEI3 of the neighboring months, which was likely also due to their autocorrelated characteristics. The variables GW(Apr) and SPEI3(Feb) were selected as the key hydro-climatic variables for the subsequent detailed analysis, together with the PR in June (PR(Jun)), representing a less significant but generally important climatic variable, and TA of February (TA(Feb)), which contrarily marks a rather unique climatic signal in contrast to previous studies.

Although some of the hydro-climatic variables failed the Shapiro–Wilk test of normality (i.e., they were indicated as differing from normal distribution at $p < 0.05$), all the variables selected for further analyses, including TRWI, followed a normal distribution. The hydro-climatic variables failing the assumptions of normality were PR in several months through the year except June, GW for the three autumn months, and SPEI3(Apr).

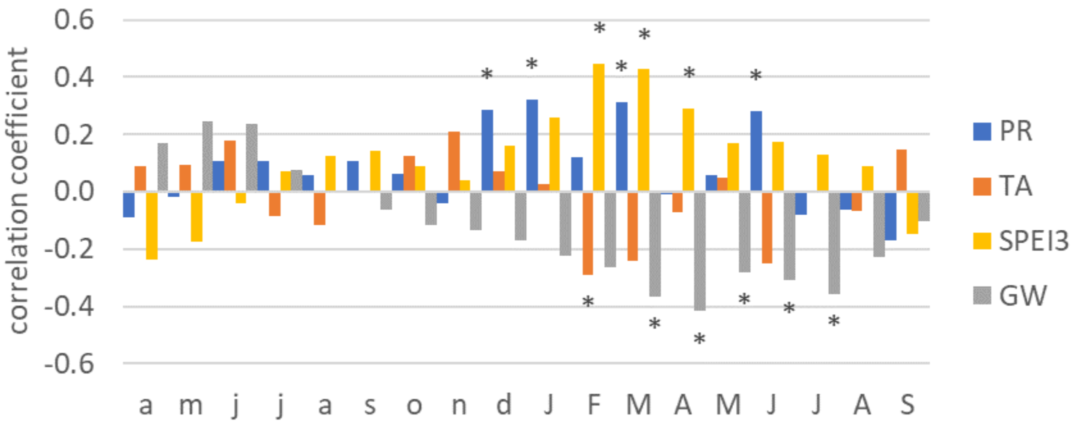

Figure 3. Correlation coefficients between the TRWI series and hydro-climatic variables PR, TA, the 3-month standardized precipitation and evaporation index (SPEI3), and GW for the period of 1961–2017. Months from April of the preceding year (lowercase initials) to tree-ring formation to September of the growing year (uppercase initials) are included; * marks significant correlation at $p < 0.05$ level.

3.2. Detailed Relationships between Radial Growth, Climate, and Groundwater

Further assessing the relationship between radial growth and the four selected hydro-climatic variables by plotting TRWI values along their gradients revealed a largely monotonous association between them but with greatly varying strength, as indicated in the moving correlations (Figure 4). Considering the 30-element moving average (MA30) trends, the differences between the mean TRWI values of the first and last MA30 windows were significant in all four cases at $p < 0.05$, revealing that the selected variables likely influenced the interannual variance of relative growth rates. Only in the case of the variable PR(Jun) was a clearer flattening of the MA30 trendline visible toward higher precipitation values. The moving correlation coefficients displayed an interesting pattern, indicating a differentiation between GW and the three climatic variables. While for GW, the significance of the correlation coefficients was sharply increasing toward higher GW values (i.e., toward drier conditions), the climatic variables showed more significant correlations with TRWI around their intermediate values.

Simultaneously, the moving correlation of TRWI with the three climatic variables also showed significant shifts and changes when calculated along the sorted series of GW (Figure 5). Besides the correlation trend of TRWI with GW(Apr) itself, this arrangement revealed that both the correlations with SPEI3(Feb) and PR(Jun) variables were more significant (although at $p < 0.1$ due to the shorter, 30-data-pair windows) in conditions characterized by lower groundwater levels during spring. Conversely, the (negative) relationship with TA(Feb) turned out to be present in conditions with a higher spring groundwater table.

