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# Radial Growth Response of European Larch Provenances to Interannual Climate Variation in Poland

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**Abstract:** The present study identified the similarities and differences in the radial growth responses of 20 provenances of 51-year-old European larch (*Larix decidua* Mill.) trees from Poland to the climatic conditions at three provenance trials situated in the Polish lowlands (Siemianice), uplands (Bliżyn) and mountains (Krynica). A chronology of radial growth indices was developed for each of 60 European larch populations, which highlighted the interannual variations in the climate-mediated radial growth of their trees. With the aid of principal component, correlation and multiple regression analysis, supra-regional climatic elements were identified to which all the larch provenances reacted similarly at all three provenance trials. They increased the radial growth in years with a short, warm and precipitation-rich winter; a cool and humid summer and when high precipitation in late autumn of the previous year was noted. Moreover, other climatic elements were identified to which two groups of the larch provenances reacted differently at each provenance trial. In the lowland climate, the provenances reacted differently to temperature in November to December of the previous year and July and to precipitation in September. In the upland climate, the provenances differed in growth sensitivity to precipitation in October of the previous year and June–September. In the mountain climate, the provenances responded differently to temperature and precipitation in September of the previous year and to precipitation in February, June and September of the year of tree ring formation. The results imply that both climatic factors and origin (genotype), i.e., the genetic factor, mediate the climate–growth relationships of larch provenances.

**Keywords:** *Larix decidua*; tree-ring; climatic sensitivity; temperature; precipitation; provenance trial; dendroecology

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## 1. Introduction

In Poland, European larch trees grow in large stands in just three regions of the country: the Swiętokrzyskie, Sudety and Carpathian Mountains. European larch is also widespread across the Polish lowlands. The presence of European larch at isolated sites and the long history of cultivation of its non-native ecotypes on plantations have differentiated the populations of this species: this is the reason for the high genetic diversity of European larch trees in Poland [1]. Provenance studies indicate that European larch populations have diverse features relating to growth, morphology and disease resistance [1–4]. Phenological observations of larch populations from the various part of Europe growing during provenance trials in Germany [5], Scotland [6], Denmark [7], the Czech Republic [8] and Slovakia [9] indicated the differences in their resistance to early and late frosts. Polish larch provenances also differ in drought resistance [10]. Nevertheless, knowledge of the intraspecies variability of sensitivity of European larch to climatic conditions at various provenance trials remains limited [11–13].

Dendroclimatological research into European larch populations growing in different geographical and climatic regions in Central Europe has shown that the relationships

linking local climate and radial growth are spatially variable [14–27]. Those relationships, identified in the above studies, were found to be mediated by the climatic conditions in each region. The populations investigated were of different ages, were growing in various habitats and, also, had a different history of growth. At our provenance trials, the same set of 51-year-old larch provenances were grown, and the habitat conditions at each site were constant—a great advantage of provenance studies. However, upscaling climate–growth relationships from young to mature larch trees requires careful consideration of the competition- and age-dependent behaviors [17]. Published dendroclimatological studies on European larch growth at provenance trials were confined to two selected provenances or to one test site or to test sites in the same climatic region [11–13,28–30]. Therefore, we decided to extend the range of studies and compare climate–growth relationships between 20 larch populations growing during three provenance trials in different climatic regions.

We hypothesized that (i) there existed supra-regional climatic elements that determined the annual radial growth in the studied larch populations in a similar manner, and (ii) the radial growth response to interannual climate variations differed among the diverse larch provenances growing at the same provenance trial. Thus, the aims of the present study were to (i) develop a chronology of radial growth indices for each larch provenance at three provenance trials (60 provenances in all) and highlight the interannual variations of this growth parameter, (ii) search for similarities and differences in the pattern of radial growth variations between and within the provenance trials and (iii) identify the climatic elements shaping these similarities and differences.

