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Variability in Larch (*Larix Decidua* Mill.) Tree-Ring Growth Response to Climate in the Polish Carpathian Mountains

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Abstract: The climate–growth relationship of larch (*Larix decidua* Mill.) in the Polish Carpathian Mountains was studied. We explored the spatial variability of the common signal observed in larch tree-ring growth, distinguished regions with uniform tree-ring growth patterns (dendrochronological signal), and determined the climatic factors that are particularly important for the growth of larch in this area. Uniformity in the growth reaction across the analyzed area was found in the positive response to May temperatures (significant correlation values range from 0.21 to 0.48); this indicates that the warm beginning of the growing season is important for larch growth across the study area. The signal variability from west to east found in the principal components analysis (PCA) results and differences in climate response between analyzed sites suggest their relation to increasing influence of the continental climate to the east. However, the observed relationship is not stable and does not occur systematically. Although the climate–growth response of larch at lower elevations is highly variable, a positive influence of July precipitation and a negative influence of April precipitation, and previous May and July temperature can be observed. The growth of larch from the highest study sites (Tatra Mountains, above 950 m a.s.l.) is related to temperature. This is manifested by a strong positive correlation with temperature during late spring, early summer, and the end of the previous growing season, and a negative or no response to late spring/summer precipitation. No relation between the observed correlations and slope aspect was found.

Keywords: tree rings; climate–growth relationship; spatial patterns; *Larix decidua* Mill.; Carpathians

1. Introduction

The climate is one of the most important factors that influence forest ecosystems, as its changes can greatly affect the growth of trees and thus forest productivity [1]. Mountainous areas are especially sensitive to changes in climate [2]. More knowledge about how forests respond to climate variability is needed to predict and assess the effect of future climate changes on mountain forest ecosystems [3]. It is also necessary to improve management strategies and adjust forestry practices accordingly [1,4,5]. In this context, tree-ring analysis is a valuable data source that provides information on the influence of past and recent climatic variations on tree growth as well as possible forest responses to predicted climate changes (see [6] for review).

Studies on the interaction between mountain forest ecosystems and climate are challenging due to very dynamic and variable environmental conditions. Climate–growth relationship analysis makes it possible to identify and assess the influence of the most growth-limiting climatic factors. Regional studies help to establish a better understanding of tree growth response to climatic conditions in mountainous areas. Taking into consideration factors such as altitude and slope aspect allow for the determination of local growth drivers. Full recognition of both regional and local factors requires dense observations in regional networks. Additionally, tree growth response is species dependent. Analysis of the climate–growth relationship makes it possible to identify and assess the influence of climatic factors that limit tree growth. Regional studies make it possible to understand tree growth response to climatic conditions in mountainous areas, while taking into consideration the other aforementioned factors that influence these responses locally (e.g., [7]).

European larch (*Larix decidua* Mill.) is considered one of the most valuable forest trees in Poland. Naturally, this montane and subalpine species grows in the Alps, Sudetes, Carpathians (mainly the Tatra Mountains), and in some smaller areas of Europe (e.g., the Holy Cross Mountains in Poland). It is a fast-growing tree [8,9] with high wood quality and high resistance to air pollution [10,11]. These features have made larch cultivation popular in Europe since the 16th century and in Poland since the start of the 19th century (for comparison, see [12]). As a result, the share of larch in Polish forests is currently largely a result of planting. This is also true of the Carpathians, where larch grows mainly as an admixture tree species, mostly with beech, fir, and spruce in the lower parts of this mountain range.

The Alps are the natural and largest continuous habitat of the European larch. Therefore, existing studies on the relationship between the growth of European larch and climate focus mainly on this region and high-altitude locations [13–15]. Detailed studies have been conducted on its climate response sensitivity over time (temporal climate signal stability) [16,17], and in terms of latitude [18] and age [19]. Sites across the Alps have been used in regional dendroclimatic studies [17,18,20,21]. Considered as a species with high dendrochronological potential (highly temperature sensitive [21]), larch from Alpine areas has been used in climatic reconstructions (e.g., [22–26]). Tree-ring studies on larch in other mountain areas of Europe are sparse. Local studies have been done in Karkonosze (Giant Mountains, [27]) as a part of an ongoing broader study in the Sudetes. Studies on the climate–growth relationship of larch in the Carpathian Mountains have so far been conducted only on a local scale, including a few locations in the outer [28] and central-western (Tatra Mountains; [29,30]) parts of this mountain range. Moreover, some locations in the Carpathian foothills have been examined [31–35]; they provided valuable information on the larch tree-ring growth dynamic and its growth response to climate. However, there is a lack of a broader regional study on larch in this area concerning spatial tree-ring growth signal variability or the influence of altitude and slope aspect on the climate–growth relationship. To assess European larch's future growth response to changing climate in the Carpathians, a regional approach is needed. A denser data network of observations provides a better means of understanding changing larch growth conditions. The creation of new growth models and the validation of existing models are also needed.

Here we present the first regional study on larch in the Polish Carpathians. We analyzed the tree rings of larches growing at different altitudes and on slopes with various aspects in the foothills and higher parts of Polish Carpathian Mountains. We explored the spatial variability of the common signal observed in larch tree-ring growth and distinguished regions with a uniform climate signal. We determined the climatic factors particularly important for the growth of larch in this area and checked if and to what extent altitude and slope aspect affect the sensitivity of trees to climatic factors.

2. Materials and Methods

2.1. Study Area Characteristics and Site Locations

The study area was situated in the central and eastern parts of the Polish Carpathian Mountains. Sites were located in the three distinguishable parts of this range: The Outer Western Carpathians, the Central Western Carpathians, and the Outer Eastern Carpathians (Figure 1). Differences between these regions are reflected in the geological, geomorphological, geographical, climatological, and geobotanical divisions of this region [36–38]. However, the boundaries (especially between the Outer Western and Eastern Carpathians) can differ slightly depending on the division type (i.e., [36,38]). The Outer

Carpathians is an area of foothills that widens to the east, with gentle hills rising to 400–500 m a.s.l. The innermost part of The Outer Carpathians is a medium-elevation mountain zone (the Beskids in the Western Carpathians and Bieszczady in the Eastern Carpathians) with mountain ranges that rarely exceed 1000 m a.s.l. [39]. Only the Tatra Mountains, a part of the Central Western Carpathians with ridges reaching elevations above 2000 m a.s.l., have the features of high mountain environments [40].

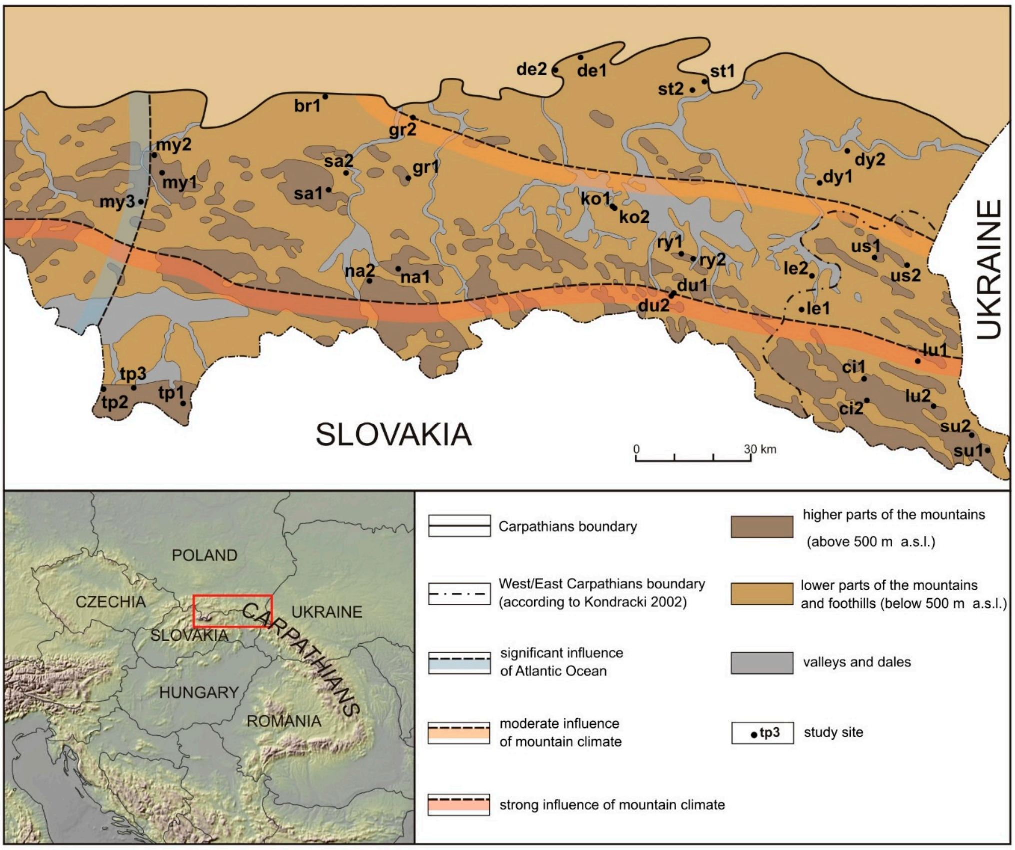


Figure 1. Study area with topography, climate, and site locations (compare [37] and [41]).

