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The stationary and non-stationary character of the silver fir, black pine and Scots pine tree-growth-climate relationships

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Abstract:	Tree-growth-climate relationships are usually assumed to have a stationary character at any given time along the lifetime of the trees. The fact that non-stationarity is more likely to actually be their general rule, has been largely neglected in dendrochronology. Nine silver fir (*Abies alba* Mill.), black pine (*Pinus nigra* Arn.) and Scots pine (*Pinus sylvestris* L.) residual ring-width index series ($RWI_{residual}$) and five seasonal climatic variables (cf. Abbreviations), covering the 20 th century and the beginning of the 21 th one, were used in this study. Heat map analyses based on rolling window correlations were conducted to evaluate the evolution and stability of tree-growth-climate relationships along the lifetime of the trees, i.e., their stationary and/or non-stationary character. The obtained results showed that stationary tree-growth-climate relationships were well conserved within trees belonging to a given genus: positive effects, both at young and mature stages, of T_{winter} (winter temperature) on the *Abies* genus and of P_{sprsum} (spring-summer precipitation of the current-to-growth year) on the *Pinus* genus. Non-stationary tree-growth-climate relationships were instead more common and divers, species- and site-dependent and stopped in the 1980s/1990s. Heat map analyses based on rolling window correlations proved to be a powerful statistical tool to disentangle between the stationary and/or non-stationary character of the tree-growth-climate relationships, an aspect of upmost importance if we want to better understand the impact of climate change on the future forest tree growth and dynamics based on past tree-growth-climate relationships.
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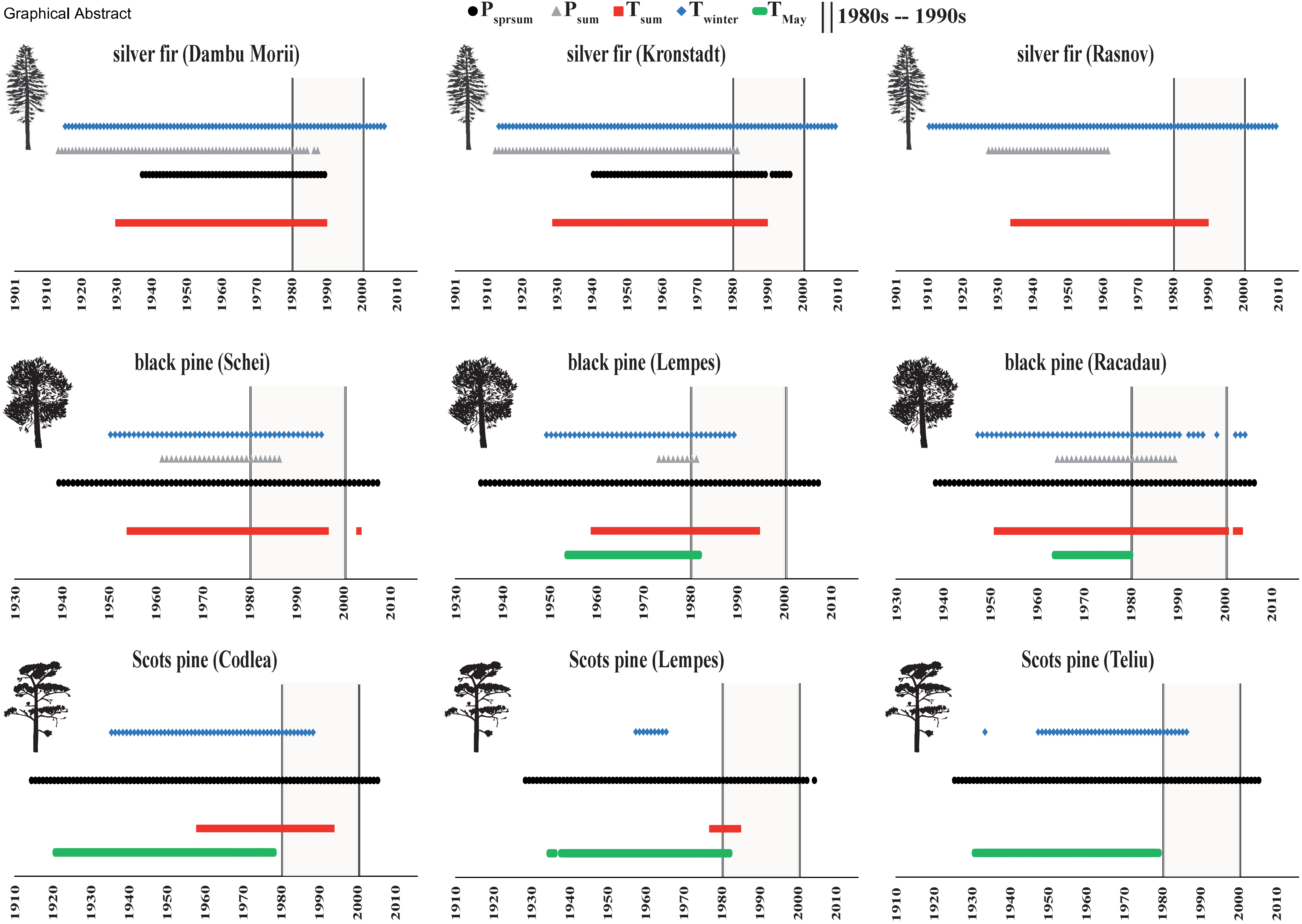
Graphical Abstract



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HIGHLIGHTS

- Tree-growth-climate relationships are rather non-stationarity than stationary
- Stationary tree-growth-climate relationships are conserved within the same genus
- Non-stationary tree-growth-climate relationships are instead more common and divers
- Tree-growth-climate relationships' stability is key to understand future climate change effects on forests

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The stationary and non-stationary character of the silver fir, black pine and Scots pine tree-growth-climate relationships

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ABSTRACT

Tree-growth-climate relationships are usually assumed to have a stationary character at any given time along the lifetime of the trees. The fact that non-stationarity is more likely to actually be their general rule, has been largely neglected in dendrochronology. Nine silver fir (*Abies alba* Mill.), black pine (*Pinus nigra* Arn.) and Scots pine (*Pinus sylvestris* L.) residual ring-width index series ($RWI_{residual}$) and five seasonal climatic variables (cf. Abbreviations), covering the 20th century and the beginning of the 21th one, were used in this study. Heat map analyses based on rolling window correlations were conducted to evaluate the evolution and stability of tree-growth-climate relationships along the lifetime of the trees, i.e., their stationary and/or non-stationary character. The obtained results showed that stationary tree-growth-climate relationships were well conserved within trees belonging to a given genus: positive effects, both at young and mature stages, of T_{winter} (winter temperature) on the *Abies* genus and of P_{sprsum} (spring-summer precipitation of the current-to-growth year) on the *Pinus* genus. Non-stationary tree-growth-climate relationships were instead more common and divers, species- and site-dependent and stopped in the 1980s/1990s. Heat map analyses based on rolling window correlations proved to be a powerful statistical tool to disentangle between the stationary and/or non-stationary character of the tree-growth-climate relationships, an aspect of upmost importance if we want to better understand the impact of climate change on the future forest tree growth and dynamics based on past tree-growth-climate relationships.

KEYWORDS

conifers, dendrochronology, heat map analyses based on rolling window correlations, non-stationary, stationary, tree-growth-climate relationships

ABBREVIATIONS

$RWI_{residual}$, residual ring-width index series; **P_{sprsum}**, spring-summer precipitation of the current-to-growth year; **P_{sum}**, summer precipitation of the previous-to-growth year; **T_{sum}**, summer temperature of the previous-to-growth year; **T_{winter}**, winter temperature; **T_{May}**, May temperature of the current-to-growth year

INTRODUCTION

Forest tree growth and dynamics are mainly governed by climatic drivers. Given that forests all over the world are currently undergoing concerning climate-related decline and mortality rates (Allen *et al.*, 2010, 2015; Hartmann *et al.*, 2018) and that we struggle to understand the impact of climate change on the future forest tree growth and dynamics based on how trees responded to stressful climatic conditions in the past (Babst *et al.*, 2017, 2019), it becomes evident that understanding tree-growth-climate relationships and their dynamics along the lifetime of the trees is critical. In this regard, tree rings are widely used long-term proxy data to assess forest tree growth and dynamics as they archive all the climatic events to which the trees have been exposed to along their lifetime, allowing their precise annual dating (Fritts, 1976). Tree rings provide thus high temporal resolution information and large tree-rings datasets are globally available (Zhao *et al.*, 2018; Kattge *et al.*, 2020).

Associations (i.e., tree-growth-climate relationships) between ecological (e.g., tree rings) variables and different environmental (e.g., climate) drivers are usually established based on transfer functions, i.e., assuming approximate linear relationships between them (Wilmking *et al.*, 2020). Accordingly, these relationships are usually assumed to have a stationary character at any given time along the lifetime of a tree (i.e., time-stable; Wilmking *et al*., 2020), meaning that trees are supposed to form a certain amount of growth as a function of particular values of different climatic drivers (Peltier & Ogle, 2020). Nevertheless, tree-growth-climate relationships are rather non-stationarity (Briffa *et al*., 1998; Carrer & Urbinati, 2006; D'Arrigo *et al*., 2008; Peltier & Ogle, 2020; Wilmking *et al*., 2020), meaning that the growth of the trees actually varies along their lifetime as a function of climate as both growth and climatic variables and/or their relationships may change over time (i.e., temporal evolution). This concept of non-stationarity has been often discussed in dendrochronology but it has been also largely neglected (Peltier & Ogle, 2020; Wilmking *et al*., 2020). In fact, non-stationarity is more likely to represent the general nature of the tree-growth-climate relationships given the numerous mechanisms, processes and causes that may influence them at some point in time, e.g., age, different physiological states, phenological events, species' specific hydraulic traits, drought stress and legacies, access to deep soil water sources, non-structural carbohydrates resources, site ecology, anthropogenic causes (Carrer & Urbinati, 2004; Cook *et al*., 2004; D'Arrigo *et al*., 2008; Leonelli *et al*., 2009; Coppola *et al*., 2012; Peltier & Ogle, 2020; Wilmking *et al*., 2020).

Tree species growing in the Romanian Carpathians offer the possibility to build long-term tree-ring chronologies that may be used to deepen into the forest tree growth and dynamics of Eastern Europe (Bouriaud & Popa, 2007). In this regard, species such as silver fir (*Abies alba* Mill.), black pine (*Pinus nigra* Arn.) and Scots pine (*Pinus sylvestris* L.) have been largely used in dendrochronological studies in Romania, their tree rings sensitivity to climatic drivers being well documented (e.g., Popa, 2003; Bouriaud & Popa, 2007, 2009; Levanič *et al*., 2013; Nagavciuc *et al*., 2019; Sidor *et al*., 2019, 2020; Hereş *et al.*, 2021). Silver fir is a native to Romania species, most of its distribution area following here the arc of the Romanian Carpathians (Wolf, 2003). Black pine [i.e., *Pinus nigra* ssp. *banatica* (Born.) Novak (*Pinus nigra* var. *banatica* Endl. Georg. et Ion)] grows naturally in Romania only in a very restricted area situated in the SW of the country (Isajev *et al.*, 2004; Levanič *et al.*, 2013), the rest of its populations being represented by plantations (i.e., mostly of *P. n.* var. *austriaca* (Hoss.) Asch. et Graebn., *P. austriaca* Höss.; Șofletea & Curtu, 2007). Scots pine, although naturally present in Romania, has been also largely planted here (Șofletea & Curtu, 2007; Bouriaud & Popa, 2009; Sidor *et al.*, 2020), this species being highly appreciated for its moderate to low site demands which makes it perfectly suitable for areas with degraded soils (Mátyás *et al.*, 2004). Deepening into the climatic drivers that have shaped the growth of these three conifer species along their lifetime, will provide important information on their past ecological behaviour and vulnerability. Based on this, more accurate estimations of their future responses to climate, marked by more frequent and severe droughts, heat-waves and mean annual precipitation decreases (Micu, 2009; Birsan *et al.*, 2014; Croitoru *et al.*, 2016; Cheval *et al.*, 2017; Piticar *et al.*, 2017), could be defined. Silver fir, black pine and Scots pine are highly appreciated species from an ecological and economical point of view both in Romania and Europe (Wolf, 2003; Isajev *et al.*, 2004; Mátyás *et al.*, 2004), understanding how these species will cope with climate change being thus of utmost importance.