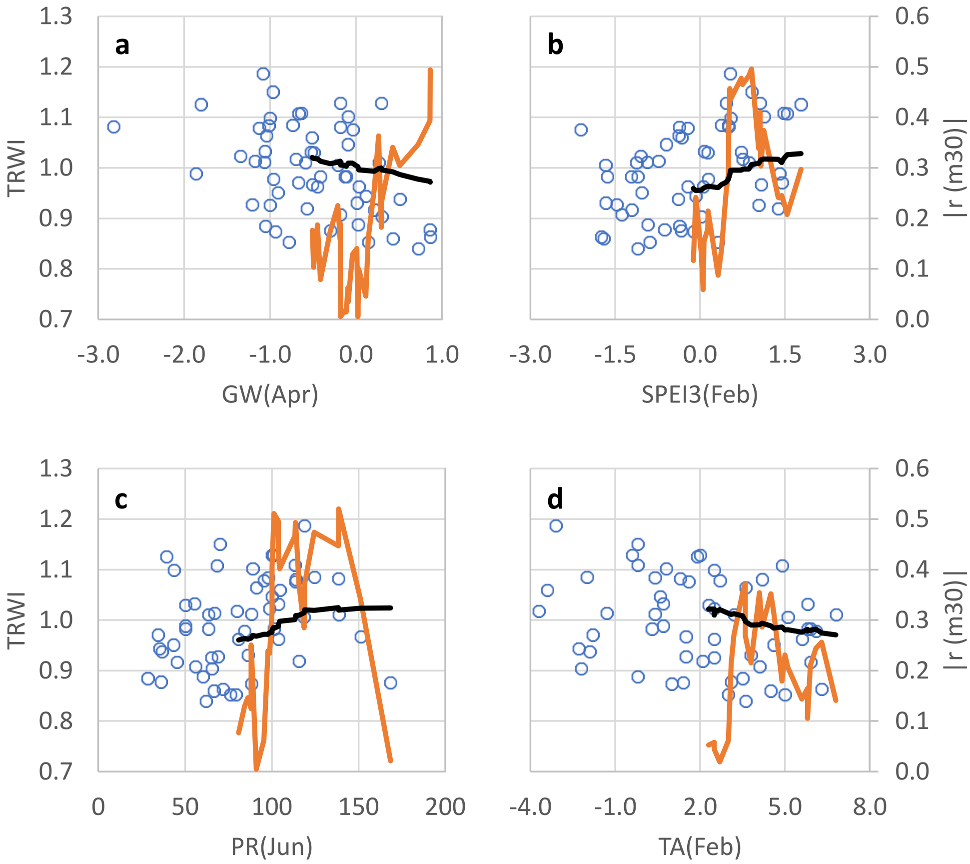

Figure 4. Relationships between TRWI and selected hydro-climatic variables of GW in April (**a**), SPEI3 of February (**b**), PR in June (**c**), and TA of February (**d**) for the common period of 1961–2017, with 30-element moving average trends (MA30; black line). Moving correlation coefficients (r(m30); orange line) in windows of 30 data pairs are also indicated. For MA30 and r(m30) the horizontal axis marks the end value of the moving windows. Differences between mean TRWI values of the first and last MA30 windows are significant in all four cases at $p < 0.05$ level.

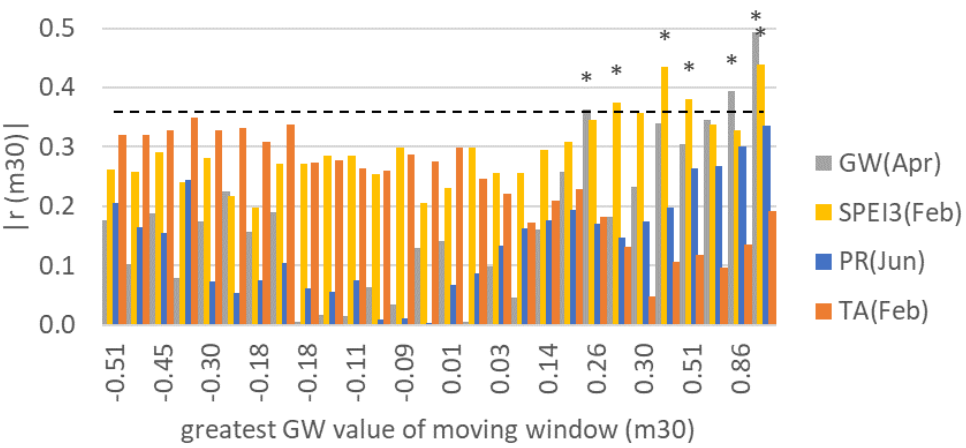

Figure 5. Correlation coefficients in absolute values between TRWI series and selected hydro-climatic variables of GW in April, SPEI3 of February, PR in June, and TA of February, based on a moving window of 30 data pairs along a sequence, with higher GW values marking drier hydrological conditions, resampling the period 1961–2017. Bars exceeding the dashed horizontal black line, marked with *, indicate significant correlations at $p < 0.1$ level. Note that correlation coefficients with GW(Apr) and TA(Feb) are characteristically negative, while for SPEI3(Feb) and PR(Jun), they are characteristically positive.