The climate of the Polish Carpathians is a mixture of climatic influences that act on three different levels. On a macroscale, from west to east, the ocean influence (characterized by smaller temperature amplitudes, early spring and summer, and short winter) is diminished by the growing influence of the continental climate (larger temperature amplitudes rising eastbound, long summer, long and cold winter). The second, mesoscale level, is the influence of the mountain climate, which rises to the south and is characterized by a decrease in altitude-dependent temperatures, shorter summers, longer winters (observed especially in the eastern part), and a possible luv/lee precipitation effect. Precipitation, whose annual totals range from 650 mm (northern part of the foothills) to more than 1000 mm (the inner, highest parts of the mountains), is usually higher in the western part of the area ([37], Figure 1). However, precipitation is strongly dependent on altitude and slope aspect (microscale level of influence).

Of the 35 study sites, 22 were located in mountainous areas and 13 were in the foothills zone (Figure 1). In the analysis, besides the new locations (18 sites), existing data from previous local studies on larch conducted by authors [33–35] were also used. The sampled trees grow at altitudes of 278 to 1287 m a.s.l., with almost a half of them in the range 400 to 600 m a.s.l. Only three locations were above 900 m a.s.l. in the Tatra Mountains (tp1–tp3), which is the highest part of the Carpathians. In the Polish part of the Tatra Mountains, there are only a few forest stands with larch more than 100 years old—all are protected by the Tatra National Park, therefore only three sites could be sampled in this area. In addition to their different altitudes, the study sites also varied in terms of slope aspect (Table 1). Sites with a north-facing component predominated; this reflects the general tendency in this area for larch to be present mostly on northern slopes (according to forest management). Tree stands with larches aged over 100 years were selected for the analysis. Trees grow in mixed stands (mainly with silver fir, Norway spruce, European beech, and sometimes Scots pine) of the mountain fresh forest type [42], usually on cambisols (Table 1).

Table 1. Characteristics of the sampled sites.

No.	Site	Longitude	Latitude	Altitude (m a.s.l.)	Slope Aspect	Forest Type	Soil Type	No. of Trees
1	tp1	20°5′1.90″ E	49°14′17.00″ N	1387	SE	MFF	cambisols	16
2	tp2	19°48′6.20″ E	49°16′2.90″ N	1211	NE	MFF	cambisols	20
3	tp3	19°54′31.00″ E	49°16′36.80″ N	971	N	MFF	cambisols	20
4	my1	19°59′34.32″ E	49°44′59.59″ N	471	WWS	MFF	cambisols	17
5	my2	19°57′30.38″ E	49°49′12.45″ N	376	NNW	MFF	cambisols	14
6	my3	19°55′26.74″ E	49°41′0.50″ N	489	S	MFF	cambisols	13
7	br1	20°33′13.54″ E	49°57′50.60″ N	278	N	USFF	cambisols	17
8	sa1	20°34′11.17″ E	49°43′2.14″ N	528	N	MFF	cambisols	11
9	sa2	20°39′31.23″ E	49°45′59.33″ N	349	SSE	UFF	cambisols	14
10	na1	20°48′53.20″ E	49°32′35.90″ N	562	SW	MFF	cambisols	15
11	na2	20°42′43.50″ E	49°31′40.70″ N	600	NE	MFF	cambisols	13
12	gr1	20°51′45.10″ E	49°44′40.10″ N	447	NE	UFF	cambisols	13
13	gr2	20°53′46.30″ E	49°55′48.70″ N	361	E	UFF	cambisols	14
14	de1	21°26′36.20″ E	50°1′29.83″ N	325	N	UFF	luvisols	14
15	de2	21°20′51.46″ E	49°59′56.94″ N	306	W	UFF	luvisols	14
16	ko1	21°33′22.68″ E	49°40′47.77″ N	340	SW	UFF	cambisols	20
17	ko2	21°33′16.10″ E	49°41′12.02″ N	325	NE	UFF	cambisols	20
18	st1	21°51′37.57″ E	49°56′39.57″ N	306	WSW	UFF	cambisols	15
19	st2	21°52′55.23″ E	49°57′52.84″ N	282	NNE	UFF	cambisols	15
20	ry1	21°48′33.12″ E	49°34′18.90″ N	474	S-SE	MFF	cambisols	17
21	ry2	21°49′36.64″ E	49°33′19.12″ N	534	N	MFF	cambisols	15
22	du1	21°45′34.52″ E	49°29′9.77″ N	536	NW	MFF	cambisols	20
23	du2	21°45′21.46″ E	49°28′44.65″ N	590	SSE	MFF	cambisols	20
24	dy1	22°15′3.50″ E	49°42′37.00″ N	487	WNW	UFF	cambisols	20
25	dy2	22°22′21.80″ E	49°47′7.40″ N	414	SW-SSW	UFF	cambisols	20
26	us1	22°27′3.09″ E	49°31′27.80″ N	522	S	MFF	cambisols	16
27	us2	22°33′47.08″ E	49°30′27.61″ N	580	N	MFF	cambisols	17
28	le1	22°11′48.80″ E	49°24′45.60″ N	582	NE	MFF	cambisols	24
29	le2	22°14′4.70″ E	49°29′4.20″ N	481	NW-SW	UFF	cambisols	20
30	lu1	22°34′33.10″ E	49°17′5.80″ N	569	NW	MFF	cambisols	20
31	lu2	22°37′50.00″ E	49°11′32.00″ N	749	N	MFF	cambisols	20
32	ci1	22°22′51.70″ E	49°15′5.10″ N	604	NNE	MFF	cambisols	20
33	ci2	22°23′56.60″ E	49°11′58.60″ N	723	SE	MFF	cambisols	19
34	su1	22°49′6.30″ E	49°4′15.80″ N	875	SW	MFF	cambisols	20
35	su2	22°48′57.50″ E	49°5′39.90″ N	760	WNW	MFF	cambisols	21

MFF: mountain fresh forest; UFF: upland fresh forest; USFF: upland strongly fresh forest [42].

2.2. Site Chronologies and Characteristics

In total, 604 trees were sampled using standard procedures: Cores were taken at breast height with a Pressler borer in a direction parallel to the slope. Two cores were collected from each tree, with the exception of sites br1, de1, de2 and my1, where one core per tree was taken. After preparation, all cores were measured using the LINTAB™ 6 tree-ring measurement system with TSAP-Win™ Professional software (4.69k, RINNTECH, Heidelberg, Germany). Tree-ring sequences from each site were compared visually in Quercus software (06.01, AGH-UST, Krakow, Poland) [43], correlated, and dated with COFECHA software (6.06, Tree-Ring Lab (TRL) and Columbia University, New York, NY, USA) [44]. Core series from the same tree were averaged. For trees showing the highest correlation to others within one site, site chronologies were then built and developed in ARSTAN software (ARS44h2 xp, Tree-Ring Lab (TRL) and Columbia University, New York, NY, USA) [45]. This procedure was performed in order to improve the intra-site common signal. Before standardization, data-adaptive power transformation was applied to stabilize variance and mitigate differences in variability between parts of the tree-ring series [46]. In dynamic environments, long systematic series of both underfitted and overfitted values are observed after the first detrending; therefore, the classic double detrending method was then applied (linear or negative exponential regression followed by a cubic smoothing spline with 50% frequency response cut-off equal to two-thirds of the series length [47]). A second detrending was applied to remove this phenomenon [48,49]. Chronologies were developed by averaging the individual series based on the biweight robust mean. For further analysis, the residual versions of site chronologies (with the effect of autocorrelation removed by autoregressive modelling) were used. High frequency variability is highlighted in this type of chronology; this makes it commonly used for climate–growth relationship studies [50]. Standard chronologies (developed after detrending, but without autocorrelation removing), especially from lower elevation sites, can be less sensitive to climate variations and show lower correlation with climatic variables (e.g., [51]). To characterize the residual site chronologies (Table 2), we calculated: mean sensitivity (MS, a measure of annual variability in a tree-ring series); first order autocorrelation (AC, a measure of the relation between growth in the previous and current year); mean inter-series correlation (mean Rbar, common variance between series); and Expressed Population Signal (EPS, the degree to which a developed chronology depicts the hypothetical chronology, based on an infinite number of trees). The use of mean sensitivity makes it possible to assess high-frequency variations in chronologies, whereas first order autocorrelation does the same for the persistence of tree-ring patterns [52]. The common variance and signal strength of each chronology can be assessed by values of mean Rbar and EPS [53]. These values were computed using a 30-year moving window with a 15-year overlap.

Table 2. Characteristics and descriptive statistics for the constructed chronologies.