In this study, we investigated growth (i.e., $RWI_{residual}$, residual ring-width index series) responses to climatic variables (precipitation- and temperature-derived), i.e., tree-growth-climate relationships, on silver fir, black pine and Scots pine trees growing in the Romanian Carpathians. Specifically, $RWI_{residual}$ series of the three conifer species, growing at nine study sites, were compared with seasonal climatic variables (P_{sprsum}, spring-summer precipitation of the current-to-growth year; P_{sum}, summer precipitation of the previous-to-growth year; T_{sum}, summer temperature of the previous-to-growth year; T_{winter}, winter temperature; T_{May}, May temperature of the current-to-growth year) along the 20th century and the beginning of the 21th one. These seasonal climatic variables have been defined based on previous published analyses and results showing strong correlations between mean monthly temperature (T °C) and total monthly precipitation (P mm) data and the growth of the same silver fir, black pine and Scots pine trees (cf. Hereş *et al.*, 2021). As both our seasonal climatic variables and dendrochronological data spanned over large periods of time, we managed to study tree-growth-climate relationships over both the young and mature stages of our sampled trees. Our main aim was to deepen into the previously published tree-growth-climate relationships in Hereş *et al.* (2021) and better understand the effect of the seasonal climatic variables that govern the growth of silver fir, black pine and Scots pine trees. Specifically, we were interested to check for the stationarity and/or non-stationarity of the obtained tree-growth-climate relationships. Our hypothesis was that tree-growth-climate relationships are rather non-stationarity than stationary along the lifetime of the trees, no matter the species and no matter the fact that the nine study sites are relatively closely located between them. To test our working hypotheses, we used heat map analyses based on rolling window correlations, a powerful and robust statistical tool that we propose here as a new method to analyse tree-growth-climate relationships and their stationarity and/or non-stationarity along the lifetime of the trees. These types of analyses, not previously used in dendrochronological studies to the best of our knowledge, have been proven to be very useful when it comes to evaluate in detail the evolution and stability of correlation results over time.

MATERIALS AND METHODS

Study sites

Three silver fir (Dambu Morii, Kronstadt, Rasnov), three black pine (Schei, Lempes, Racadau) and three Scots pine (Codlea, Lempes, Teliu) study sites were used in this study (Table **1**). All nine study sites are located in the Romanian Carpathians, in the Braşov region, at elevations that vary from 456 m to 1250 m a.s.l. (Curiel Yuste *et al*., 2019; Hereş *et al*., 2021; Table **1**). Silver fir study sites are all natural, while black pine and Scots pine study sites are all represented by plantations (Hereş *et al*., 2021). Note that, although black pine and Scots pine study sites have been planted, the level of human-related interventions within these study sites has been always minimal (i.e., sanitation harvesting; Hereş *et al*., 2021). For further details on the nine study sites and their exact location (Table **1**) see Curiel Yuste *et al*. (2019) and Hereş *et al*. (2021).

Dendrochronological data

The nine (i.e., Dambu Morii, Kronstadt, Rasnov, Schei, Lempes, Racadau, Codlea, Lempes, Teliu) residual ring-width index series ($\mathrm{RWI}_{\mathrm{residual}}$) used in this study were available from Hereş *et al*., 2021. The original dataset contained silver fir, black pine and Scots pine $\mathrm{RWI}_{\mathrm{residual}}$ series of both living and dead trees, as all nine study sites have been affected by high drought-associated mortality events that peaked in 2012 (Hereş *et al*., 2021). Nevertheless, for this study, only the $\mathrm{RWI}_{\mathrm{residual}}$ series of the living trees have been used as preliminary results of our analyses (i.e., heat map analyses based on rolling window correlations; cf. *Statistical analyses*) did not show significant differences between the living and dead trees of the three conifer species.

Sample size varied between 21 and 30 trees per study site (Table **1**). Mean cambial age varied between 133 and 161 yrs for silver fir, 99 and 105 yrs for black pine and 109 and 117 yrs for Scots pine (Hereş *et al.*, 2021), all the trees used in this study being thus mature (Şofletea & Curtu, 2007). All $\mathrm{RWI}_{\mathrm{residual}}$ series ended in 2015 but covered different periods of time depending on the species and study site (Table **1**; Fig. **S1**). Detailed descriptions of the fieldwork sampling, wood cores preparation, tree-rings measurements and crossdating may be found in Hereş *et al.*, 2021. The *spline* detrending method available from the "dplR" R package (Bunn, 2008; Bunn *et al.*, 2020) was used to calculate the $\mathrm{RWI}_{\mathrm{residual}}$ series. Specifically, to define the rigidity of the smoothing spline, a 0.50 frequency response cutoff and 30 yrs were considered. The resulting individual RWI values were then prewhitened using an autoregressive model in order to obtain the nine $\mathrm{RWI}_{\mathrm{residual}}$ series (Hereş *et al.*, 2021).

Climatic data

The climatic data used in this study was available from the Climatic Research Unit (CRU TS v. 4; Harris *et al.*, 2020). Specifically, mean monthly temperature (T, °C) and total monthly precipitation (P, mm) data were available at a 0.5° resolution from 1901 to 2015. Given the 0.5° resolution and the location of the nine study sites (Table **1**; Hereş *et al.*, 2021), seven study sites (i.e., Dambu Morii, Kronstadt, Schei, Lempes, Racadau, Teliu) fell within the same grid and had thus the same climatic datasets. The remaining two study sites (i.e., Rasnov, Codlea) fell within two different grids, so they had their own climatic datasets. At the nine study sites, the hottest months are June, July and August, while the coldest months are December, January and February (Fig. **S2a,b,c**). As for precipitation, the months when it most rains are May, June and July, while January, February and March are the months when less precipitation is registered

(Fig. **S2a,b,c**). Mean annual temperature varies between 6.3°C (Rasnov), 7.6°C (Codlea) and 7.8°C (the other study sites), while mean annual precipitation varies between 875 mm (Rasnov), 676 mm (Codlea) and 637 mm (the other study sites) (CRU TS v. 4; Harris *et al.*, 2020). Rasnov is the coldest ($p < 0.001$) and rainiest ($p < 0.001$) among all nine study sites (Fig. **S2d**). The CRU climatic dataset used in this study provides reliable data across the nine study sites as it takes into account local climatic data registered at both low and high elevations (Harris *et al.*, 2020; Hereş *et al.*, 2021).

Previous published analyses and results on tree-growth-climate relationships

Spearman correlations were run between mean monthly T (°C) and total monthly P (mm) data and the nine $\mathrm{RWI}_{\mathrm{residual}}$ series in order to account for tree-growth-climate relationships. These analyses were performed using the "Hmisc" R package (Harrell *et al.*, 2020). The results of these analyses have been published in Hereş *et al.* 2021 and are being used in this study as base to perform heat map analyses based on rolling window correlations (cf. *Statistical analyses*). Specifically, the results of the Spearman correlations showed that the three conifer species responded differently to mean monthly T (°C) and total monthly P (mm) (Hereş *et al.*, 2021). Based on these results, different periods of time have been defined to calculate different T (°C) and P (mm) subsets: spring-summer precipitation of the current-to-growth year (P_{sprsum}), summer precipitation of the previous-to-growth year (P_{sum}), summer temperature of the previous-to-growth year (T_{sum}), winter temperature (T_{winter}) and May temperature of the current-to-growth year (T_{May}) (Table **2**). For Scots pine alone, as our results published in Hereş *et al.*, 2021 showed no significant correlations with the previous-to-growth year summer months, we based our P_{sum}- and T_{sum}-related heat map analyses on the tree-growth-climate relationships published by Bouriaud & Popa, 2009. This could be done as their study site is located nearby (i.e., less than 100 km in straight line from our Scots pine study sites), has a south-facing orientation as our Scots pine study sites and they used dominant Scots pine individuals of similar age (over 100 yrs old) with those we sampled at Codlea, Lempes and Teliu (Hereş *et al*., 2021). For further details on these analyses, see Hereş *et al*. (2021) and Bouriaud & Popa (2009).

Statistical analyses

To test for differences in temperature (T °C) among the three climatic datasets (cf. *Climatic data*), one-way ANOVA analyses followed by a Tukey's Honest Significant Difference (HSD) post hoc test were performed. To test for differences in precipitation (P mm) among the three climatic datasets (cf. *Climatic data*), Kruskal-Wallis analyses followed by a pairwise Wilcoxon test with a Bonferroni correction were performed.

To analyse the trends of all our seasonal climatic variables (i.e., P_{sprsum}, P_{sum}, T_{sum}, T_{winter}, T_{May}; Table **2**) from 1901/1902 to 2015, we run linear regressions using the "fit.lr" function (R base functions). Additionally, in order to detect significant break-points within the trend of our seasonal climatic variables, we fitted regression models with segmented relationships between them and time (i.e., yrs from 1901/1902 to 2015) using the "segmented" R Package (Muggeo, 2003) and applying the Davies test.

To calculate climatic anomalies for all our seasonal climatic variables (i.e., P_{sprsum}, P_{sum}, T_{sum}, T_{winter}, T_{May}; Table **2**), we first calculated their overall mean values from 1901/1902 to 2015. We then subtracted their 1901/1902 -- 2015 overall mean values from their individual mean annual values to obtain climatic anomalies. Finally, in order to look for patterns along time for all the calculated climatic anomalies, we applied a loess smoother using the “ggplot” function (“ggplot2” R package; Wickham, 2016). By doing so, we fitted local regressions considering a small span value (i.e., 0.1) to control the smoothness of the curve and a 0.95 level of confidence interval. We considered as climatic anomalies all deviations from the 1901/1902 -- 2015 overall mean values, i.e., both above (“+”) and below (“-“) this overall mean values.

We conducted heat map analyses based on rolling window correlations (the bi-variate case) to evaluate the evolution and stability of tree-growth-climate relationships, i.e., between the $RWI_{residual}$ series and the seasonal climatic variables (P_{sprsum}, P_{sum}, T_{sum}, T_{winter}, T_{May}; Table **2**), over time. For this, we used the “rolwincor_heatmap” and “plot_heatmap” functions available from the “RolWinMulCor” R package (Polanco-Martínez, 2020, 2021). Specifically, we used the “rolwincor_heatmap” function to run rolling window correlations between the $RWI_{residual}$ series and the above mentioned seasonal climatic variables (i.e., two-time series that had identical time points, as required; Polanco-Martínez, 2020). Rolling window correlations are powerful statistical tools used to evaluate the evolution and stability of correlation-derived relationships along time (Polanco-Martínez, 2019, 2020). We defined the syntax of the “rolwincor_heatmap” function considering the Spearman correlation method and window-lengths of 5 to 81 yrs. As the window-length of 5 yrs showed very noisy, instable results, this window-length was finally discarded from our results, the window-length of 11 yrs being the first considered. The maximum window-length (i.e., 81 yrs) was determined by the period (yrs) covered by the shortest of the nine $RWI_{residual}$ series (i.e., Schei; Table **1**). Also, we used the “center” option to align the rolling object and to ensure that the variations of the correlations and those of the relationships between the two-time series (i.e., $RWI_{residual}$ series and the seasonal climatic variables) are aligned rather than being shifted to the left or to the right (Polanco-Martínez 2019, 2020). Finally, we used the BH (i.e., the false discovery rate method described in Benjamini & Hochberg, 1995) p-value correction method to obtain corrected ($p < 0.05$) p-values and thus avoid type I errors (Polanco-Martínez, 2020 and references therein). To plot the heat maps of the resulting correlation coefficients and their corresponding corrected p-values, we used the "plot_heatmap" function considering all possible window-lengths (i.e., of 11 to 81 yrs) (Polanco-Martínez, 2020, 2021). In order to visually appreciate if the resulting Spearman correlation coefficients showed different trends over the studied periods (see Table **1**) and over the considered window-lengths (i.e., 11 to 81 yrs), we averaged their significant values per each year and window-length, respectively. Finally, in order to define the "young" and "mature" stages of our sampled trees and check if the obtained tree-growth-climate relationships are age-dependent (Carrer & Urbinati, 2004), we followed Şofletea & Curtu (2007). In this regard, silver fir trees were considered to be mature starting from 71 yrs old, black pine trees were considered to be mature starting from 31 yrs old, while Scots pine trees were considered to be mature starting from 51 yrs old (Table **1**).

All statistical analyses were carried out in R (v. 4.0.5, R Core Team 2021). Statistically and marginally significant relationships were considered at $p < 0.05$ and $p < 0.1$, respectively.

RESULTS

Seasonal climatic variables and their anomalies

Details on all calculated seasonal climatic variables (i.e., P_{sprsum}, P_{sum}, T_{sum}, T_{winter}, T_{May}), for each species and study site, may be found in Table **2**. Only two (i.e., T_{sum},

T_{winter}) out of the five seasonal climatic variables showed statistically significant ($p < 0.05$) or marginally significant ($p < 0.1$) positive trends (i.e., warmer summers and winters) from 1902 to 2015 (Table **2**). Additionally, for T_{sum}, we found that the yrs 1997 (Dambu Morii, Kronstadt, Rasnov; Fig. **S3a,b**) and 1998 (Schei, Lempes, Racadau, Codlea, Lempes, Teliu; Fig. **S3c,d,e**) represented significant break-points that marked the starting point of a steeper trend for this seasonal climatic variable. Several intense and extended in time climatic anomalies (i.e., "+" and "-") were registered between 1901/1902 and 2015 at the nine study sites (Table **S1**; Figs. **1, 3, 5**).