3.3. Climatic Trends and Changing Correlation with Radial Growth

The correlation between the TRWI chronology and the hydro-climatic variables also showed significant changes in its 30-year moving windows of analysis of the entire study between 1920 and 2017 (Figure 6b). The relationship of radial growth with SPEI3(Feb) was clearly becoming stronger during the period, starting off from non-significant coefficient values but staying above the significance level $p < 0.1$ since the 30-year period of 1960–1989, reaching r > 0.5 several times. In the case of PR(Jun), after almost no correlation with the TRWI chronology found during the first few decades of the analyzed period, it steadily strengthened and reached its highest correlation during the 30-year period of 1943–1972 (r = 0.53). After this period, it dropped again below the $p < 0.1$ level and recovered only in the last decade after a sudden increase, climbing again to reach r > 0.5. The relationship of TRWI with TA(Feb) followed a contrasting course to that with PR(Jun) in absolute terms, being non-significant in the first and last periods and reaching its strongest correlation (r = −0.53) between 1961 and 1990.

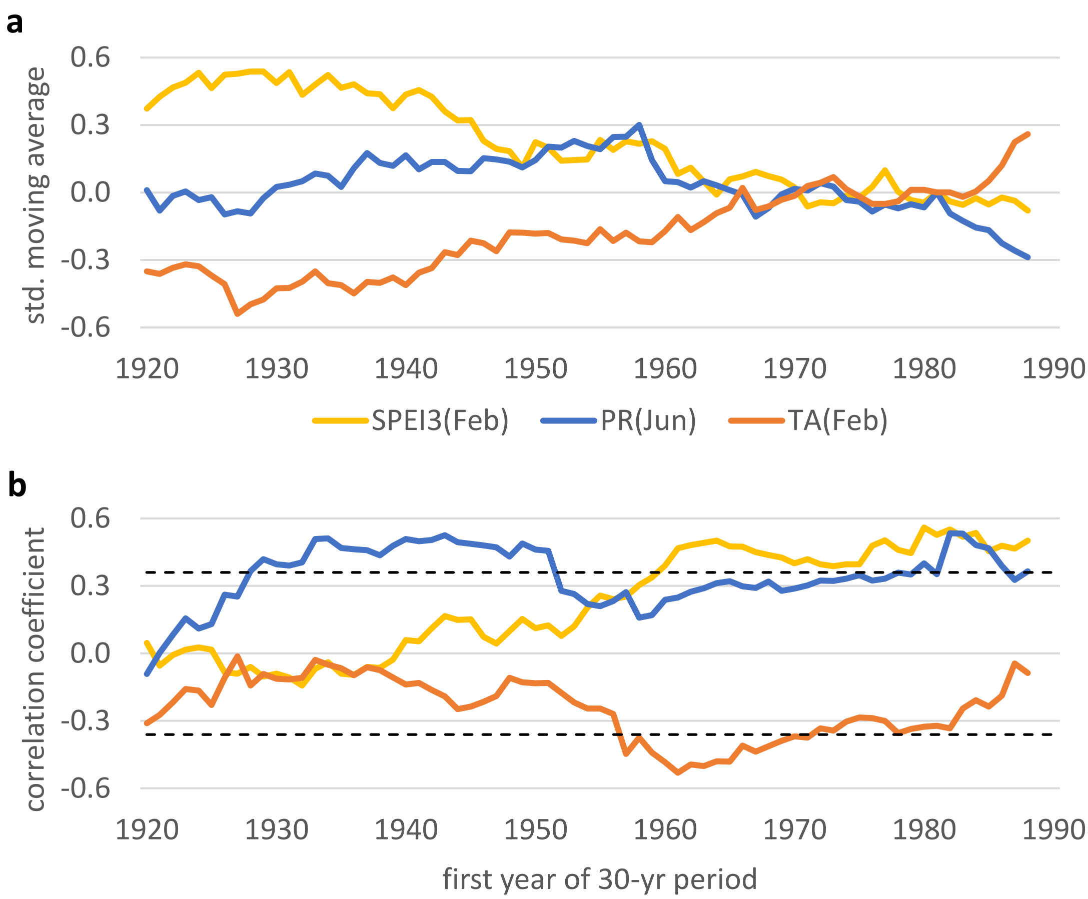

Figure 6. Standardized 30-year moving average trends relative to the period 1981–2010 for the selected climatic variables of PR in June (blue), and TA (orange) and SPEI3 (yellow) in February, for the period 1920–2017 (**a**). Running correlation coefficients for moving 30-year windows between TRWI series and the same climatic variables are plotted for the same period (**b**). Horizontal axes show the first year of the moving 30-year windows; dashed black lines correspond to the significance level of $p < 0.1$.

Such changes in the correlation of the TRWI chronology with climatic variables coincided with clear shifts in the climatic conditions, assessed comparably in 30-year moving averages (Figure 6a). Considering its moving average trend, SPEI3(Feb) showed an almost monotonous decreasing trend during the study period, marking more arid winter water balance conditions over time. PR(Jun) also decreased, following an initial slight increase during the mid-20th century. The clearest trend among the selected three climatic variables was associated with winter warming indicated by TA(Feb) and in line with Figure 2b.

4. Discussion

4.1. Coupled Hydro-Climatic Signals in the Radial Growth

With the inclusion and merging of additional sample trees and shifting the timescale of analysis, our results only partly confirmed the previously identified missing climatic signal in the radial growth of oaks in the Szenta Forest [16,17]. The correlation analysis revealed the remarkably weaker influence of the summer weather conditions, e.g., of early summer precipitation, on growth, compared with a number of sites in the greater region and in Central Europe, including floodplain forests and sites with various hydrological regimes [3,8,16,54,55]. A common climatic signal of March precipitation previously reported from the region [16], including by studies dealing with different oak species [50], was also reflected in these results. The presence of the rather unique negative relationship with February temperature remained in our revisited analyses. This is probably associated with an earlier physiological activity of the trees, compared with other sites from the region, where infrequent but existing similar-sign relationships for the early spring months were reported [16].