No.	Site Code	Cluster	Full Period Covered	Number of Years	No. of Trees in Chronology	MSL	AGR (mm)	AC	MS	mRbar (30_15)	mEPS (30_15)
1	tp1	C4	1743–2015	274	14	225	0.620	0.76	0.25	0.55	0.96
2	tp2	C4	1869–2015	147	18	133	1.295	0.79	0.25	0.70	0.97
3	tp3	C4	1868–2015	148	17	136	1.542	0.79	0.20	0.68	0.97
4	my1	C3	1873–2008	136	12	131	1.834	0.76	0.23	0.56	0.93
5	my2	C3	1874–2009	136	11	127	1.646	0.62	0.25	0.59	0.92
6	my3	C3	1866–2009	144	11	139	1.717	0.77	0.25	0.59	0.94
7	br1	C3	1871–2008	138	12	129	1.829	0.73	0.26	0.54	0.92
8	sa1	C3	1900–2009	110	10	101	1.964	0.68	0.25	0.50	0.9
9	sa2	C2	1916–2009	94	10	89	2.568	0.74	0.23	0.47	0.9
10	na1	C3	1895–2010	116	14	99	2.795	0.63	0.23	0.45	0.91
11	na2	C3	1896–2010	115	13	112	2.015	0.79	0.23	0.58	0.95
12	gr1	C2	1894–2010	117	12	110	1.904	0.81	0.21	0.47	0.91
13	gr2	C3	1889-2010	122	13	119	1.625	0.63	0.26	0.49	0.92
14	de1	C3	1911–2008	98	11	93	2.534	0.65	0.26	0.45	0.88
15	de2	C3	1898–2008	112	11	105	1.964	0.77	0.23	0.40	0.87
16	ko1	C3	1888–2014	127	16	118	1.760	0.69	0.25	0.52	0.94
17	ko2	C3	1895–2014	120	19	112	1.960	0.65	0.25	0.52	0.95
18	st1	C3	1879–2013	135	15	130	1.549	0.78	0.21	0.55	0.95
19	st2	C3	1894–2013	120	15	110	2.012	0.70	0.20	0.54	0.94
20	ry1	C2	1901–2013	113	16	107	1.601	0.69	0.21	0.47	0.92
21	ry2	C2	1898–2013	116	13	110	1.679	0.68	0.23	0.55	0.94
22	du1	C2	1907-2014	108	17	102	1.981	0.80	0.21	0.45	0.93
23	du2	C2	1897–2014	118	19	111	1.651	0.83	0.19	0.43	0.93
24	dy1	C2	1908–2015	108	18	99	1.858	0.73	0.19	0.50	0.94
25	dy2	C2	1906–2015	110	13	104	1.465	0.78	0.17	0.51	0.93
26	us1	C2	1893–2014	122	15	116	1.898	0.69	0.21	0.48	0.91
27	us2	C2	1898–2014	117	14	111	2.573	0.64	0.22	0.58	0.94
28	le1	C2	1907–2015	109	19	102	1.932	0.76	0.19	0.57	0.96
29	le2	C2	1887–2015	129	18	110	1.466	0.75	0.19	0.47	0.94
30	lu1	C1	1911–2014	104	17	97	2.784	0.67	0.22	0.49	0.94
31	lu2	C1	1900–2014	115	18	111	2.233	0.88	0.23	0.57	0.96
32	ci1	C1	1905–2014	110	17	105	2.600	0.72	0.20	0.53	0.95
33	ci2	C1	1916–2014	99	18	94	2.287	0.74	0.20	0.48	0.94
34	su1	C1	1918–2014	97	17	92	1.919	0.79	0.21	0.56	0.95
35	su2	C1	1912–2014	103	19	92	2.292	0.67	0.25	0.54	0.96

Chronology statistics: Mean series length (MSL), average growth rate (AGR), standard deviation (SD), and first-order serial autocorrelation (AC) were computed on the raw tree-ring series; mean sensitivity (MS), mean interseries correlation (mRbar), and mean EPS (mEPS) were computed for indexed chronologies (30-year EPS window and 15-year lag). The cluster identification was also provided.

2.3. Climate Data

CRU TS v. 1.2 grid data (the average monthly air temperature and total monthly precipitation for the period 1901–2000 from a $10' \times 10'$ grid network) were used [54] due to the lack of weather stations or stations with long-term data sets available for many of the analyzed sites (compare [55]). Their applicability was checked. Data covering the longest possible periods of time from the main eight weather stations in the analyzed area (Kraków-Balice, Tarnów, Zakopane, Kasprowy Wierch (data available since 1951), Nowy Sącz (since 1954), Rzeszow-Jasionka (since 1952), Krosno (temperature since 1961, precipitation since 1951), and Lesko (since 1954)) were compared with grid data from corresponding grid boxes. Data were compared for the maximum available overlapping period for gridded and weather station data. Unfortunately, no data covering the first half of the century were available. The mean Pearson correlation coefficients for temperature and precipitation were 0.986 and 0.876, respectively. The biggest difference between grid and weather station data was observed for Kasprowy Wierch (0.742 for precipitation) and Lesko (0.977 for temperature; [56]); this can be explained by the mean height of the grid box for this location (height amendment). Box-whisker plots for particular months were also compared. The size and value ranges in the boxes for each month were similar. Visible differences were found only for Kasprowy Wierch and Zakopane precipitation data. Outlier and extreme values were more often presented in weather station data. The difference in mean values between grid and weather station data (checked with *t*-Student test and ANOVA analysis) was statistically insignificant, with the exception of Kasprowy Wierch. Determination coefficients (R^2) for linear regression models were also computed. Weather station data and grid data were chosen as dependent and independent datasets, respectively. The mean R^2 value for temperature was 0.97 and for precipitation was 0.77. Using these regression models (without Kasprowy Wierch and Zakopane (precipitation)), a mean linear regression model for all weather stations was established. This helped to compute possible differences between grid and weather station data. The results of the performed analysis (high values of correlation coefficients, insignificant difference in mean value, except for Kasprowy Wierch precipitation data, and the high similarity seen on box-whisker plots) support the idea of using grid data in the presented study (for details see [56]).

2.4. Regional Patterns of Common Variation among Site Chronologies

Hierarchical agglomerative clustering (Ward's method) was applied to distinguish regions with similar tree-ring patterns and to show differences and similarities between site chronologies in growth response to climate. A value of $1-\mathrm{r}$ Pearson distance was used as a measure of similarity between the constructed chronologies. This analysis was performed for the common period 1922–2008. The common period starts from the year in which replication for every site chronology reached a minimum of five trees, thus ensuring sufficient signal strength (compare [18,30]).

To quantify factors causing the differences revealed by cluster analysis, principal component analysis was performed using a covariance matrix. This technique replaces the original p variables (here, indices of tree-ring chronology) with a smaller number (q) of derived variables (principal components) which are linear combinations of the original variables. Often, it is possible to retain most of the variability in the original variables, with q very much smaller than p [57]. Varimax rotation was applied to improve the interpretability of the results [58]; this involves scaling the loadings by dividing them by the corresponding communality, and then rotation, which maximizes this quantity. In this step, only the components that expressed at least 5% of the variability were used, as guided by other similar studies (e.g., [7,55]). To confirm the identification of factors, the first three principal components (PCs) were plotted against geographical position, altitude, and slope aspect.

2.5. Climate Influence on Tree-Ring Growth

In order to investigate the influence of climate on tree-ring growth, DENDROCLIM 2002 [59] was used to calculate the values of correlation coefficients between residual versions of particular site chronologies, average monthly temperatures, and monthly precipitation totals. Analysis was performed in the same common period (1922–2000).

To identify the climate variables most likely to have associations with tree-ring growth of larch from the analyzed area, the spatial replication criterion described in [60] was applied. In the presented study of 35 study sites, a climate variable meets spatial replication criterion if $n \geq 6$ sites have significant correlations with the same sign. This value is obtained using a binomial distribution with n = 35, p = 0.05, and a cut-off probability of 0.997, determined by Bonferroni adjustment 0.003 (0.05/17) with 17 monthly variables for each climate characteristic. The results that met this criterion were analyzed to find the geographical, altitudinal, and slope aspect patterns.

3. Results

3.1. Chronologies Characteristics

Table 2 presents statistics for 35 site chronologies. The ages of the constructed chronologies range from 94 to 148 years, with one exception: the chronology from the highest site, tp1, which was much older (274 years). The mean values of first order autocorrelation computed on the raw tree-ring series range from 0.62 to 0.88; this indicates a strong relationship between tree-ring growth in the current and previous year. The values of mean sensitivity vary from 0.17 to 0.26. For 30 chronologies, they were equal or higher than 0.2; such values are usually considered as intermediate in terms of their applicability for dendroclimatological studies (compare [61]). The mean inter-series correlation values (mRbar) for indexed tree-ring series were relatively high (varied from 0.40 to 0.70). Neither a visible pattern nor a gradient related to altitude or slope aspect was found. The mean values of EPS varied from 0.87 to 0.97 and were higher than the frequently applied threshold of 0.85 [51].

3.2. Tree-Ring Growth and Its Spatial Variability, Influence of Altitude and Slope Aspect

Cluster analysis using the hierarchical agglomerative method distinguished four main groups of chronologies (clusters C1–C4, Figure 2). The first two clusters contain the chronologies from the most southeastern part of the analyzed area (with the exceptions of two sites (gr1 and sa2) that are situated farther to the west, Figures 1 and 2). The group of sites located in the innermost and highest parts of this region is clearly separated (cluster C1); this is called Western Bieszczady (according to physical-geographical regionalization, [36]). The third cluster consists of chronologies from the Outer Western Carpathians (both foothills and mountainous locations (Figure 2)). The last, very distinct cluster contains chronologies from the highest region: the Tatra Mountains (Central Western Carpathians).