Silver fir heat maps

Silver fir trees were found to be mostly sensitive to T_{winter}, no matter the study site. Stationary significant positive tree-growth-climate relationships with T_{winter} were found both at young and mature stages, at window-lengths of 11 to 81 yrs (Figs. **1, 2**). Between the 1930s and the mid-1970s, these significant relationships slightly weakened, this pattern being especially evident for the Dambu Morii and Rasnov study sites. From the mid-1970s onwards, these relationships showed a positive trend for all silver fir study sites (Fig. **2**).

Silver fir trees from Dambu Morii and Kronstadt also showed high sensitivity to P_{sum}. The significant positive influence of P_{sum} was present both at young and mature stages, at window-lengths of 11/19 to 81 yrs (Dambu Morii / Kronstadt) (Figs. **1, 2**). Nevertheless, these relationships showed a non-stationary character as, starting from the 1980s, silver fir trees from Dambu Morii and Kronstadt showed no sensitivity to P_{sum} (Fig. **2**). For the silver fir trees from Rasnov, the significant positive influence of P_{sum} was restricted between 1927 and 1961 (i.e., mature stage), at window-lengths of 51 to

81 yrs (Figs. **1, 2**). The significant effect of P_{sum} showed an overall negative trend both at Kronstadt and Rasnov (Fig. **2**).

Between the 1930s and the end of the 1980s, both at young and mature stages, silver fir trees from Dambu Morii also showed non-stationary significant tree-growth-climate relationships with the P_{sprsum} (positive; window-lengths of 37 to 81 yrs) and T_{sum} (negative; window-lengths of 43 to 81 yrs) (Figs. **1, 2**). Silver fir trees from Kronstadt also showed an overall negative response to T_{sum} from the end of the 1920s to the end of the 1980s (i.e., mature stage), at window-lengths of 51 to 81 yrs (Figs. **1, 2**). Instead, their significant positive response to P_{sprsum} showed a patchy pattern during the mature stage: i.e., from the beginning of the 1940s to the mid-1970s (window-lengths of 59 to 81 yrs), from the mid-1970s to the end of the 1980s (window-lengths of 35 to 49 yrs) and from 1991 to 1996 (window-lengths of 19 to 23 yrs) (Figs. **1, 2**). From the mid-1950s onwards, the response of the silver fir trees from Dambu Morii and Kronstadt to P_{sprsum} showed a positive trend (Fig. **2**). As for the silver fir trees from Rasnov, from the beginning of the 1930s to the end of the 1980s (i.e., mature stage) at window-lengths of 49 to 81 yrs, they showed non-stationary significant tree-growth-climate relationships only with T_{sum} (Figs. **1, 2**).

Black pine heat maps

Black pine trees were found to be mostly sensitive to P_{sprsum}, no matter the study site. Stationary significant positive tree-growth-climate relationships with P_{sprsum} were found both at young and mature stages, at window-lengths that varied between 11/15/19 and 81 yrs (Schei / Lempes / Racadau) (Figs. **3, 4**). These relationships showed discrete positive trends until the mid-1980s (Schei) or the mid-1990s (Lempes and Racadau), followed by a short period of weakening (i.e., until the beginning of the 2000s) and then an attempt to recover positive trends (Fig. **4**).

Black pine trees from all three study sites also showed a strong sensitivity to T_{sum} and T_{winter}, their effects largely overlapping in time. These relationships were non-stationary, being present only at mature stages (Figs. **3, 4**). At all three study sites, T_{sum} had an overall significant negative effect that lasted from the 1950s to the mid-1990s (Lempes) or to the beginning of the 2000s (Schei and Racadau), at window-lengths that varied between 25/27/15 and 81 yrs (Schei / Lempes / Racadau) (Figs. **3, 4**). The effect of T_{sum} showed a negative trend until the end of the 1980s when it started to show a positive trend (Fig. **4**). T_{winter} instead, had an overall significant positive effect at all three study sites: from the beginning of the 1950s to mid-1990s (window-lengths of 25 to 81 yrs; Schei); from the end of the 1940s to the end of the 1980s (window-lengths of 19 to 81 yrs; Lempes); and from the end of the 1940s to the mid-2000s (window-lengths of 17 to 81 yrs) with two gaps between 1996 and 2001 when these trees showed almost no sensitivity to T_{winter} (Racadau) (Figs. **3, 4**). The effect of T_{winter} mainly showed a discrete negative trend (Fig. **4**).

At mature stages, black pine trees from all study sites showed a low, non-stationary, positive sensitivity to P_{sum} (Figs. **3, 4**). At Schei and Racadau, the significant effect of P_{sum} followed a patchy pattern: from the beginning of the 1960s to the end of the 1970s at window-lengths of 65/73 to 75 yrs (Schei / Racadau) and from the beginning of the 1970s to the end of the 1980s at window-lengths of 13 to 31 yrs (Schei) and of 11 to 37 yrs (Racadau) (Figs. **3, 4**). Both at Schei and Racadau, from the beginning of the 1970s to the beginning of the 1980s, the effect of P_{sum} showed a strong positive trend but then this trend became negative (Fig. **4**). At Lempes, the significant effect of P_{sum} was restricted to the period comprised between 1973 and 1981 (window-lengths of 29 to 41 yrs) (Figs. **3, 4**).

At mature stages, black pine trees from Lempes and Racadau also showed some sensitivity (i.e., significant negative relationships) to T_{May}: from the mid-1950s to the beginning of the 1980s (Lempes) and from the mid-1960s to the end of the 1970s (Racadau) at window-lengths of 53/73 to 81 yrs (Lempes / Racadau) (Figs. **3, 4**). Starting from the beginning of the 1960s, the effect of T_{May} at Lempes showed a positive trend (Fig. **4**).

Scots pine heat maps

Similar to the black pine trees, Scots pine trees were found to be mostly sensitive to P_{sprsum}, no matter the study site. The stationary significant positive effect of P_{sprsum} extended over large periods of time (i.e., both at young and mature stages): from the mid-1910s (Codlea) or the 1920s (Lempes and Teliu) to the mid-2000s at window-lengths of 15/11/11 to 81 yrs (Codlea / Lempes / Teliu) (Figs. **5, 6**). At Codlea, the effect of P_{sprsum} showed a negative trend from the mid-1910s to the beginning of the 1920s, then it was maintained constant until the end of the 1990ss when it started to show again a negative trend (Fig. **6**). At Lempes, the effect of P_{sprsum} showed several negative and positive trends, the most extended positive trend being registered between the end of the 1940s and the beginning of the 1980s (Fig. **6**). At Teliu, the effect of P_{sprsum} also showed several negative and positive trends, with an extended positive trend between the beginning of the 1940s and the mid-1990s (Fig. **6**).

Scots pine trees from Codlea also showed a high non-stationary sensitivity to T_{May}, T_{winter} and T_{sum} (Figs. **5, 6**). The significant negative effect of T_{May} extended from the beginning of the 1920s to the end of the 1970s (window-lengths of 25 to 81 yrs) although starting with the mature stage, the sensitivity of Scots pine trees from Codlea to T_{May} was scarce (Fig. **5**). The effect of T_{May} at Codlea showed an almost continuous positive trend (Fig. **6**). The significant positive effect of $T_{winter.}$ extended from the mid-1930s to the end of the 1980s (window-lengths of 17 to 81 yrs), at both young and mature stages (Fig. **5**), showing a positive trend up until the mid-1950s and then a negative trend (Fig. **6**). Finally, the significant negative effect of T_{sum} extended from the end of the 1950s to the beginning of the 1990s (i.e., only at mature stages), at window-lengths of 25 to 81 yrs (Fig. **5**). The effect of T_{sum} showed a negative trend until the beginning of the 1980s when this trend started to be positive (Fig. **6**).

T_{May} was the second seasonal climatic variable to which Scots pine trees from Lempes showed sensitivity both at young and mature stages. This non-stationary significant negative effect of T_{May} extended from the mid-1930s to the beginning of the 1980s (window-lengths of 27 to 81 yrs) (Fig. **5**) and showed a positive trend (Fig. **6**). Instead, the sensitivity of the Scots pine trees from Lempes to T_{sum} and T_{winter} was very reduced and covered short periods of time during the mature stage, i.e., from 1977 to 1984 (window-lengths of 43 to 45 yrs) and from 1957 to 1965 (window-lengths of 27 to 37 yrs), respectively (Figs. **5, 6**).

Scots pine trees from Teliu were also highly sensitive to T_{May} and T_{winter}. The significant negative effect of T_{May} extended from the beginning of the 1930s to the end of the 1970s (i.e., both at young and mature stages), at window-lengths of 25 to 81 yrs.

Nevertheless, starting from the beginning of the 1960s it was restricted to large time-scales (window-lengths of 67 to 81 yrs) (Figs. **5, 6**). The effect of T_{May} at this study sites showed a positive trend (Fig. **6**). As for the significant positive effect of T_{winter}, it extended from the end of the 1940s to the mid-1980s (i.e., mostly during the mature stage), at window-lengths of 11 to 71 yrs (Figs. **5, 6**). The effect of T_{winter} showed a positive trend up until the 1960s when it started to show a negative trend (Fig. **6**).

DISCUSSION

This study is an important step towards an improved understanding on the stationary and non-stationary character of the tree-growth-climate-relationships of silver fir, black pine and Scots pine, three of the most representative conifer species of the European forests. Specifically, it shows that the growth of each of these conifer species is largely dominated (i.e., both at young and mature stages) by only one seasonal climatic variable (i.e., stationary tree-growth-climate relationships), i.e., T_{winter} in the case of the *Abies* genus and P_{sprsum} in the case of the *Pinus* genus. It further shows that the rest of the tree-growth-climate relationships that were found, although significant, had a non-stationary character and tree growth decoupled at some point in time (i.e., mostly in the 1980s and 1990s) from them. This decoupling from climatic variables or loss of sensitivity, a phenomenon that has been previously reported in different studies (e.g., Briffa *et al.*, 1998; Carrer & Urbinati, 2006; D'Arrigo *et al.*, 2008; Babst et al., 2019), is critical to be taken into account in order to better understand tree-growth-climate relationships (Peltier & Ogle, 2020; Wilmking *et al.*, 2020). The need to conduct studies using powerful statistical tools such as heat maps analyses based on rolling window correlations, not previously used in dendrochronological studies to the best of our knowledge, becomes evident as it allows to evaluate in detail the evolution and stability of the tree-growth-climate-relationships over time. Such studies are thus of upmost importance if we want to better understand the impact of climate change on the future forest tree growth and dynamics based on how they responded to stressful climatic conditions in the past (Babst *et al.*, 2017; 2019).

The results of the heat maps analyses based on rolling window correlations allowed a better understanding of the seasonal climatic variables that govern the growth of the studied *Abies* and *Pinus* genera by deepening into the obtained tree-growth-climate-relationships and their stationary and non-stationary character. Accordingly, silver fir trees, all growing at high elevations where usually low temperatures limit tree growth, have been all found (i.e., no matter the study site) to be highly sensitive (i.e., stationary positive tree-growth-climate relationships) to T_{winter}. Black pine and Scots pine instead, all growing at low-to-mid elevations where precipitation during the growing season may limit tree growth, have been all found (i.e., no matter the study site) to be highly sensitive (i.e., stationary positive tree-growth-climate relationships) to P_{sprsum}. In the case of silver fir, it looks like this species is taking advantage of the significant T_{winter} increase (Table **2**) that is probably determined by the significant increasing trend of the winter mean maximum temperature registered in the Braşov area (Tomozeiu *et al.*, 2002). Additionally, winter warming over Eastern Europe has been also confirmed by Ionita & Nagavciuc (2021), being further backed-up by the decreasing number of days with snow coverage and by the decrease of the snow depth (i.e., drier winters) that have been found for the Romanian Carpathians (Micu, 2009; Birsan & Dumitrescu, 2014). In line with these findings we now have some piece of evidence that the significant positive growth trends, previously found for silver fir trees growing in Romania (Bouriaud & Popa, 2009; Gazol *et al.*, 2015; Hereş *et al.*, 2021), might be probably explained by the significant positive effect of T_{winter}. Given that silver fir is a late frost sensitive species, the significant T_{winter} increase probably prevents deep soil frost creating optimum conditions at the beginning of the growing season (Wolf, 2003; Kern & Popa, 2007; Tinner *et al.*, 2013). For black pine, Levanič *et al.* (2013) have also found that May to July precipitations along with the summer standardized precipitation index (SPI) are critical for their growth. Additionally, the sensitivity of black pine trees to the spring-summer precipitation of the current-to-growth year has been also highlighted in other studies from central-eastern Europe (e.g., Strumia *et al.*, 1997; Leal *et al.*, 2008; Móricz *et al.*, 2018; Stajič & Kazimirovič, 2018). Scots pine's dependence on precipitation during the growing season has been also previously reported for Romania (Bouriaud & Popa, 2009; Sidor *et al.*, 2019) indicating that this species, although considered to be drought-resistant (Ellenberg, 1988), is actually very susceptible to be affected by dry conditions (Bhuyan *et al.*, 2017). Altogether, the obtained results indicate that black pine trees from Schei, Lempes and Racadau and Scots pine trees from Codlea, Lempes and Teliu have been permanently growing under limited water availability conditions and continue to do so.