The knowledge of which larch provenances from different climatic regions of Poland are best suited to growth in the climatic conditions of the lowland, upland and mountain areas can be utilized in adaptive forest management [31]. Good breeding values of the Northern Polish provenances growing in the Carpathians indicted that there is a possibility of transferring a forest reproductive material of larch between geographical-climatic regions [1]. European larch is often planted on poor soils in agricultural areas so as to create a typical forest microclimate that protects underplanted saplings of such shade tree species as European beech and Silver fir from strong winds and temperature extremes [32]. The results of our study may therefore be helpful when planning tree plantations, as the seedling survival rate recorded in European larch plantations is closely connected, among other things, with their adaptation to the new climatic conditions [1,33]. Given the current rate of stand conversion in Poland, where the percentage of Scots pine in newly formed stands at fertile sites is falling because of its incompatibility with the habitat, an opportunity arises to increase the percentage of European larch in forests [32].

## 2. Materials and Methods

### 2.1. Study Area and Climate

The present study was carried out at three European larch provenance trials in Western (Siemianice—SI), Central (Bliżyn—BL) and Southern (Krynica—KR) Poland, locations that were part of the 1967 Polish Provenance Experiment (Figure 1b and Table 1). Twenty-one to twenty-three different larch provenances were grown during each trial. Our research addressed the same set of 20 European larch provenances from Poland, listed in Table 2. We rejected the provenances that were grown at just one or two provenance trials. The seeds originated from stands located in various geographical, i.e., lowland, upland and mountain, and climatic regions of Poland (Figure 1b). Soil fertility was the lowest at the BL provenance trial and the highest at KR [1,34].