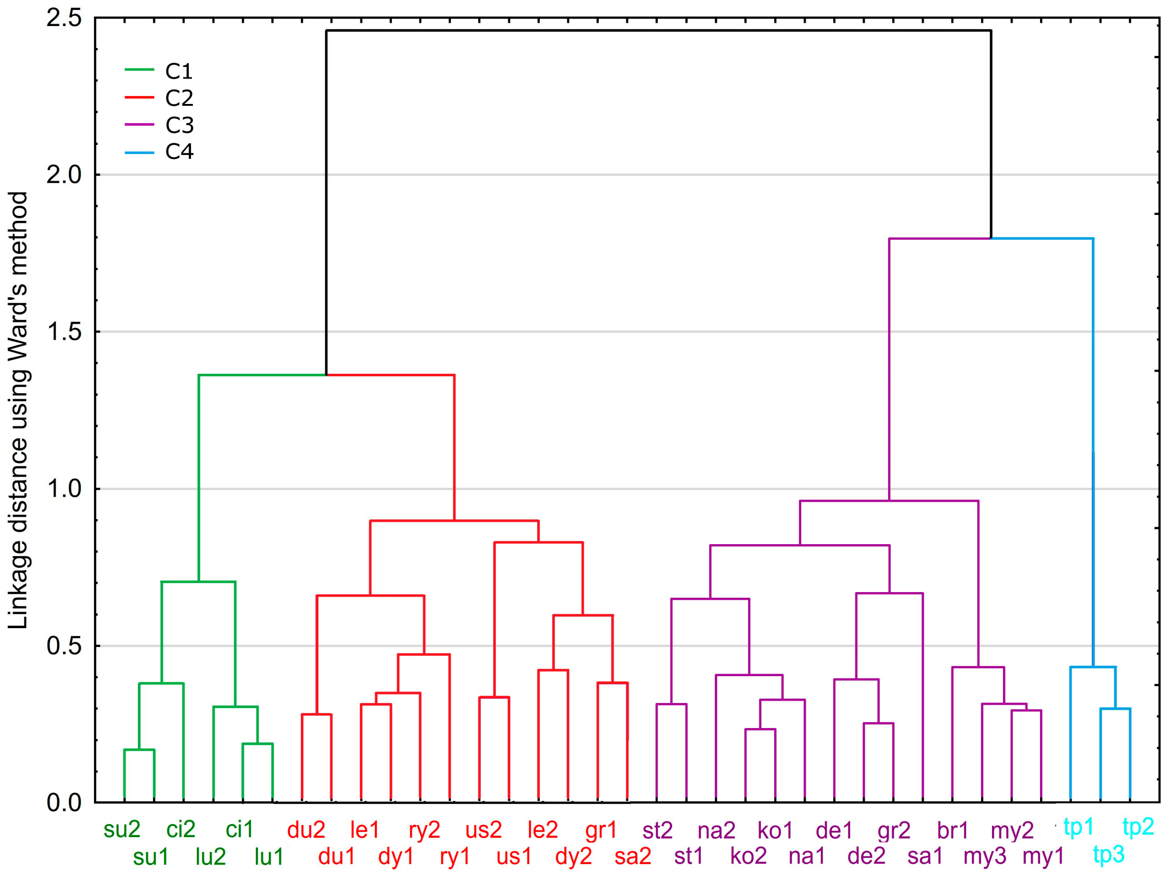
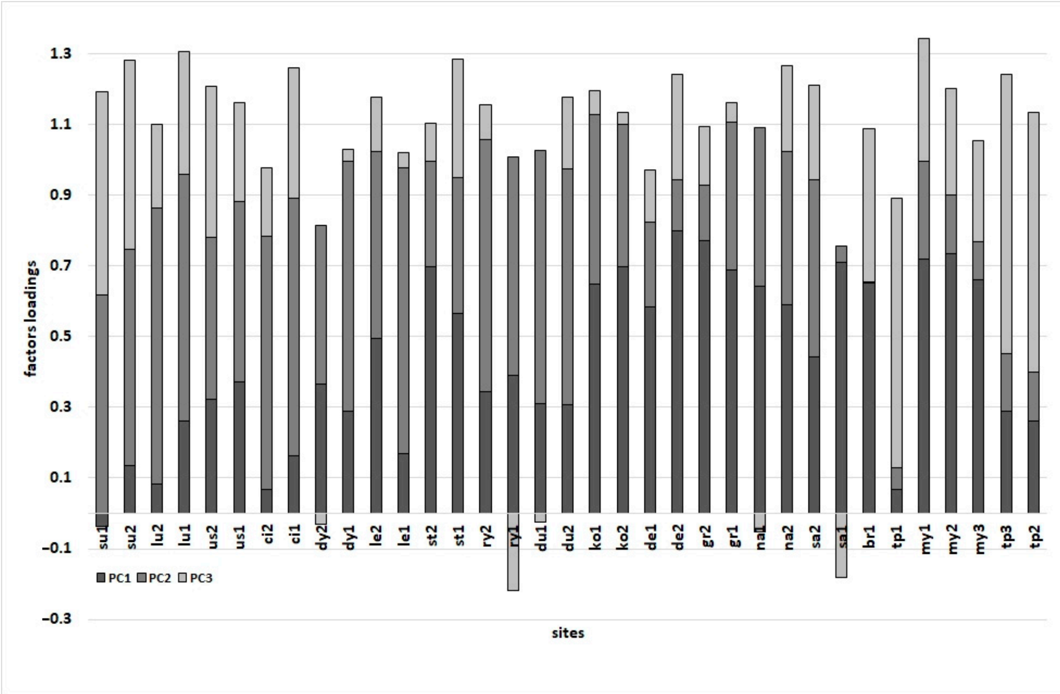
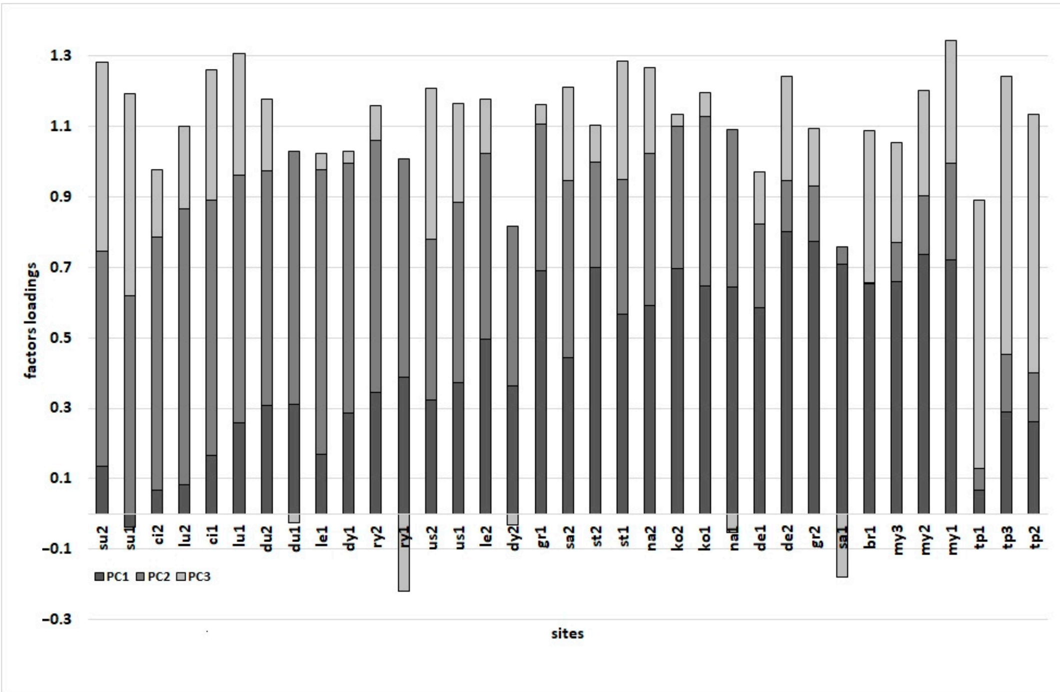


Figure 2. Results of clustering analysis. Distinguished clusters (C1–C4) are marked.

Principal component analysis was performed for deeper analysis of the observed clustering and understanding of the obtained division. The first principal component explained 44% of the variance, whereas PC2 and PC3 contribute 10% and 7%, respectively. Varimax rotation was performed for the first three PCs, taking into account other dendroecological studies (e.g., [7,55]) and the shape of the eigenvalues curve, with its flattening after PC3. The results of Varimax rotation are presented in Figures 3 and 4; the former presents the share of the first three PCs attributed to each of the site chronologies. It can be observed that generally, when moving from west to east, the PC2 loading increases while the values of PC1 decrease. When distinguished clusters are considered, the aforementioned relation is even more visible. This could be a confirmation of the results of the cluster analysis (Figure 3b). The relationship between PC 1 and PC 2 observed for the Outer Carpathian sites (cluster C1, C2, and C3) is also shown in Figure 4, where the relation between particular PCs is presented. Tatra sites, where the third PC loading dominates (Figure 4b), are not part of this relation (see also Figure 4a). An increased PC3 is also observed in the highest sites of the Outer Eastern Carpathians (su1 and su2 from cluster C1), which suggests that PC3 is related to altitude.