The results of the heat maps analyses based on rolling window correlations have also revealed that non-stationary tree-growth-climate-relationships may actually be more common and divers than stationary ones. For instance, silver fir trees have been sensitive at some point in time, i.e., mainly when the effect of T_{winter} slightly weakened between the 1930s and the mid-1970s, to water limited conditions (i.e., P_{sprsum}, P_{sum}) but also to warm summers (T_{sum}). Overall, silver fir's sensitivity to P_{sprsum} and P_{sum} largely overlapped in time with the period when these trees also showed sensitivity to T_{sum}. Water limited conditions along with the effect of T_{sum} may have caused increased vapour pressure deficit and/or atmospheric drought conditions to which silver fir trees have been found to be very sensitive (Aussenac, 2002; Gazol *et al.*, 2015) and even intolerant, no matter the elevation (Bhuyan *et al.*, 2017). In the case of black pine and Scots pine instead, the temperature-derived seasonal climatic variables (T_{winter}, T_{sum}, T_{May}) have been found to have mainly played a critical role at some point in time. Specifically, for black pine, the significant negative effect of T_{sum} probably translated into a low nutrient storage and thus into a negative effect on the tree ring formed within the next growing season (Shishkova & Panayotov, 2013), a response that could not be compensated by the positive effect of T_{winter} and that was further backed up by the negative effect of T_{May}. For Scots pine, the obtained results are in line with previous findings (Hereş *et al.*, 2021) and show that, overall, the climatic conditions of the previous-to-growth year do not seem to have ever had a critical effect on their growth. Instead, T_{winter} and T_{May}, two seasonal climatic variables previously reported as being critical for Scots pine growth in Romania (Nagavciuc *et al.*, 2019; Sidor *et al.*, 2019, 2020), had significant effects on their growth. Nevertheless, the positive effect of T_{winter} was very limited comparing with the negative effect of T_{May}, despite the fact that T_{winter} registered a marginally significant positive trend (Table **2**). Summing up, unlike stationary tree-growth-climate-relationships, which were well conserved within trees belonging to a given genus (i.e., *Abies* and *Pinus*), non-stationary tree-growth-climate-relationships were species- and even site-dependent. This suggests that different mechanisms, processes and causes (e.g., age, different physiological states, phenological events, species' specific hydraulic traits, drought stress and legacies, access to deep soil water sources, non-structural carbohydrates resources, site ecology, anthropogenic causes) along with local environmental conditions (e.g., soil, microclimate) determine to some extent the transient shifts on how different seasonal climatic variables control tree growth (Carrer & Urbinati, 2004; Cook *et al.*, 2004; D'Arrigo *et al.*, 2008; Leonelli *et al.*, 2009; Coppola *et al.*, 2012; Peltier & Ogle, 2020; Wilmking *et al.*, 2020). Additionally, the emergence of these non-stationary tree-growth-climate-relationships overlapped in some cases with periods when the stationary tree-growth-climate-relationships weakened or with periods when several intense and extended in time climatic anomalies (i.e., "+" and "-") registered (Table **S1**; Figs. **1, 3, 5**). Nevertheless, this was not necessarily the rule, a clear cause-effect relationship in this regard being difficult to be established. This last statement stands correct even in the case of the 1997/1998 significant break-points that marked the starting point of a steeper trend for T_{sum}, a trend that is probably determined by the significant increasing trend of the summer mean maximum temperature in the Braşov area (Tomozeiu *et al.*, 2002) and of the mean air temperature in Eastern Europe (Ionita & Nagavciuc, 2021).

Interestingly, for all three studied species, most of the non-stationary tree-growth-climate-relationships have stopped in the 1980s and 1990s when tree growth decoupled from these seasonal climatic variables. In the case of the silver fir trees, this loss of sensitivity seems to be compensated, at least for the moment, by the effect of T_{winter}. Indeed, living silver fir trees from Dambu Morii, Kronstadt and Rasnov have been previously found to show significant positive growth trends and perform well in terms of resilience to severe drought events (Hereş *et al.*, 2021). In the case of the black pine and Scots pine trees instead, this loss of sensitivity might be probably related with their loss of vigour. Indeed, living black pine trees from Schei, Lempes and Racadau and Scots pine trees from Codlea, Lempes and Teliu have been previously found to show significant negative growth trends and low resilience to severe drought events (Hereş *et al.*, 2021), patterns that put their future at these study sites under question as trees that show low growth resilience to disturbances eventually die (DeSoto *et al.*, 2020; Peltier & Ogle, 2020).

To conclude, heat maps analyses based on rolling window correlations have proven to be a powerful and robust statistical tool to evaluate the evolution and stability of tree-growth-climate relationships along the lifetime of the trees. To the best of our knowledge, this statistical tool has not been previously used in dendrochronological studies but proves to be very useful as it disentangles the stationary and/or non-stationary character of the tree-growth-climate relationships. Thus, based on the obtained results we could clearly show that, although significant tree-growth-climate relationships might be obtained with different seasonal climatic variables, only two of those seasonal climatic variables actually govern the growth of the studied *Abies* and *Pinus* genera (i.e., stationary tree-growth-climate relationships), i.e., T_{winter} and P_{sprsum}, respectively. Interestingly, all these stationary tree-growth-climate relationships have not been found to be age-dependent (see Carrer & Urbinati, 2004), being present both at young and mature stages. Nevertheless, it needs to stressed out the fact that this study did not specifically look for the effect of age on the obtained tree-growth-climate relationships, as we used a rather arbitrary way to define the “young” and “mature” stages based on literature (Şofletea & Curtu, 2007) and no real old trees have been considered. Although this study might be seen as a rather local one, the obtained results are of upmost importance as they add a critical piece of information to the understanding of the tree-growth-climate relationships of silver fir, black pine and Scots pine, three of the most representative conifer species of the European forests. Furthermore, they put into perspective the critical aspect of looking at the stationary and/or non-stationary character of the tree-growth-climate relationships, an essential aspect if we want to better interpret future tree-growth-climate relationships and thus better understand the impact of climate change on the future forest tree growth and dynamics based on how they responded to different climatic drivers in the past.

TABLES

Table 1. Main characteristics of the nine study sites and the three conifer species.

Species	Site	Coordinates	Elevation (m a.s.l)	No. of trees	Period (years)	Year of maturity
silver fir	Dambu Morii	45°34'47.86"N 25°37'38.95"E	825	27	1901 - 2015	1953
	Kronstadt	45°34'59.54"N 25°36'13.51"E	945	29	1901 - 2015	1931
	Rasnov	45°29'32.48"N 25°25'42.18"E	1250	28	1901 - 2015	1925
black pine	Schei	45°37'56.32"N 25°34'24.65"E	456	21	1929 - 2015	1943
	Lempes	45°43'31.50"N 25°38'41.58"E	561	27	1928 - 2015	1941
	Racadau	45°37'58.37"N 25°35'59.84"E	753	23	1928 - 2015	1947
Scots pine	Codlea	45°42'9.70"N 25°25'53.79"E	712	30	1907 - 2015	1949
	Lempes	45°44'6.75"N 25°38'38.47"E	545	25	1921 - 2015	1957
	Teliu	45°41'55.69"N 25°51'37.09"E	606	26	1917 - 2015	1949

No. of trees, number of individuals considered to calculate each residual ring-width index series ($\mathrm{RWI}_{\mathrm{residual}}$); ***Period (years)***, period covered by each of the nine $\mathrm{RWI}_{\mathrm{residual}}$ series; ***Year of maturity***, the year that marks the beginning of maturity at each of the nine study sites (i.e., 71 yrs old for the silver fir trees; 31 yrs old for the black pine trees and 51 yrs old for the Scots pine trees; Şofletea & Curtu, 2007).

Table 2. Seasonal climatic variables calculated separately for each of the three conifer species and for each of the nine study sites.

Seasonal climatic variable	Species	Site	Months	Mean ± SD	Period (years)	Linear trend
spring-summer precipitation of the current-to-growth year (**P$_{\mathbf{sprsum}}$**)	silver fir	Dambu Morii, Kronstadt	Mar (t) – Jul (t)	341.80 ± 66.36	1901 - 2015	not significant
		Rasnov	Mar (t) – Jul (t)	465.40 ± 92.01	1901 – 2015	not significant
	black pine	Schei, Lempes, Racadau	Apr (t) – Aug (t)	384.50 ± 73.94	1901 – 2015	not significant
	Scots pine	Codlea	Mar (t) – Jul (t)	363.60 ± 68.42	1901 – 2015	not significant
		Lempes, Teliu	Mar (t) – Jul (t)	341.80 ± 66.36	1901 – 2015	not significant
summer precipitation of the previous-to-growth year (**P$_{\mathbf{sum}}$**)	silver fir	Dambu Morii, Kronstadt	Jul (t-1) – Aug (t-1)	164.70 ± 47.12	1902 - 2015	not significant
		Rasnov	Jul (t-1) – Aug (t-1)	207.10 ± 64.99	1902 - 2015	not significant
	black pine	Schei, Lempes, Racadau	Aug (t-1) – Sep (t-1)	123.42 ± 44.47	1902 - 2015	not significant
	Scots pine	Codlea	Aug (t-1) – Sep (t-1)	130.95 ± 46.39	1902 - 2015	not significant
		Lempes, Teliu	Aug (t-1) – Sep (t-1)	123.42 ± 44.47	1902 - 2015	not significant
summer temperature of	silver fir	Dambu Morii, Kronstadt	Jul (t-1) – Sep (t-1)	16.64 ± 0.95	1902 - 2015	**significant positive**
		Rasnov	Jul (t-1) – Sep (t-1)	14.71 ± 0.96	1902 – 2015	**significant positive**

the previous-to-growth year **(T_{sum})**	black pine	Schei, Lempes, Racadau	Aug (t-1) – Sep (t-1)	15.83 ± 1.10	1902 – 2015	**significant positive**
	Scots pine	Codlea	Aug (t-1) – Sep (t-1)	15.50 ± 1.11	1902 – 2015	**significant positive**
		Lempes, Teliu	Aug (t-1) – Sep (t-1)	15.83 ± 1.10	1902 – 2015	**significant positive**
winter temperature **(T_{winter})**	silver fir	Dambu Morii, Kronstadt	Nov (t-1) – Mar (t)	-0.68 ± 1.45	1902 – 2015	**significant positive**
		Rasnov	Nov (t-1) – Mar (t)	-1.56 ± 1.41	1902 – 2015	**significant positive**
	black pine	Schei, Lempes, Racadau	Dec (t-1) – Mar (t)	-1.62 ± 1.71	1902 – 2015	**marginally significant positive ($p = 0.05$)**
	Scots pine	Codlea	Dec (t-1) – Mar (t)	-1.58 ± 1.72	1902 – 2015	**marginally significant positive ($p = 0.06$)**
		Lempes, Teliu	Dec (t-1) – Mar (t)	-1.62 ± 1.71	1902 – 2015	**marginally significant positive ($p = 0.05$)**
May temperature of the current-to-growth year **(T_{May})**	silver fir	Dambu Morii, Kronstadt	May (t)	13.40 ± 1.48	1901 - 2015	not significant
		Rasnov	May (t)	11.20 ± 1.47	1901 – 2015	not significant
	black pine	Schei, Lempes, Racadau	May (t)	13.40 ± 1.48	1901 – 2015	not significant
	Scots pine	Codlea	May (t)	13.10 ± 1.50	1901 – 2015	not significant

		Lempes, Teliu	May (t)	13.40 ± 1.48	1901 - 2015	not significant

Months, the different months of the year that were used to calculate the different seasonal climatic variables (separately for each species and study site) based on the results published in Hereş *et al*., 2021 and in Bouriaud & Popa, 2009 (cf. *Previous published analyses and results on tree-growth-climate relationships*); ***Mean (SD)***, mean values and their corresponding standard deviation values, i.e., covering the time intervals mentioned in the ***Period (years)*** column, for each of the seasonal climatic variables; ***Linear trend***, indicates if the calculated seasonal climatic variables had or not a significant trend, based on linear regression analyses, from 1901/1902 to 2015.