Nevertheless, the dominance of the hydro-climatic conditions of the dormant period, including the winter months and early spring, is clearly illustrated in the present case, whereas this had been rather sporadically reported by previous results [11]. The significant hydrological signal in the radial growth for these months also suggests the importance of winter water balance and groundwater recharge addressed elsewhere as a crucial but sometimes underestimated source of summer droughts with severe ecological impacts [56]. Based on the annual tree-ring width series, it is out of the scope of this work to clarify how and on which (delayed) temporal scale the hydrological conditions of pre-vegetation seasons may directly influence tree growth. However, our findings suggest a clear line of evidence that the hydro-climatic drivers of cumulative annual growth can vary greatly between oak-dominated temperate forest ecosystems depending on groundwater availability or with only precipitation as their primary water source [16,50,54].

The few studies available that investigate the direct relationship of radial growth with hydrological variables reported different periods within the year, for which significant correlations were found, and these also depended on the type of the hydrological regime and recharge mechanisms. Among these previous results, positive correlations with the summer water level of river flow in floodplain forests were found in southeastern (Central) Europe [7,8], in some cases with the significantly correlating period starting earlier already during the spring months [8]. Bearing a greater similarity to the results presented here, a relationship between early spring groundwater levels to drought was reported from Czech floodplain forest sites. These, however, were outperformed in their significance by drought indices for a similar period [11]. While the late winter series of the 3-month SPEI also showed more significant correlations with radial growth in absolute terms than the GW series, the culmination of growth–GW correlation in April indicated that it was a highly relevant independent variable, crucial to the understanding of the complete patterns of the hydro-climatic signals present in the radial growth of oaks at the study site.

Although the complex coupled effects of groundwater availability and climatic variability on tree growth had previously been hypothesized [2,17], any validation of these results based on the actual time series of multiple hydro-climatic variables is generally under-represented within the existing literature. A more detailed analysis of the relationship between radial growth and GW reveals how groundwater shortage is clearly becoming a strong and even primary limiting factor, both in terms of reduced growth rates and variability. A sharp increase in the significance of the growth–groundwater correlations along its gradient also hints at a threshold-based role of it, in all probability depending on the effective root zone of the trees.