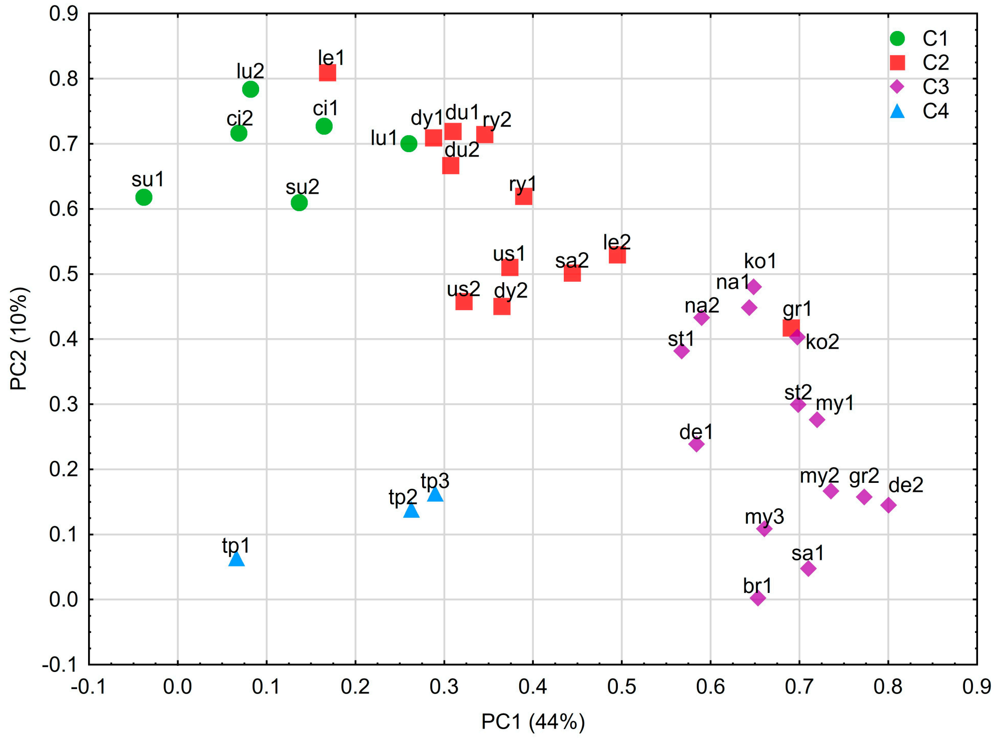


(**a**)

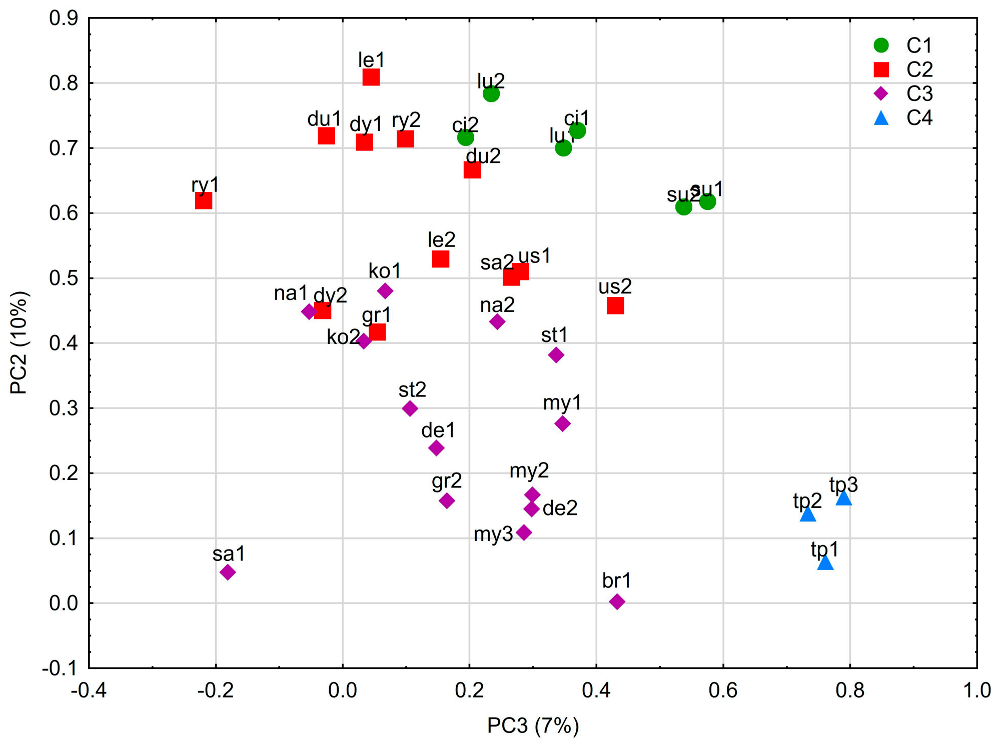


(**b**)

Figure 3. Results of principal component analysis (PCA) analysis. The share of the first three principal components (PCs) in each site are presented. (**a**) East to West site order; (**b**) site order according to clustering.



(**a**)



(**b**)

Figure 4. Scatterplot of the PCA results (after Varimax rotation). Sites and clusters (C1–C4) are marked. (**a**) PC1 vs. PC2; (**b**) PC2 vs. PC3.

The results suggest that the obtained grouping, although locally modified by the influence of other site-related factors, is a mixed result of altitudinal and geographical site location. Figure 5 presents the first three PCs plotted against geographical position and altitude. A relationship between PC1, geographical position (mainly latitude), and altitude can be observed (Figure 5a). The influence of longitude on PC2 is also visible (Figure 5b). PC3 is exclusively related to site altitude (Figure 5c). The suggestion made in the previous paragraph seems confirmed: this relation is becoming clear for higher locations (Figure 5c). The results for slope aspects (not presented here) did not show any clear pattern.

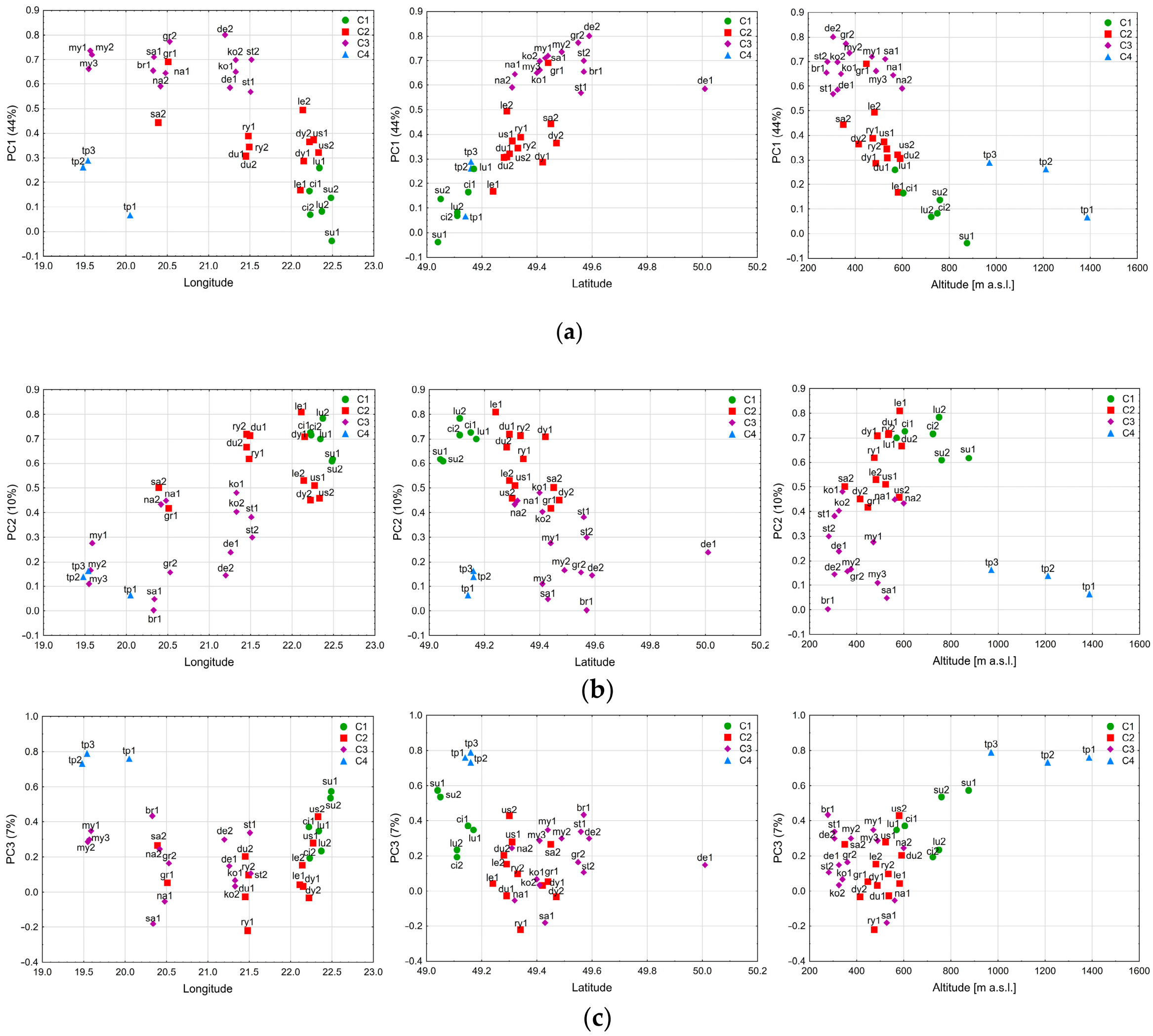


Figure 5. Plot of the relationship between the three first PCs and site longitude, latitude, and altitude. Sites and clusters are marked. (**a**) PC1; (**b**) PC2; (**c**) PC3.