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AUTOR CONTRIBUTION

AMH, JCY and JMPM planned and conceived the research, designed the methodology and performed the statistical analyses. ICP and AMP measured the tree rings and compiled the ring-width database. AMH drafted and led the manuscript writing with continuous inputs from JCY and revision from JCY, JMPM, ICP and AMP. All authors agreed with the final version of the manuscript.

DATA AVAILABILITY

Data available on request from the authors, i.e., the data that support the findings of this study are available from the corresponding author upon reasonable request.

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FIGURE CAPTIONS

Fig. 1 Heat maps showing corrected p-values (i.e., through the BH false discovery rate method described in Benjamini & Hochberg 1995) that were obtained from conducting rolling window Spearman correlations between **silver fir** $\mathrm{RWI}_{\mathrm{residual}}$ (residual ring-width index) series from **Dambu Morii, Kronstadt and Rasnov** study sites and seasonal climatic variables ($\mathbf{P}_{\mathbf{sprsum}}$, spring-summer precipitation of the current-to-growth year; $\mathbf{P}_{\mathbf{sum}}$, summer precipitation of the previous-to-growth year; $\mathbf{T}_{\mathbf{sum}}$, summer temperature of the previous-to-growth year; $\mathbf{T}_{\mathbf{winter}}$, winter temperature). The reddish and blueish colours indicate significant ($p < 0.05$) positive and negative, respectively, tree-growth-climate relationships, while the greenish colours indicate non-significant ($p > 0.05$) tree-growth-climate relationships. Window-lengths (yrs) are indicated on the y-axis, while the x-axis shows the period considered to run the analyses (see Tables **1, 2**). Additionally, below the x-axis, the young and mature stages are indicated for each of the study sites.

Fig. 2 Trends, over the studied periods (left hand panels) and over the considered window-lengths (i.e., 11 to 81 yrs; right hand panels), of the Spearman correlation coefficients resulted from the heat map analyses based on rolling window correlations that were conducted between **silver fir** $\mathrm{RWI}_{\mathrm{residual}}$ (residual ring-width index) series from **Dambu Morii, Kronstadt and Rasnov** study sites and seasonal climatic variables

(**P_{sprsum}**, spring-summer precipitation of the current-to-growth year; **P_{sum}**, summer precipitation of the previous-to-growth year; **T_{sum}**, summer temperature of the previous-to-growth year; **T_{winter}**, winter temperature). Different colours and symbols indicate different seasonal climatic variables. Only significant Spearman correlation coefficients are shown.

Fig. 3 Heat maps showing corrected p-values (i.e., through the BH false discovery rate method described in Benjamini & Hochberg 1995) that were obtained from conducting rolling window Spearman correlations between **black pine** $RWI_{residual}$ (residual ring-width index) series from **Schei, Lempes and Racadau** study sites and seasonal climatic variables (**P_{sprsum}**, spring-summer precipitation of the current-to-growth year; **P_{sum}**, summer precipitation of the previous-to-growth year; **T_{sum}**, summer temperature of the previous-to-growth year; **T_{winter}**, winter temperature; **T_{May}**, May temperature of the current-to-growth year). The reddish and blueish colours indicate significant ($p < 0.05$) positive and negative, respectively, tree-growth-climate relationships, while the greenish colours indicate non-significant ($p > 0.05$) tree-growth-climate relationships. Window-lengths (yrs) are indicated on the y-axis, while the x-axis shows the period considered to run the analyses (see Tables **1, 2**). Additionally, below the x-axis, the young and mature stages are indicated for each of the study sites.

Fig. 4 Trends, over the studied periods (left hand panels) and over the considered window-lengths (i.e., 11 to 81 yrs; right hand panels), of the Spearman correlation coefficients resulted from the heat map analyses based on rolling window correlations that were conducted between **black pine** $RWI_{residual}$ (residual ring-width index) series from **Schei, Lempes and Racadau** study sites and seasonal climatic variables (**P_{sprsum}**, spring-summer precipitation of the current-to-growth year; $\mathbf{P_{sum}}$, summer precipitation of the previous-to-growth year; $\mathbf{T_{sum}}$, summer temperature of the previous-to-growth year; $\mathbf{T_{winter}}$, winter temperature; $\mathbf{T_{May}}$, May temperature of the current-to-growth year). Different colours and symbols indicate different seasonal climatic variables. Only significant Spearman correlation coefficients are shown.

Fig. 5 Heat maps showing corrected p-values (i.e., through the BH false discovery rate method described in Benjamini & Hochberg 1995) that were obtained from conducting rolling window Spearman correlations between **Scots pine** $\mathrm{RWI_{residual}}$ (residual ring-width index) series from **Codlea, Lempes and Teliu** study sites and seasonal climatic variables ($\mathbf{P_{sprsum}}$, spring-summer precipitation of the current-to-growth year; $\mathbf{T_{sum}}$, summer temperature of the previous-to-growth year; $\mathbf{T_{winter}}$, winter temperature; $\mathbf{T_{May}}$, May temperature of the current-to-growth year). The reddish and blueish colours indicate significant ($p < 0.05$) positive and negative, respectively, tree-growth-climate relationships, while the greenish colours indicate non-significant ($p > 0.05$) tree-growth-climate relationships. Window-lengths (yrs) are indicated on the y-axis, while the x-axis shows the period considered to run the analyses (see Tables **1, 2**). Additionally, below the x-axis, the young and mature stages are indicated for each of the study sites.

Fig. 6 Trends, over the studied periods (left hand panels) and over the considered window-lengths (i.e., 11 to 81 yrs; right hand panels), of the Spearman correlation coefficients resulted from the heat map analyses based on rolling window correlations that were conducted between **Scots pine** $\mathrm{RWI_{residual}}$ (residual ring-width index) series from **Codlea, Lempes and Teliu** study sites and seasonal climatic variables ($\mathbf{P_{sprsum}}$, spring-summer precipitation of the current-to-growth year; $\mathbf{T_{sum}}$, summer temperature of the previous-to-growth year; $\mathbf{T_{winter}}$, winter temperature; $\mathbf{T_{May}}$, May temperature of the current-to-growth year). Different colours and symbols indicate different seasonal climatic variables. Only significant Spearman correlation coefficients are shown.

SUPPLEMENTARY MATERIAL

FIGURE CAPTIONS

Fig. S1 Residual ring-width index series ($RWI_{residual}$) calculated based on the tree-rings measurements that were made on the wood cores sampled from silver fir (Dambu Mori, Kronstadt and Rasnov study sites), black pine (Schei, Lempes and Racadau study sites) and Scots pine (Codlea, Lempes and Teliu) trees growing in the Romanian Carpathians (i.e., Braşov region). The sample depth shows the number of trees included in each of the nine $RWI_{residual}$ series.

Fig. S2 Climagrams of the nine study sites that were grouped in three datasets depending on the grid of the CRU (TS v. 4; Harris *et al*., 2020) database: Dambu Morii, Kronstadt, Schei, Lempes, Racadau and Teliu study sites (**a** panel), Rasnov (**b** panel) and Codlea (**c** panel) (cf. *Climatic data*). Results of ANOVA and Kruskal-Wallis analyses showing differences in temperature (T °C) and precipitation (P mm), respectively, between the three climatic datasets mentioned above (**d** panel).

Fig. S3 Significant break-points detected within the trend of the $\mathbf{T_{sum}}$ (summer temperature of the previous-to-growth year) seasonal climatic variable, i.e., yrs 1997 for the silver fir (Dambu Morii, Kronstadt and Rasnov) study sites (**a** and **b** panels) and 1998 for the black pine (Schei, Lempes and Racadau) and Scots pine (Codlea, Lempes and Teliu) study sites (**c, d** and **e** panels). The grey lines show raw $\mathbf{T_{sum}}$ data, while the black lines show the fitted regression models with segmented relationships between seasonal climatic variables and time (i.e., yrs from 1901/1902 to 2015).

Table S1. Climatic anomalies (i.e., deviations from the 1901/1902 -- 2015 overall mean values of the seasonal climatic variables).

Seasonal climatic variable	**Species**	**Site**	**Period covered by the anomaly (yrs)**	**Sign of the anomaly**
spring-summer precipitation of the current-to-growth year (**P_{sprsum}**)	silver fir	Dambu Morii Kronstadt	beginning of the 1910s **to** the end of the 1910s	“+”
			beginning of the 1940s **to** the beginning of the 1950s	“-”
			end of the 1960s **to** mid-1980s	“+”
	black pine	Schei Lempes Racadau	beginning of the 1940s **to** the end of the 1940s	“-”
			1960 **to** the end of the 1960s	“-”
			end of the 1960s **to** mid-1980s	“+”
			mid-1980s **to** the end of the 1980s	“-”
			end of the 1990s **to** the beginning of the 2000s	“-”
	Scots pine	Codlea	beginning of the 1910s **to** 1916	“+”
			end of the 1930s **to** the beginning of the 1940s	“+”
			beginning of the 1940s **to** the beginning of the 1950s	“-”
			end of the 1960s **to** the beginning of the 1980s	“+”

			end of the 1930s **to** the beginning of the 1940s	“+”
		Lempes	beginning of the 1940s **to** the end of the 1940s	“-”
		Teliu	end of the 1960s **to** 1976	“+”
			end of the 1970s **to** mid-1980s	“+”
summer precipitation of the previous-to-growth year (**P$_{\text{sum}}$**)			beginning of the 1920 **to** mid-1920s	“-”
		Dambu Morii	beginning of the 1940 **to** the end of the 1940s	“-”
	silver fir	Kronstadt	end of the 1950s **to** the end of the 1960s	“-”
		Rasnov	end of the 1960s **to** mid-1980s	“+”
			mid-1980s **to** the end of the 1990s	“-”
			beginning of the 2000 **to** 2010	“+”
			beginning of the 1930s **to** the beginning of the 1940s	“+”
		Schei	beginning of the 1940 **to** mid-1950s	“-”
	black pine	Lempes	end of the 1950s **to** the end of the 1960s	“-”
		Racadau	end of the 1960s **to** the beginning of the 1970s	“+”
			end of the 1970s **to** the beginning of the 1980s	“+”

			mid-1990s **to** the end of the 2000s	“+”
summer temperature of the previous-to-growth year (**T**$_{\mathbf{sum}}$)	silver fir	Dambu Morii Kronstadt Rasnov	beginning of the 1900s **to** the end of the 1920s	“-”
			beginning of the 1940s **to** the end of the 1950s	“+”
			end of the 1950s **to** the end of the 1980s	“-”
			end of the 1990s **to** mid-2010s	“+”
	black pine	Schei Lempes Racadau	beginning of the 1950s **to** the end of the 1950s	“+”
			end of the 1950s **to** the beginning of the 1960s	“-”
			1976 **to** the beginning of the 1980s	“-”
			1996 **to** 2000	“-”
			2000 **to** mid-2010s	“+”
	Scots pine	Codlea	beginning of the 1910s **to** the end of the 1910s	“-”
			beginning of the 1940s **to** the end of the 1950s	“+”
			mid-1960s **to** the beginning of the 1980s	“-”
			2000 **to** mid-2010s	“+”
		Lempes	1940 **to** 1943	“-”

			1943 **to** the end of the 1940s	“+”
			beginning of the 1950s **to** the end of the 1950s	“+”
			1976 **to** 1982	“-”
			mid-1990s **to** the end of the 1990s	“-”
			end of the 1990s **to** mid-2010s	“+”
winter temperature (**T**$_{\textbf{winter}}$)	silver fir	Dambu Morii Kronstadt Rasnov	end of the 1920s **to** 1935	“-”
			end of the 1930s **to** the end of the 1940s	“-”
			end of the 1960s **to** the beginning of the 1980s	“+”
			end of the 1990s **to** mid-2010s	“+”
	black pine	Schei Lempes Racadau	end of the 1920s **to** 1935	“-”
			end of the 1930s **to** the end of the 1940s	“-”
			beginning of the 1960s **to** mid-1960s	“-”
			beginning of the 1970s **to** the end of the 1970s	“+”
			beginning of the 1980s **to** the end of the 1980s	“-”
			end of the 1980s **to** the beginning of the 1990s	“+”

			mid-2000s **to** mid-2010s	“+”
	Scots pine	Codlea	beginning of the 1910s **to** the beginning of the 1920	“+”
			end of the 1920s **to** mid-1930s	“-”
			end of the 1930s **to** the end of the 1940s	“-”
			beginning of the 1960s **to** the beginning of the 1970s	“-”
			beginning of the 1970s **to** the beginning of the 1980s	“+”
			mid-2000s **to** mid-2010	“+”
		Lempes Teliu	end of the 1920s **to** mid-1930s	“-”
			end of the 1930s **to** the end of the 1940s	“-”
			beginning of the 1960s **to** the end of the 1960s	“-”
			beginning of the 1970s **to** the end of the 1970s	“+”
			beginning of the 1980s **to** the end of the 1980s	“-”
			mid-2000s **to** mid-2010	“+”
May temperature of the current-to-growth year	black pine	Lempes Racadau	end of the 1920s **to** the end of the 1930s	“+”
			end of the 1930s **to** mid-1940s	“-”