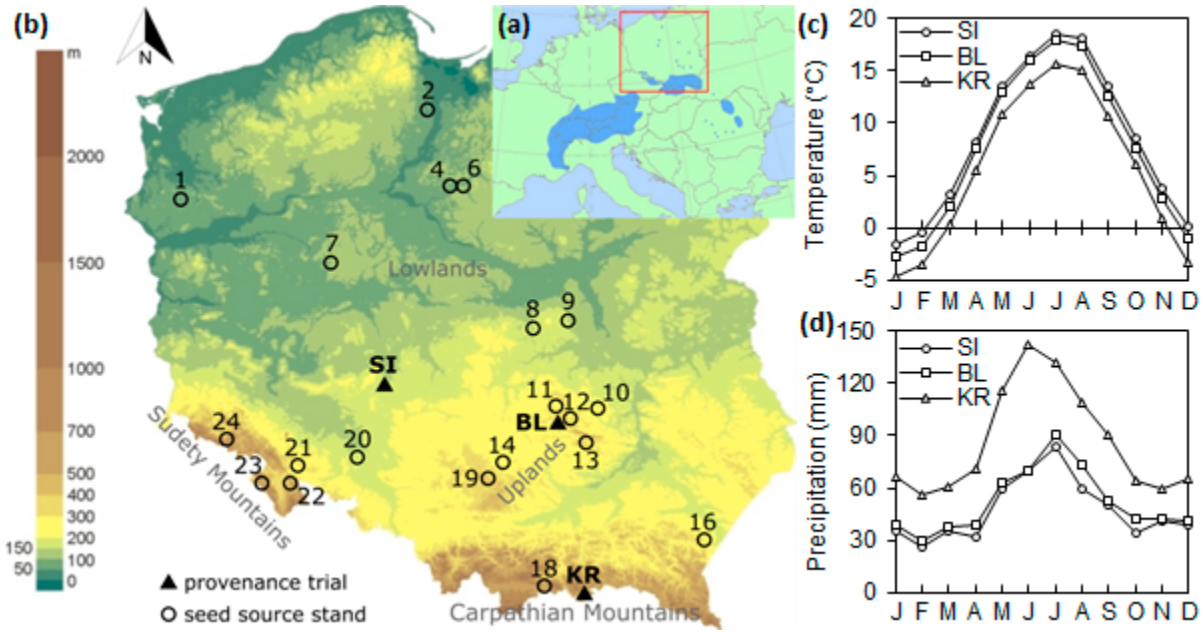



**Figure 1.** Natural distribution range of European larch (**a**) [35]. Locations of the provenance trials in Siemianice (SI), Bliżyn (BL) and Krynica (KR), and locations of the seed source stands (**b**) (dots with provenance numbers; their names are in Table 2; source of map layer: [36]). The climate diagrams for the provenance trials show the mean monthly air temperature (**c**) and total monthly precipitation (**d**) for the period 1970–2015.

**Table 1.** Summary information on the main characteristics of the larch provenance trials [1,4,34].

| Location | Siemianice (SI) | Bliżyn (BL) | Krynica (KR) |
|---|---|---|---|
| Latitude coordinate | 51°13′ N | 51°02′ N | 49°20′ N |
| Longitude coordinate | 18°03′ E | 20°40′ E | 20°59′ E |
| Altitude (m a.s.l.) | 170 | 305 | 790 |
| Slope aspect and inclination | flat | flat | SE, W, 5° (ridge) |
| Mean annual air temperature (°C) | 8.5 | 7.6 | 5.6 |
| Total annual precipitation (mm) | 565 | 618 | 1032 |
| Soil type | *Haplic Podzol* | *Gleyic Podzol* | *Haplic Cambisol* |
| Parent material | glacial sandstone | glacial sandstone | Carpathian flysch |
| Soil texture | sand | clay loam | silty clay loam |
| Humus type | moder/mor | mor | mull |
| Provenance trial size ($m^2$) | 49,100 | 28,000 | 40,800 |
| Number of provenances at provenance trial | 21 | 23 | 21 |
| Plots per provenance (replications) | 5 | 3 | 5 |
| Plot size ($m^2$) | 384 | 400 | 400 |
| Seedlings per plot | 96 | 100 | 121 |
| Planting spacing (m) | 2.0 × 2.0 | 2.0 × 2.0 | 1.8 × 1.8 |
| Planting year | 1967 | 1968 | 1967 |
| Current number of trees per provenance | 37–114 | 9–92 | 6–162 |

**Table 2.** Location and climate parameters of seed source stands and dendrometric statistics of the studied larch provenances growing during the provenance trials in Siemianice (SI), Bliżyn (BL) and Krynica (KR) [4,36,37].