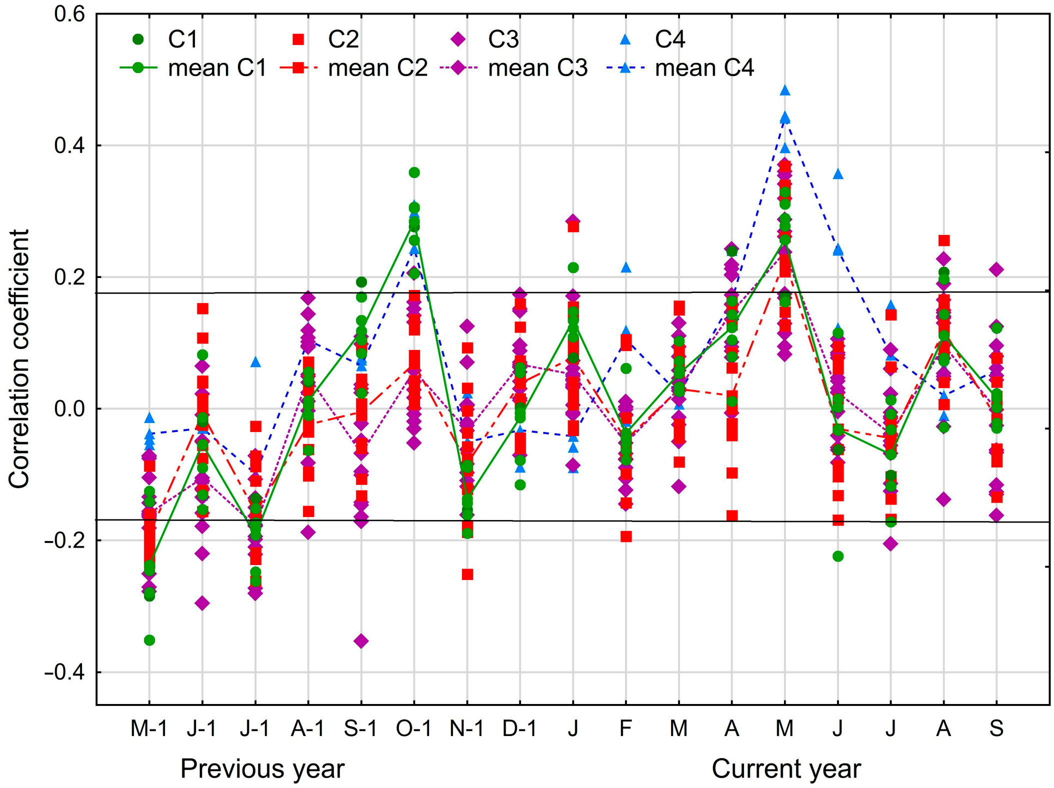
3.3. Climate–Growth Relationship

The results of the correlation between residual versions of particular site chronologies and climate variables are presented in Figure 6. The replication criterion described in Section 2.5 is met for the temperature of the previous May, July, October, the current May, and for precipitation of the current April, June, July, and September. Selected results were plotted against altitude/latitude/longitude; they are presented in Figure 7.

Results for temperatures show a positive correlation of tree-ring growth with the current May and the previous October. The positive correlation with May temperature all over the area is the most noticeable: significant correlation coefficients for the majority of sites (21 of 35) were obtained for this month (Figure 6a). The highest values were recorded for the high-altitude sites in the Tatra Mountains

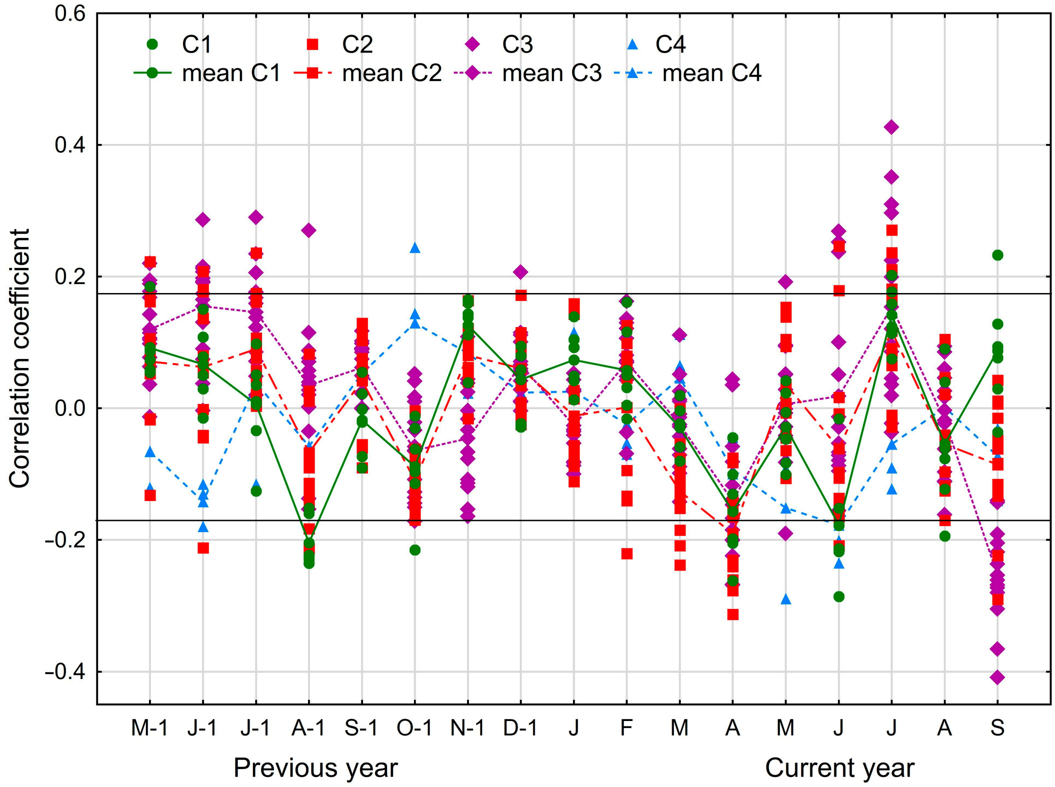
(Figure 7a). For the highest two of these sites, a positive, significant correlation also occurred for the month of June. A significant positive correlation with the previous October temperature was observed for the first (Western Bieszczady) and fourth (Tatra Mountains) clusters (Figure 6a). These clusters include the highest analyzed sites; this could suggest that the observed correlation is related to altitude (Figure 7b). However, the results show that the association with geographical position (mainly latitude) cannot be discounted (Figure 7b). For the highest analysed site (tp1), this correlation was much weaker and insignificant (Figure 7b).

A negative correlation between tree-ring growth and temperature was observed for the previous May and July (Figure 6a). For the previous May, significant values were obtained for clusters C1–C3 (13 sites, Figure 7c), which represents more than one third of the analysed sites. For the previous July, 10 statistically significant values were obtained. No clear pattern showing a relation between the obtained correlations and the spatial distribution or assigned cluster of the analyzed sites was found (Figure 7d).



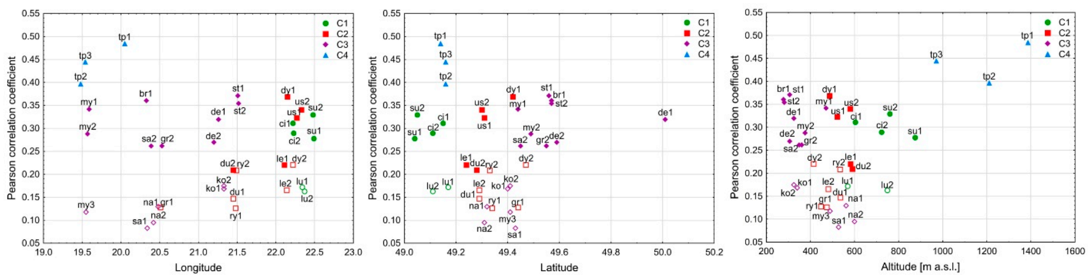
(a)

Figure 6. *Cont.*

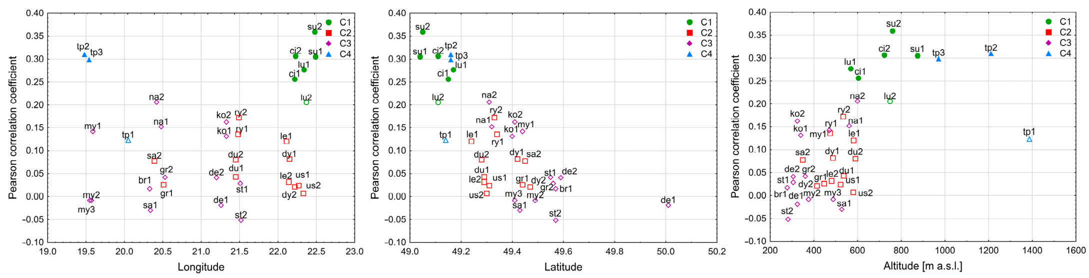


(**b**)

Figure 6. Results of climate–growth relationship analysis. Correlations were calculated from previous-year May (M-1) to current-year September (S). Mean values for particular clusters (as lines) were also presented (red line shows significant level). (**a**) Temperature; (**b**) precipitation.

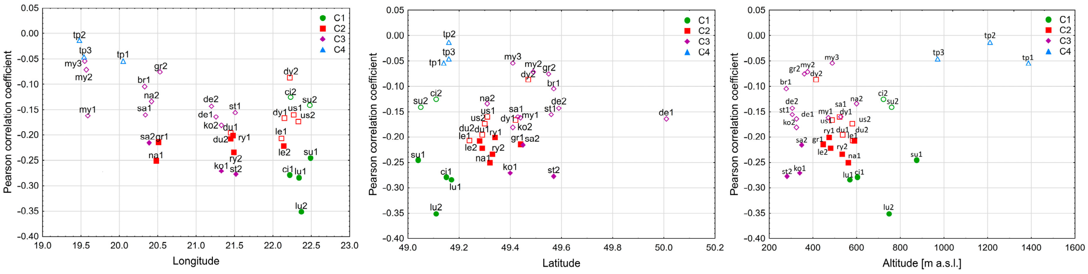


(**a**) May temperature.