While the other selected climatic variables also showed a clear relationship with relative growth rates in general, the varying strength of their correlation and its maxima around intermediate values indicate that they are not the ultimate growth limiting factors in the case of the studied area. GW, on the other hand, also seemed to influence the correlation of radial growth with other variables. A lower groundwater table in spring implied a stronger dependency on summer precipitation and also highlighted the role of winter aridity as a possible driver of groundwater shortage in spring. From the other perspective, this also showed how adequate groundwater availability can mitigate the effect of summer precipitation scarcity and meteorological drought [2,11]. An interesting pattern of the flattening of the increase in radial growth rates toward more abundant June precipitation may also originate from cooler summers and less radiation because of the higher cloud cover associated with higher precipitation.

Compared with summer precipitation and winter SPEI, the interplay between the climatic signal of the mean temperature of February in growth and groundwater availability seemed to be different. Interestingly, stronger correlations were found for it during the years with higher groundwater tables. On the other hand, this unique climatic signal also seemed to be a more significant driver of growth variations toward higher growth rates, in general, assessed by hydrological conditions as more favorable years for growth.

4.2. Observed Trends and Their Implications on Tree Growth

Near-surface groundwater levels and waterlogging may negatively affect the productivity and vitality of oaks due to anaerobic environments at the root zone [9]. However, most studies agree that in the case of established forest stands on sites without direct flooding risk but benefitting from groundwater availability, tree growth and vitality increase with wetter conditions in general [2,7]. In terms of the results presented here, specifically those related to the sampling sites excluding periodically waterlogged depressions, no evidence of any negative effect of near-surface groundwater could be discovered, while higher groundwater levels, especially during the spring months, contributed to increased relative growth rates.

Except for June precipitation during the first few decades of the study period, all the climatic variables with distinct relationships to radial tree growth displayed almost monotonous unfavorable shifts during the extended period of analysis. Taken together with the changes in the correlation between them and radial growth, and in view of the coupled signals with GW, these mark possible changes in the effective groundwater availability and use efficiency. It may be a decisive driver of growth sensitivity, even when a decreasing trend of the annual or the spring groundwater availability was not detectable in the available data dating back to 1961. In particular, the strengthening trend of the moving correlation coefficients between the radial growth and precipitation in June and the SPEI3 in February may also mark historic and long-term deteriorating conditions in the hydrological balance of the region [8] and highlight the role of (sustaining) groundwater availability. However, the remarkably weakening relationship between the radial growth and precipitation in June during the earlier decades of the first half of the 20th century should be considered cautiously, coinciding with a period when the number of precipitation gauges included in the reanalysis product fell to zero within the 5×5 neighboring 0.5° grid cells of the study area [43].

The climate model-projected increase in winter precipitation for the region [57–59] may induce enhanced capacities of such forest ecosystems to benefit from some changing climatic trends, counteracting increasing summer aridity. However, the unfavorable changes in climatic conditions during the past few decades and the uncertainties of the groundwater regime detailed above do imply that additional active measures aimed at the melioration of groundwater conditions can be highly beneficial for maintaining forest vitality and tree growth in the study area, as well as elsewhere in oak forests with similar site conditions, history of the hydro-climatic regime, and projected climatic trends [2,3,7,17].

5. Conclusions

Our findings, based on assessing and comparing radial growth variations in pedunculate oak with the hydro-climatic variables of monthly groundwater depth, precipitation, mean temperature, and drought indices, reveal a crucial role of groundwater availability and provide novel insights into the investigated groundwater-dependent oak-dominated forest ecosystem. The coupled effects shown between the belowground hydrologic and climatic signals in tree growth also provide quantitative evidence on previous hypotheses on the complex water-use regime of such ecosystems. The radial growth of the studied trees showed the strongest relationship in a pre-vegetation season with late winter and early spring groundwater and drought conditions. These results suggest that groundwater recharge during the dormant period preceding the vegetation season is a crucial factor for tree growth and vitality in the study area.

Although climate models project an increase in winter precipitation for the region, unfavorable shifts in climatic conditions during the past few decades imply that active measures of maintaining and restoring groundwater conditions can be highly beneficial for sustaining groundwater-dependent forest ecosystems and their productivity, highlighting, among others, also an opportunity for European forest ecosystem restoration and related climate change adaptation efforts.

While the research design presented here was capable of providing an overall representation of the oak-dominated forest ecosystems of the study area, some limitations of the scope of our work may also call for further research in the field. These may include the investigation of the potential differences in the response of individual trees to groundwater availability, including differentiating between young and mature trees with different depths of their root systems. Furthermore, local ecophysiological research could also help in understanding the water use mechanisms underlying our findings.

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