| No * | Name of Provenance | Region of Poland | Coordinate of Seed Stand | | Elevation of Seed Stand (m a.s.l.) | Annual Air Temperature (°C) | Total Annual Precipitation (mm) | Mean DBH (mm) ** | | | Mean H (m) ** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Latitude N | Longitude E | | | | SI | BL | KR | SI | BL | KR |
| 1 | Myślibórz | northwestern lowland | 52°54′ | 14°52′ | 60 | 8.8 | 568 | 316.4 | 214.2 | 244.1 | 26.3 | 21.1 | 23.8 |
| 2 | Pelplin | north lowland | 53°56′ | 18°43′ | 60 | 8.2 | 510 | 309.1 | 180.9 | 260.9 | 24.6 | 19.2 | 23.7 |
| 4 | Płonne | north lowland | 53°07′ | 19°04′ | 60 | 8.4 | 540 | 325.8 | 199.3 | 258.2 | 25.9 | 20.4 | 24.8 |
| 6 | Tomkowo | north lowland | 53°07′ | 19°04′ | 60 | 8.4 | 540 | 297.8 | 230.7 | 268.3 | 24.7 | 21.5 | 23.9 |
| 7 | Czerniejewo | western lowland | 52°26′ | 17°30′ | 110 | 8.8 | 516 | 288.2 | 197.9 | 260.2 | 25.0 | 20.4 | 23.6 |
| 8 | Rawa | central lowland | 51°48′ | 20°15′ | 180 | 8.3 | 540 | 322.0 | 250.4 | 260.3 | 24.9 | 21.4 | 21.9 |
| 9 | Grójec | central lowland | 51°52′ | 20°52′ | 180 | 8.5 | 565 | 342.1 | 239.4 | 257.9 | 23.8 | 20.9 | 22.7 |
| 10 | Marcule | central upland | 51°08′ | 21°15′ | 210 | 7.8 | 662 | 327.8 | 235.7 | 258.7 | 25.0 | 20.7 | 21.3 |
| 11 | Skarżysko | Swietokrzyskie Mts | 51°10′ | 20°46′ | 375 | 7.6 | 687 | 308.9 | 253.8 | 245.6 | 24.8 | 22.9 | 22.4 |
| 12 | Bliżyn | Swietokrzyskie Mts | 51°05′ | 20°45′ | 300 | 7.6 | 618 | 319.8 | 214.0 | 247.9 | 26.5 | 21.1 | 23.0 |
| 13 | Chełmowa | Swietokrzyskie Mts | 50°55′ | 21°04′ | 350 | 6.8 | 769 | 400.6 | 234.1 | 259.1 | 28.2 | 20.9 | 23.3 |
| 14 | Moskorzew | central upland | 50°39′ | 19°56′ | 250 | 8.3 | 627 | 300.0 | 218.9 | 259.4 | 22.8 | 22.1 | 24.2 |
| 16 | Hołubla | Carpathian foothill | 49°48′ | 22°48′ | 325 | 8.2 | 670 | 330.5 | 202.0 | 266.5 | 26.4 | 19.4 | 24.0 |
| 18 | Krościenko | Carpathian Mts | 49°27′ | 20°26′ | 650 | 7.0 | 847 | 266.7 | 205.6 | 226.5 | 23.7 | 20.2 | 22.0 |
| 19 | Pilica | central upland | 50°28′ | 19°40′ | 450 | 8.0 | 655 | 285.3 | 231.7 | 254.9 | 23.6 | 21.8 | 23.2 |
| 20 | Prószków | western lowland | 50°35′ | 17°52′ | 180 | 9.0 | 604 | 319.1 | 182.0 | 249.9 | 24.7 | 19.5 | 24.5 |
| 21 | Henryków | Sudety foothill | 50°41′ | 17°01′ | 325 | 8.1 | 717 | 320.4 | 245.5 | 259.8 | 25.9 | 20.4 | 22.7 |
| 22 | Kłodzko | Sudety Mts | 50°22′ | 16°45′ | 375 | 7.6 | 592 | 311.8 | 191.8 | 277.5 | 25.5 | 20.9 | 24.0 |
| 23 | Szczytna | Sudety Mts | 50°25′ | 16°26′ | 525 | 6.5 | 921 | 289.0 | 214.8 | 242.0 | 24.4 | 23.8 | 24.3 |
| 24 | Kowary | Sudety Mts | 50°48′ | 15°50′ | 525 | 7.2 | 1028 | 323.4 | 208.0 | 245.9 | 26.2 | 21.3 | 24.4 |
| | | Mean for provenance trial | | | | | | 315.5 | 218.1 | 255.2 | 25.2 | 20.9 | 23.4 |

* Provenances are numbered in according to the applicable numeration for the 1967 Polish Provenance Experiment [34]. ** Tree diameter at breast height (DBH) and tree height (H) were measured at SI and BL in 2011 and at KR in 2012.