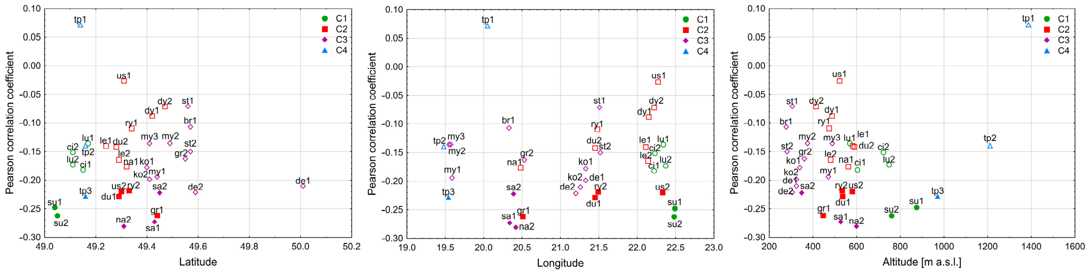


(**b**) Previous October temperature.

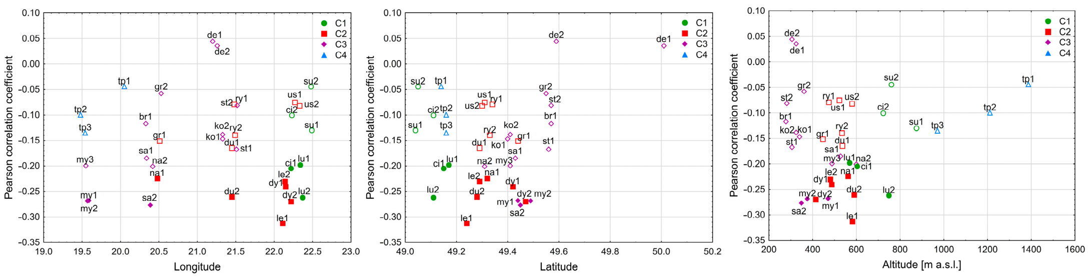
Figure 7. *Cont.*



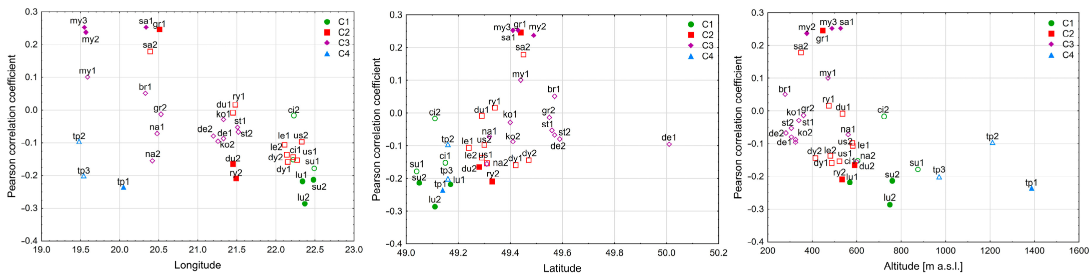
(**c**) Previous May temperature.



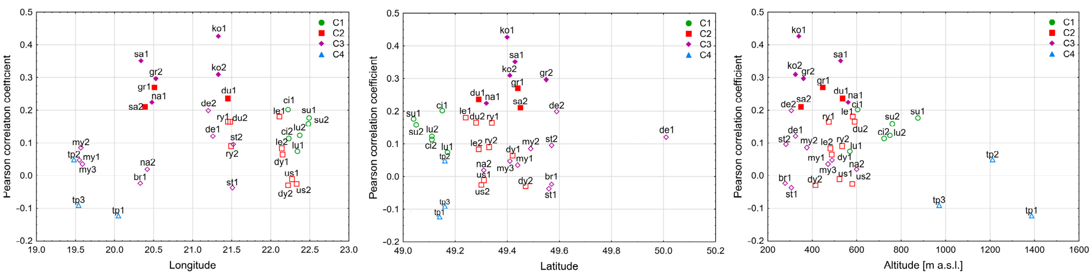
(**d**) Previous July temperature.



(**e**) April precipitation.

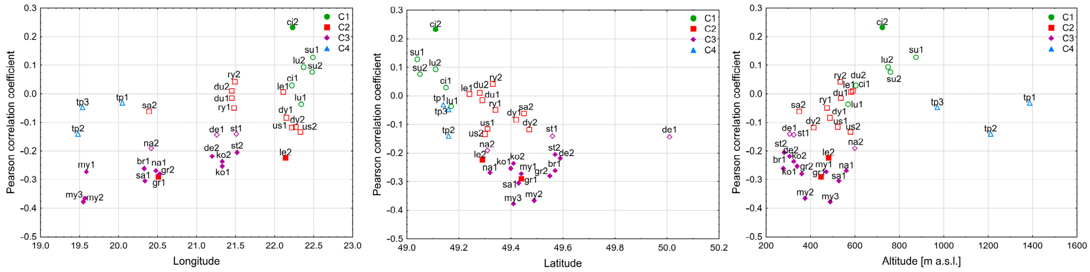


(**f**) June precipitation.



(**g**) July precipitation.

Figure 7. *Cont.*



(**h**) September precipitation.

Figure 7. Results of climate–growth relationship analysis plotted against longitude, latitude, and altitude for the selected months (filled dots represent significant values).

The results obtained for precipitation are more complex across the studied area. A negative correlation between tree-ring growth and April precipitation was found, with significant values for 12 sites (Figure 6e). No clear pattern was found in the spatial distribution of these sites; however, no correlation was found for cluster 4 (Figures 6b and 7e). The results observed for June depend on site location. Positive correlations were recorded for sites in the western part of the study area (with the exception of sites in the Tatra Mountains), whereas negative correlations characterize sites located farther to the east (Figure 7f). However, the number of sites with significant correlation values is low (four positive and six negative values). A generally positive correlation between larch growth and July precipitation can be seen; however, significant correlation values were obtained for only eight sites in clusters 2 and 3 (Figures 6b and 7g). No clear relation to geographical position was found for July, but the precipitation in this month seems to be unimportant for sites in the Tatra Mountains (Figures 6b and 7g). The negative correlation with September precipitation mainly concerns sites in the third cluster (significant correlation values were observed for 11 of 13 sites (Figures 6b and 7h).

A possible relation between the observed correlations and slope aspect was also explored, but no clear pattern was found in this case. This suggests that slope aspect is not one of the main factors related to tree-ring growth in the study area; however, it could be a result of the relatively small amount of data used for comparison of different slopes. Most of the locations had a northern aspect, which is typical for this area (compare Section 2). More detailed studies on this subject are needed to confirm this.

4. Discussion

The presented study showed variations in the climatic signal observed in the tree rings of larches growing in the Polish Carpathians. The distinguished clusters reflect the general climate characteristics of the region (macroscale influence), which is strongly affected by the morphological diversity of this mountainous area (mesoscale influence, Figure 1). The Tatra Mountains region is clearly different from the others. The chronologies of larch in this region revealed big differences in their response to climatic factors compared to other areas (see Sections 3.2 and 3.3); this is a result of the very different features of this high mountain region, especially the climate. For the rest of the area, which consists of mountains of medium elevation and the foothills zone, variability in the climatic signal from west to east can be observed, as shown by the results of PCA analysis (Figures 3 and 4). Almost all these sites are in an area where the continental influence prevails (with the exceptions of sites my1, my2, and my3, which according to the climatic division shown in Figure 1 are on the border of the prevailing Atlantic influence). The given results suggest that the signal variability could be affected by the increasing importance of the influence of the continental climate to the east, but this transition is not clearly visible in the tree-ring growth response. This can be explained by the fact that the observed response variability is additionally affected by the increasing mountain climate influence to the south (mesoscale influence, compare Section 2, Figure 1). The combination of these two influences, which are affected to some degree by other site-related factors (microscale influences), results in the observed diversity of the climatic signal of larch in the area of medium elevation mountains and the foothills zone and is responsible for the observed clustering (C1–C3).

May temperature is the main climatic factor that limits larch growth in the Polish Carpathian Mountains. The positive influence of a warm May can be seen at low and high locations in both the foothills and mountains (Figures 6a and 7a). Higher temperatures positively influence the onset of cambial activity in trees ([62–64]), which is high at the beginning of the growing season. The obtained correlation coefficients for lower sites (cluster C1–C3) are relatively low (<0.4); this is typical for medium elevation locations, where climate response is very complex [65]. The highest dependence on May temperature can be seen in sites in the Tatra Mountains, all of which are located much higher than the other analyzed sites (above 950 m a.s.l., Table 1). This was expected, because the temperature of the vegetation season is the main factor that restricts tree-ring growth at high altitudes ([6,21,65]).