(T_{May})			mid-1940s **to** the beginning of the 1950s	“+”
			1970 **to** the beginning of the 1980s	“-”
			end of the 1980s **to** the beginning of the 1990s	“-”
			2000 **to** mid-2010	“+”
	Scots pine	Codlea	beginning of the 1910s **to** the beginning of the 1920s	“-”
			beginning of the 1920s **to** the end of the 1920s	“+”
			end of the 1920s **to** the end of the 1930s	“+”
			beginning of the 1950s **to** the end of the 1960s	“-”
			beginning of the 1970s **to** the beginning of the 1980s	“-”
			end of the 1990s **to** mid-2010s	“+”
		Lempes	end of the 1930s **to** mid-1940s	“-”
			mid-1940s **to** the beginning of the 1950s	“+”
			beginning of the 1970s **to** the beginning of the 1980s	“-”
			2000 **to** mid-2010	“+”
		Teliu	beginning of the 1920s **to** the end of the 1920s	“+”

			end of the 1920s **to** the end of the 1930s	“+”
			end of the 1930s **to** mid-1940s	“-”
			mid-1940s **to** the beginning of the 1950s	“+”
			beginning of the 1970s **to** the beginning of the 1980s	“-”
			2000 **to** mid-2010	“+”

Figure 1

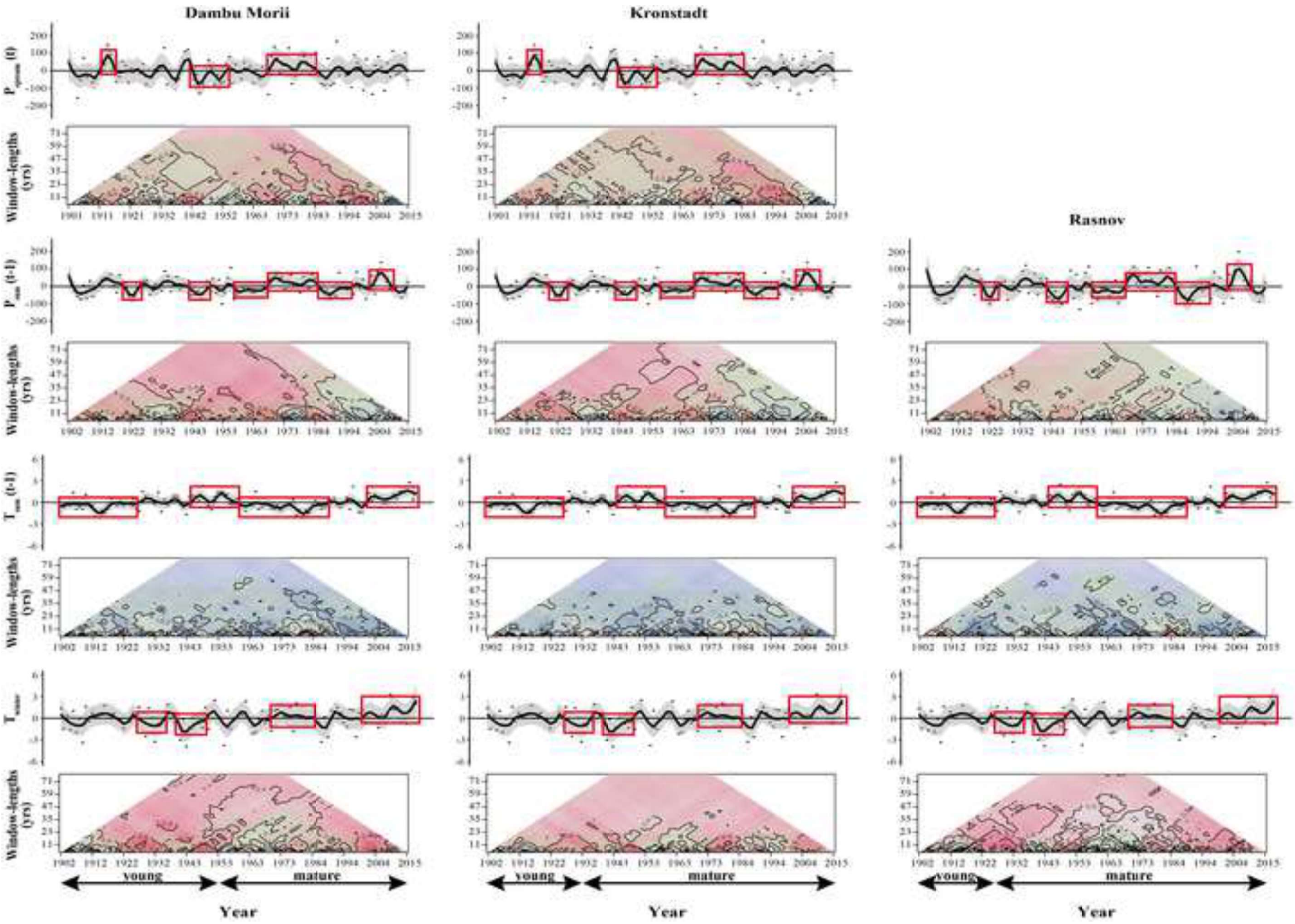
Dambu Morii
Kronstadt
Rasnov
P_spring (t)
Window-lengths (yrs)
P_sum (t-1)
Window-lengths (yrs)
T_sum (t-1)
Window-lengths (yrs)
T_winter
Window-lengths (yrs)
200
100
0
-100
-200
6
3
0
-3
-6
71
59
47
35
23
11
1901 1911 1921 1932 1942 1952 1963 1973 1983 1994 2004 2015
1902 1912 1922 1932 1943 1953 1963 1973 1984 1994 2004 2015
young
mature
Year

Figure 2

Click here to access/download;Figure;Fig 2_Heres et al.tif

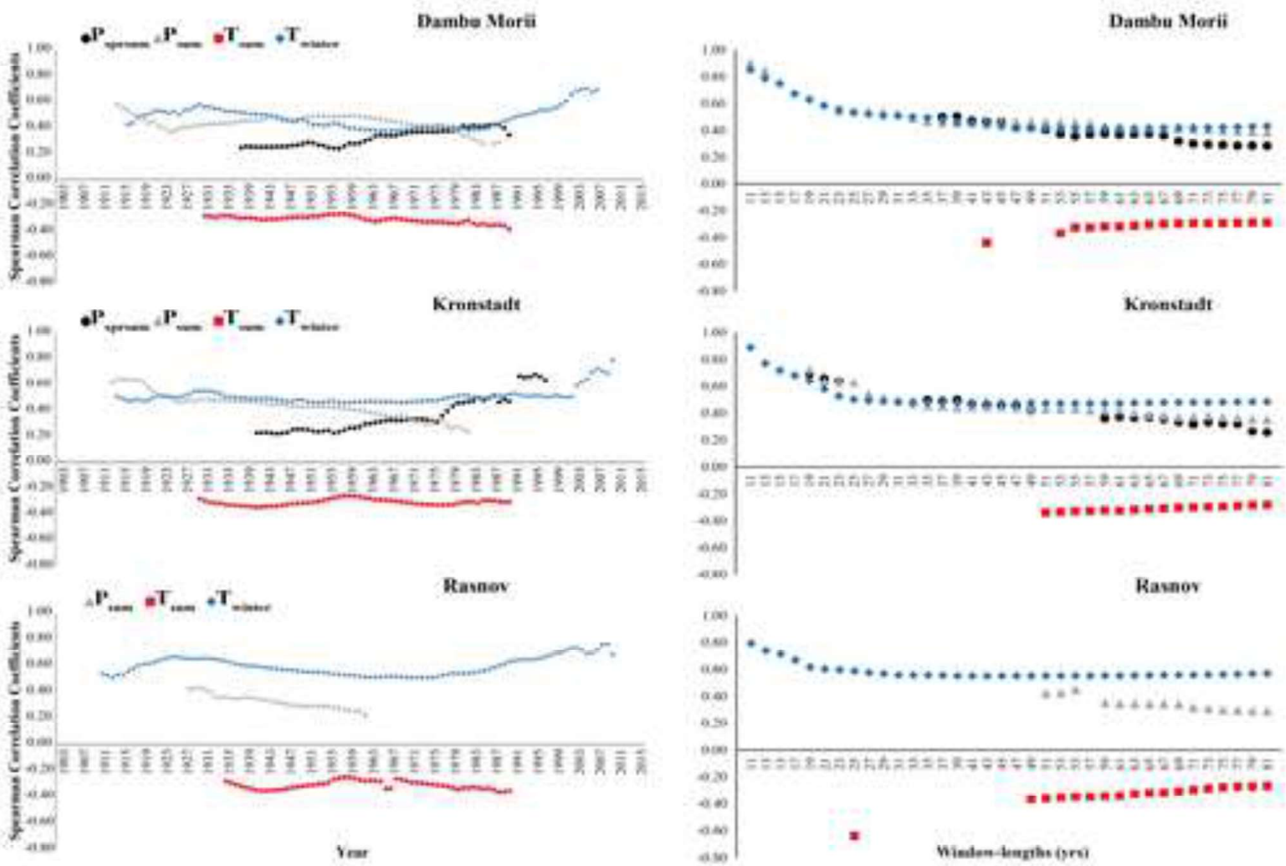

Figure 3

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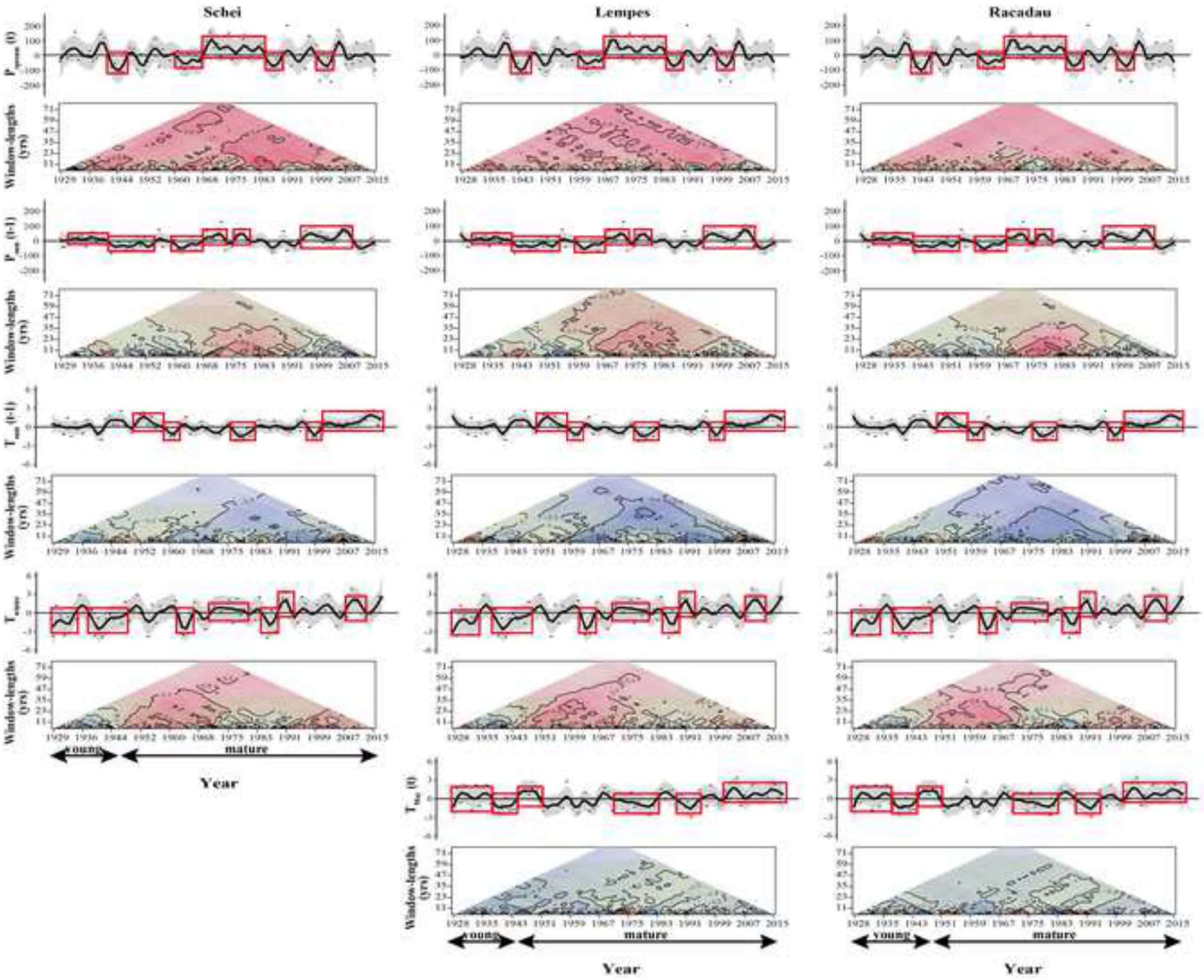