The positive influence of temperature for the two highest study sites (tp1, tp2) continues until June. A similar relation to temperature was observed for four other previously analyzed locations from the Tatra Mountains ([29,30]). A positive influence of a warm late spring and early summer temperatures (May–July or June–July) on larch growth was also recorded across the Alps ([17,21]). At an elevation of 1350 m a.s.l., ring formation starts in mid-May, or later as altitude increases [62]. It could be conjectured that it starts earlier at lower elevations. For most of the study sites the positive response to temperature is usually restricted to May; a similar response has been observed for larch growing in the lowlands of central and northeast Poland [66] and Lithuania [67]. For some locations the positive influence of a warm April was also observed, similarly as observed for larch from Lithuania [67]. However, statistically significant correlation values were obtained for only four of the analyzed sites (st1, br1, lu1, and tp3, Figure 6a). Sometimes the positive response was related to both April and May temperatures (among the sites with significant values, it concerns st1, br1, and tp3). The difference between low and high elevation sites suggests its relation to elevation, as lower sites show response to April–May or only May temperature and the highest sites to May–June temperature, however, no clear relation to altitude was found (Figures 6a and 7a). On the other hand, the earlier start of the growing season in some locations could also be a result of the non-uniform start and strength of the response of trees within sites (compare [68]).

It seems that a warm May positively influences tree-ring formation; however, it can negatively influence other processes that can indirectly reduce ring growth in the next growing season, in particular, the bud formation. This is manifested by the negative correlation with the previous May temperature that is observed in many sites (Figures 6a and 7c). It is possible that high temperature negatively influences the initiation of the bud formation process, which starts in the spring of the year before ring formation (compare [69]). This can indirectly affect tree-ring growth by influencing the quality of the assimilation apparatus that will develop in the next year. The possible impact of the previous year's climate on bud formation and tree-ring growth is discussed by Feliksik [28]. However, the aforementioned study concerns the positive effect of precipitation on bud formation in the previous spring (March–May period precipitation totals were analyzed). One of the features of the climate of the studied area is that cooler years are usually related to increased precipitation and high temperature can reflect droughts to some degree [70]; this could represent a link between the results of this study and the study of Feliksik [28]. A negative influence of temperature was also found for the previous July (Figure 6a), which is in agreement with other studies from Poland and Lithuania [66,67,71], where an adverse effect of the previous summer's temperature was recorded. This effect could be related to water stress, temperature impact on respiration, bud initiation, and other processes that can reduce carbohydrate reserves [71].

Growth of larch in the highest studied locations is also related to the temperature at the end of the previous vegetation season: sites in the Tatra Mountains and Western Bieszczady reacted positively to the previous October's temperatures. A positive correlation between conifer tree-ring growth and previous autumn temperatures is known from other studies of higher mountain locations in the Tatra

Mountains [30,49] and Alps (e.g., [21]) and has been observed for high-latitude locations (e.g., [72]). For European larch, besides the Alps and Tatra Mountains (studies mentioned above), this relation has also been observed for higher sites in the Karkonosze Mountains [27] and larch stands outside of their natural range (central and northern Poland, [66]). Higher temperatures on short days enable proper bud formation and lignification of the leading shoot [73]; they also support carbon storage and, by preventing soils from freezing, prolong mycorrhizal root growth [74]. As a result, higher temperatures positively influence wood formation the following spring [30]. A warm end of the previous growing season seems important, especially for higher study sites with a harsher climate and, consequently, a shorter growing season (this concerns sites above 600 m a.s.l., Figure 7b). One possible reason could be related to the previously mentioned maturation process and the fact that conifer cuticles require either a long growing season or a warm summer to thicken (compare [74]). The positive influence of October temperature disappears for the highest study site (tp1). In the light of the previously mentioned studies from the Tatra Mountains and Alps, such a reaction is unusual and further research is necessary to explain it.

The study of Feliksik [28] of a few locations in the Polish Carpathians, in which no relation to temperature was found, indicated water-related larch growth. A positive correlation was found for current year/vegetation period precipitation totals. Similarly, in a study from an experimental plot in mid-east Poland [71], tree-ring growth of larch was mainly related to summer precipitation and was explained by the high water needs of larch (e.g., [75,76]. A positive influence of summer precipitation (mainly June–July, but sometimes also May) was recorded for sites in other regions of Poland located north of the study area [60,66,77] and Lithuania [67]. In the presented study, a mainly positive response to July precipitation is indicated; however, significant correlations were recorded only for some of the analyzed sites (Figure 6b). No clear relation to geographical position or altitude could be found (Figure 7g). It seems reasonable that no positive influence was observed for all sites in the Tatra Mountains, as summer precipitation is not usually a growth-limiting factor at high elevations of Central Europe due to its abundance [78]. The diversity of the results within the other clusters (much lower locations) could be caused by the influence of other site-related factors. As has been mentioned, non-uniform response of trees within a site should also be taken into consideration here (compare [68]). Relatively low values of correlation with precipitation could also be caused by the dynamic spatial variability of this climatic factor. Precipitation itself can affect results because it has a very local character and can significantly vary from one area to the next, especially in mountain areas (e.g., from valley to valley). This variability could be suppressed even more when gridded data are used. Results from our study and others indicate that water availability in early summer can positively influence radial growth of larch at lower elevations under certain local site conditions. However, a wet start of the vegetation season can negatively influence larch tree-ring growth at lower elevations; this is supported by the negative correlation with April precipitation observed for sites in the analyzed clusters C1–C3 (Figures 6b and 7e). The fact that no relation was observed for the Tatra Mountains cluster could be explained by the aforementioned temperature-related larch growth at high altitudes.

In the context of the studies from other regions [66,67,71,77], interesting results were observed for June. The aforementioned positive precipitation effect—although weak—was recorded only in the western part of the study area. An adverse effect was observed for sites located in the eastern part and in the Tatra Mountains (Figure 7f). A transition to a negative response appears when moving to the east; however, it is also affected by the growing influence of the mountain climate to the south. A negative response was recorded for higher locations (mainly Western Bieszczady and the Tatra Mountains, Figure 7f), but the number of sites with significant correlation values is low. This negative response is typical of high elevation larch stands, as was observed in the Alps [16]. This could suggest that the reaction of the trees in higher sites of the study area is more similar to high elevation trees. However, this needs to be confirmed by increasing the number of sites at elevations above 600 m a.s.l. As it was mentioned before, larch mainly grows in the lower parts of the Polish Carpathians and finding older larches above this elevation is, unfortunately, difficult. Moreover, the described reaction of the Western Bieszczady sites could be a result of the combined effect of geographical and altitudinal position.

This change in response to climatic factors from west to east can be also observed for September precipitation (Figure 7h). This is surprising because it is widely accepted that the tree-ring growth of larch ends with minimal growth rate in September [69,71]. A negative influence of September precipitation was also observed by Wilczyński et al. [77] for a site beyond the Carpathians in southern Poland. This suggests that some factors can prolong the tree-ring growth season. In our study, the negative influence of the moist end of the growing season concerns sites of the second cluster (Figure 6b), with the highest correlations observed for the two sites (my2 and 3, Figure 7h) that are under the strongest ocean influence (Figure 1). Because the amount of precipitation is usually higher in the western part of the area [37], the obtained geographical pattern suggests that too much moisture in September has a negative impact on larch growth. This relation disappears to the east (this is more clear when Tatra Mountain sites are excluded, Figure 7h). Only for one of the eastern sites (ci2) is the correlation significant but positive. This could be explained by the southern aspect of this site, which makes it more sensitive to drought.

5. Conclusions

Larch growth response to climatic factors in the Polish Carpathians is highly variable. Uniformity of the reactions across the analyzed area was found in the positive growth response to May temperatures, thus indicating that a warm beginning of the growing season is critical for larch growth across the study area.

The recorded larch growth variability reflects the varied climate of this region, which is mainly constrained by two kinds of influence that overlap and mix. The transition from a more oceanic to a more continental influenced climate (macroscale influence) seems responsible for the larch signal variability from west to east in the results of PCA analysis; however, this transition is not clearly visible in the results of the climate–growth relationship analysis. This could be explained by the fact that the observed response variability is additionally affected by the second influence, which is related to the increasing strength of the mountainous climate, itself related to morphological changes and higher altitudes (mesoscale influence).

Although the climate–growth response of larch at lower elevations is highly variable, a positive influence of precipitation in early summer (July) is observed. This is similar to the response of larch in lowlands, where growth is water related. However, a wet start of the vegetation season (April), as well as previous May and July temperatures, can negatively influence larch tree-ring growth at lower elevations.

The growth of larch in the highest study sites in the inner part of the Carpathians with high mountain environment type (Tatra Mountains, above 950 m a.s.l.) is similar to the temperature-related growth of coniferous trees at high elevations in the Alps. This is manifested by a strong positive correlation with temperature during late spring, early summer, and the end of the previous growing season, and a negative or no response to late spring/summer precipitation. The altitudinal relevance of the climate–growth response and the possible change in response pattern at about 600 m a.s.l. is suggested by similarities found between the Tatra Mountains and the Western Bieszczady (sites above 600 m a.s.l.). However, the signal observed in trees from the latter region could also be influenced by the aforementioned west-east transition that is not visible in the Tatra Mountains, where tree-ring growth response is dominated by altitude. More studies on larch at these elevations in other parts of the Carpathians (e.g., western part) are needed to confirm this suggestion.

The presented results provide new information on the climate–growth response of larch in the Carpathians and prove its spatial variability. These studies increase the knowledge about the response of European larch to climatic factors, especially in medium-elevation mountains. However, more studies in other parts of the Carpathians are needed to understand regional variations in larch growth better. These studies can be used for more detailed analysis of the larch growth process as a function of climatic factors.

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Conflicts of Interest: The authors declare no conflict of interest.

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