Figure 4

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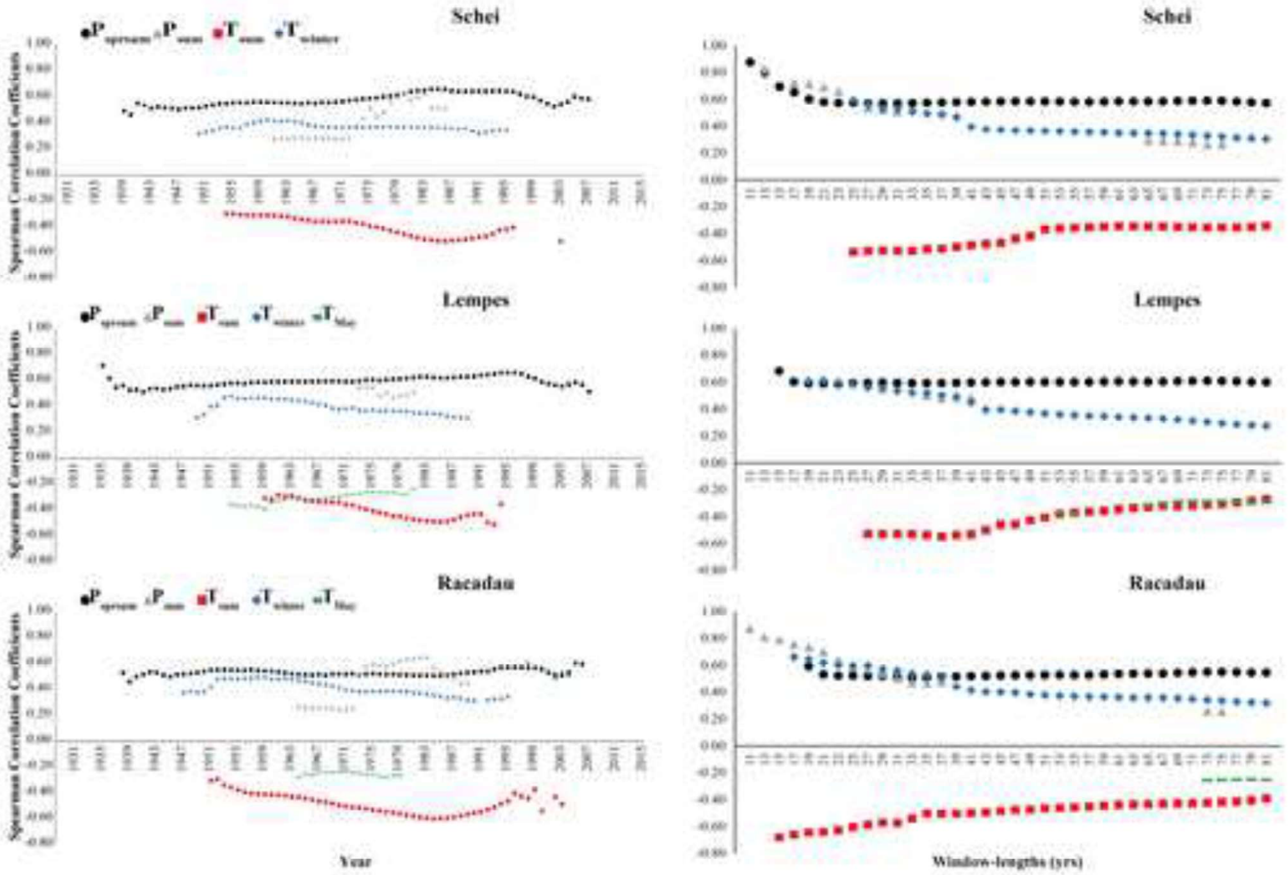

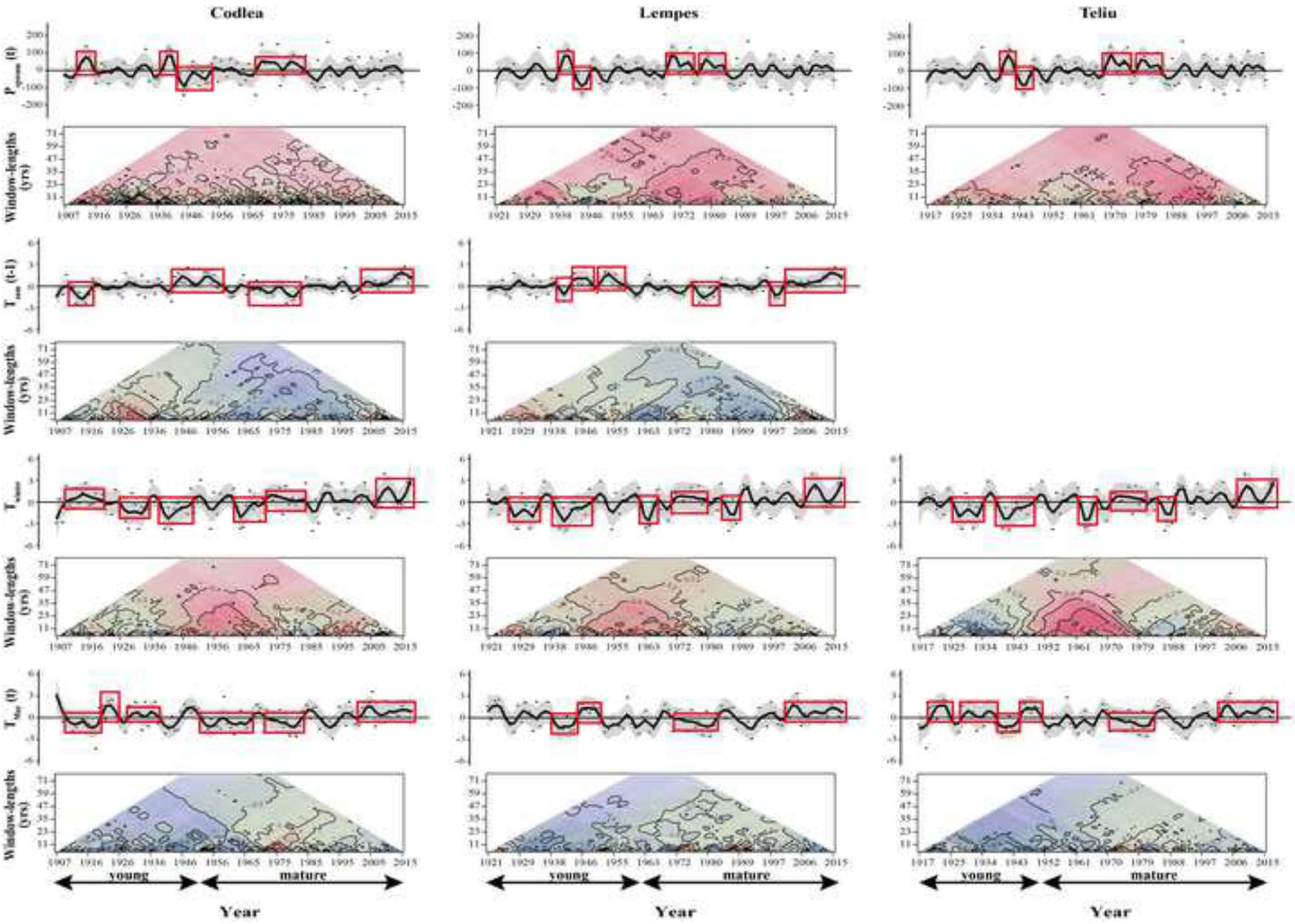
Codlea
Lempes
Teliu
P_{spring} (t)
200
100
0
-100
-200
T_{sum} (t-1)
T_{winter}
T_{May} (t)
6
3
0
-3
-6
Window-lengths (yrs)
71
59
47
35
23
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1907 1916 1926 1936 1946 1956 1965 1975 1985 1995 2005 2015
1921 1929 1938 1946 1955 1963 1972 1980 1989 1997 2006 2015
1917 1925 1934 1943 1952 1961 1970 1979 1988 1997 2006 2015
young
mature
Year

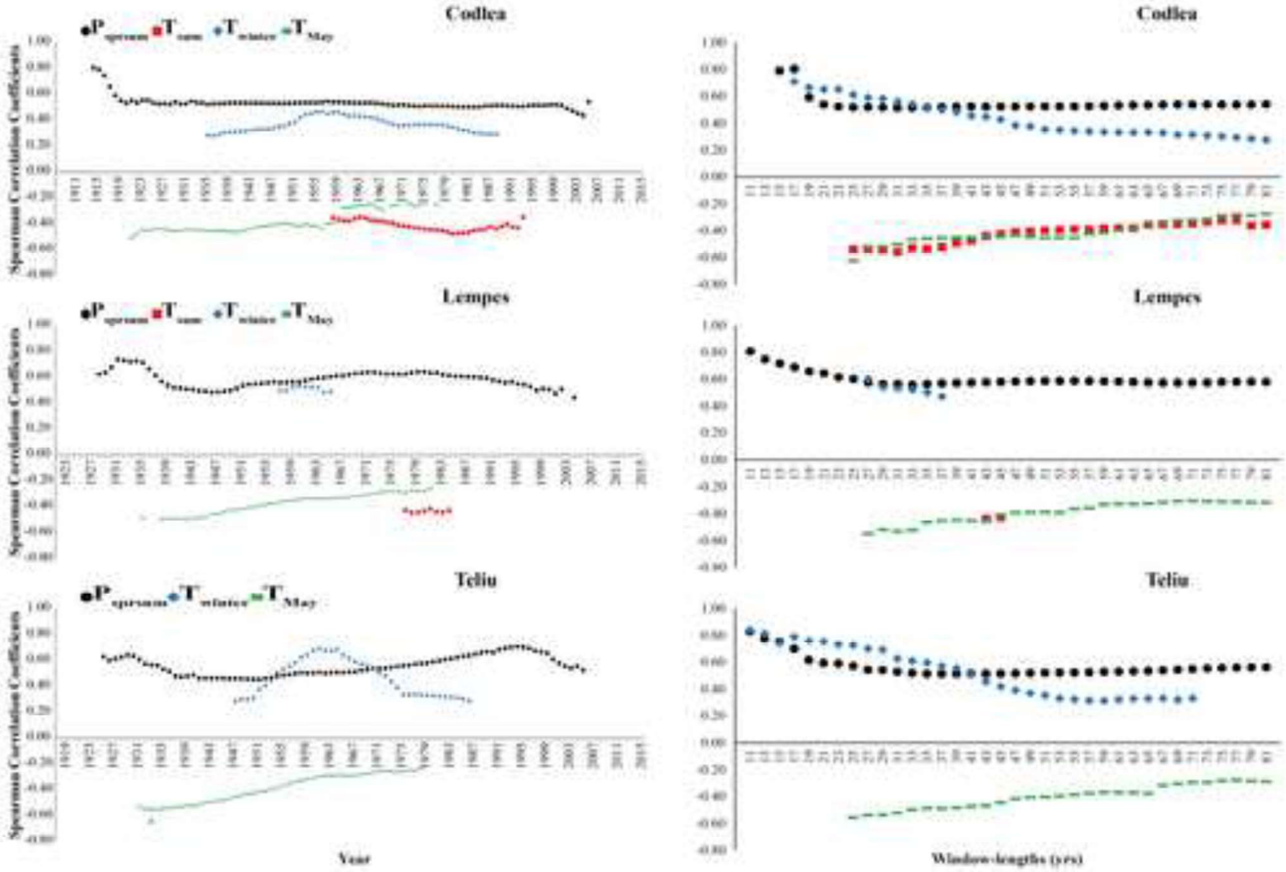
Codlea
Lempes
Teliu
P sprsum
T sum
T winter
T May
Spearman Correlation Coefficients
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Year
Window-lengths (yrs)

Figure S1

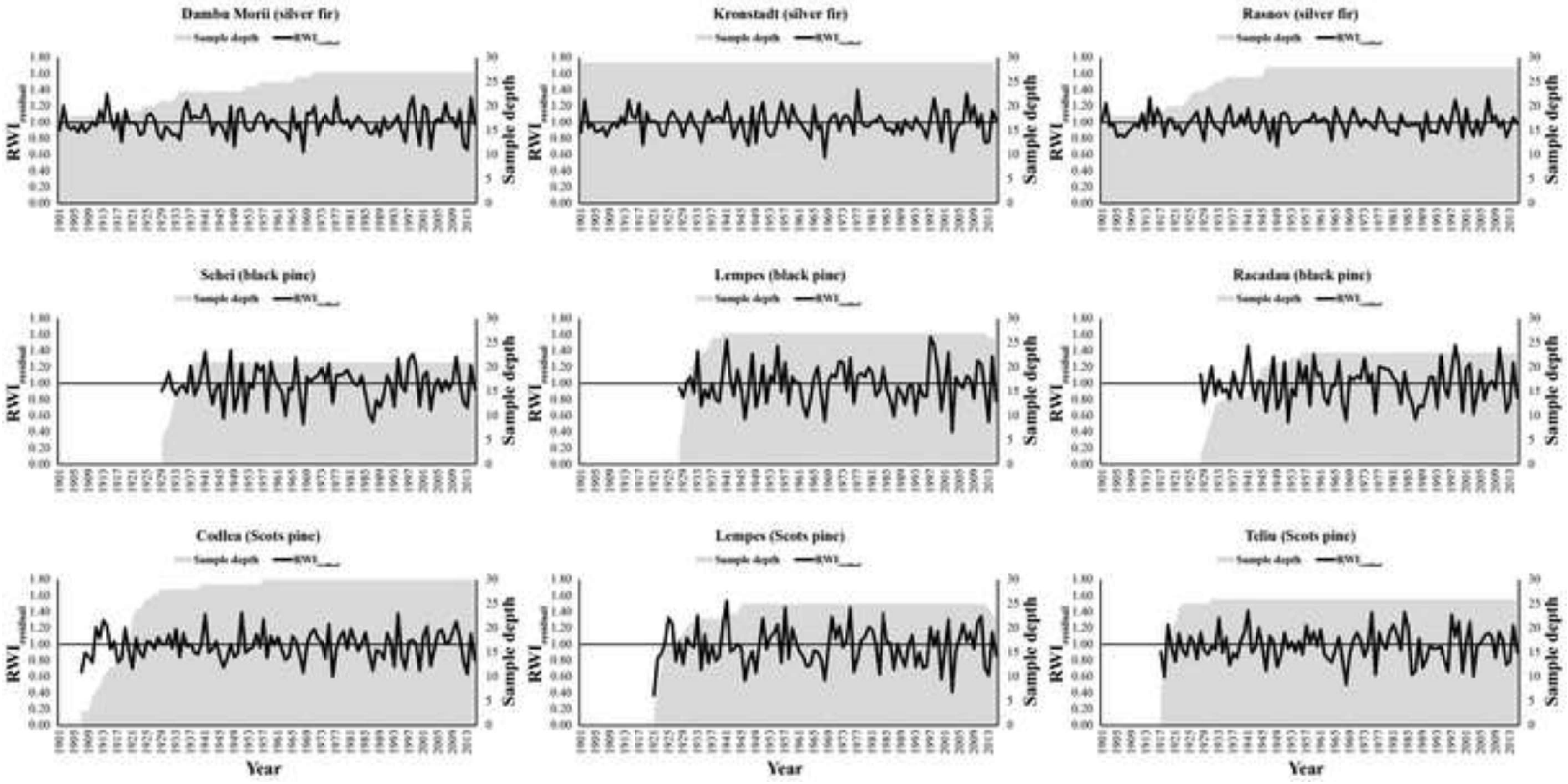
Dambu Morii (silver fir)
Kronstadt (silver fir)
Rasnov (silver fir)
Schei (black pine)
Lempes (black pine)
Racadau (black pine)
Codlea (Scots pine)
Lempes (Scots pine)
Teliu (Scots pine)
Sample depth
RWI residual
$RWI_{residual}$
Sample depth
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
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Figure S2

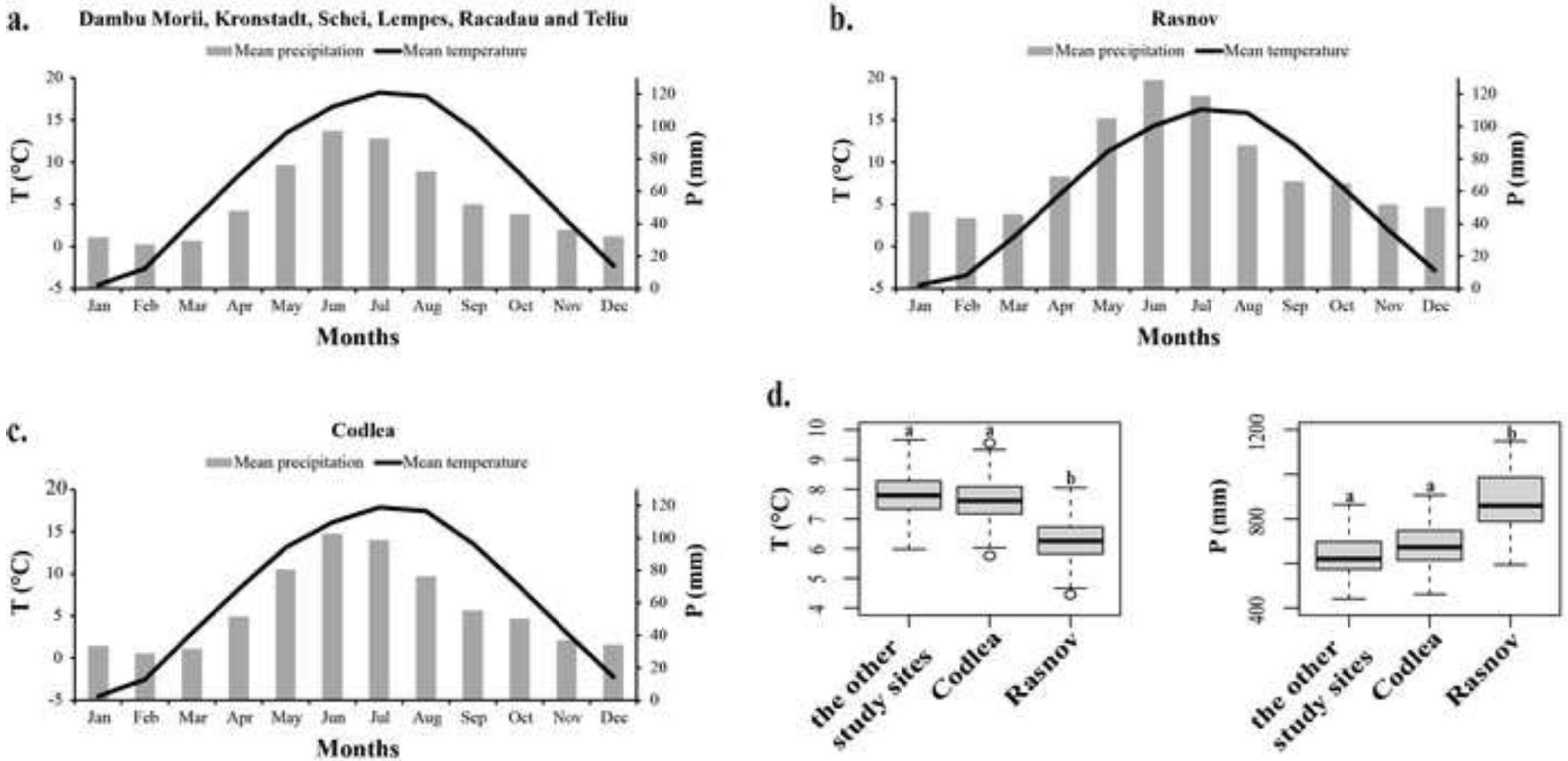
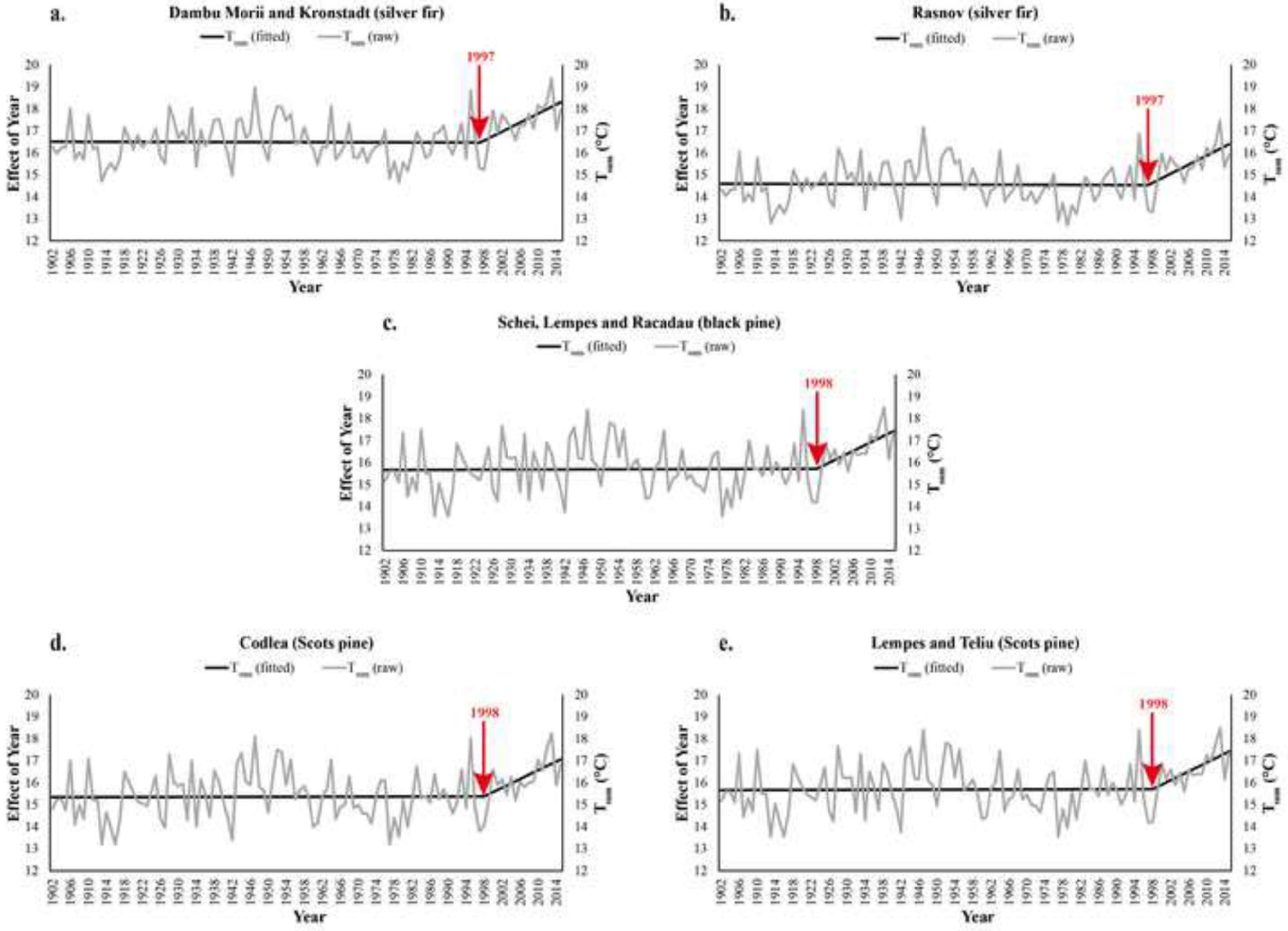

a.
Dambu Morii, Kronstadt, Schei, Lempes, Racadau and Teliu
Mean precipitation
Mean temperature
T (°C)
P (mm)
-5
0
5
10
15
20
0
20
40
60
80
100
120
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
b.
Rasnov
Mean precipitation
Mean temperature
T (°C)
P (mm)
Months
c.
Codlea
Mean precipitation
Mean temperature
T (°C)
P (mm)
Months
d.
T (°C)
4
5
6
7
8
9
10
a
a
b
the other study sites
Codlea
Rasnov
P (mm)
400
800
1200
a
a
b
the other study sites
Codlea
Rasnov

Figure S3


a.
Dambu Morii and Kronstadt (silver fir)
b.
Rasnov (silver fir)
c.
Schei, Lempes and Racadau (black pine)
d.
Codlea (Scots pine)
e.
Lempes and Teliu (Scots pine)
T_{sum} (fitted)
T_{sum} (raw)
1997
1998
Effect of Year
T_{sum} (°C)
Year
12
13
14
15
16
17
18
19
20
1902
1906
1910
1914
1918
1922
1926
1930
1934
1938
1942
1946
1950
1954
1958
1962
1966
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1974
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1982
1986
1990
1994
1998
2002
2006
2010
2014

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