The air temperature and precipitation conditions prevailing at the three provenance trials are illustrated in Figure 1c,d. The mean monthly air temperatures and monthly precipitation totals for the period 1970–2015 were obtained from three weather stations (IMGW–PIB in Wieluń—51°13′ N, 18°33′ E, 201 m a.s.l.; IMGW–PIB in Kielce—50°49′ N, 20°43′ E, 261 m a.s.l. and Kopciowa—49°27′ N, 20°57′ E, 720 m a.s.l.), which are situated near the provenance trials and have sufficiently long and homogeneous sequences of meteorological measurements. The normal distribution of climatic data set was checked by the Shapiro–Wilk test. Tukey's honestly significant difference (HSD) test showed that the differences between the monthly climatic parameters for the provenance trials were statistically significant ($p < 0.05$), except for the monthly temperatures and precipitation totals at SI and BL [38]. The climate of the KR provenance trial was the coldest and the most abundant in precipitation. The warmest and driest location was SI, while intermediate air temperatures and precipitation levels were recorded at BL. At KR, the air temperature in the summer months was slightly in excess of 15 °C, and the total annual precipitation frequently surpassed 1000 mm, a figure that was almost twice as high as that for SI. At each provenance trial, the precipitation levels peaked in the summer and dropped to a minimum in the winter. The coldest month at the three provenance trials was January, and the warmest was July. The annual air temperature amplitude at BL and KR was higher than at SI. The meteorological vegetation period (with a 24-h mean temperature of at least 5 °C) started the earliest (in the middle of March) and was the longest (235 days) at SI and, at KR, started the latest (in the beginning of April) and was the shortest (218 days). The precipitation in the vegetation period was the lowest at SI (413 mm) and the highest at KR (726 mm).

### 2.2. Sampling and Development of Chronologies

For each provenance at each provenance trial, a total of 20 dominant and codominant 51-year-old European larch trees were drilled twice at a height of 1.3 m above the ground (from the west (W) and east (E) directions). The sanded cores were scanned using an optical scanner, and tree ring widths were measured in graphical images of the cores (2400 DPI) to the nearest 0.01 mm using CooRecorder & CDendro 7.8 computer software (Pålnäsvägen, Sweden) [39]. The quality of the measurement data and cross-dating were examined using the COFECHA program [40]. All the tree ring width (TRW) series passed the cross-dating check and were used to develop the chronologies. Thus, 40 TRW series (2 cores per tree) were used for each provenance in the analyses, except for provenance No. 2 (Pelplin) at BL, where only 12 trees were suitable for sampling (24 TRW series used). The TRW of two series from one tree were averaged for each year. The tree chronologies were then indexed to minimalize the first-order autocorrelation and remove the nonclimatic trends caused, among other things, by tree aging and to highlight the short-term variations of the radial growth due to the interannual variations of the meteorological conditions. For this purpose, the TRW values were converted into annual sensitivity values (growth indices) for each year using the following formula: $as_i = 2 \times (x_i - x_{i-1}) \times (x_i + x_{i-1})^{-1}$, where $as_i$—annual sensitivity in year $i$ and $x_i$—tree ring width in year $i$ [41]. The $as_i$ values range from −2.0 to 2.0. Negative values indicate a decrease and positive values indicate an increase in the TRW compared to the TRW in the previous year.

Consequently, each European larch tree was represented by an individually indexed chronology. One indexed chronology for each larch provenance at each provenance trial was developed on the basis of 20 indexed tree chronologies. The first-order autocorrelation of the indexed chronologies was close to zero. Subsequently, a mean indexed chronology (local chronology) for each provenance trial was created by averaging 20 indexed provenance chronologies. The time period common to all the indexed chronologies used in the study was 1971–2015. The following chronology statistics were calculated for each larch provenance: mean correlation coefficient for the indexed tree chronologies ($r_{bt}$), mean sensitivity (MS), expressed population signal (EPS) and signal-to-noise ratio (SNR). The MS exhibited interannual changes in tree sensitivity to climate conditions [42], and $r_{bt}$ indicated

the similarities of the short-term radial growth responses of trees from each of the larch provenances. The EPS allows one to estimate the fraction of the variance of the hypothetical population chronology that is explained by the sample chronology in question [43]. The SNR shows the strength of the common high-frequency (climatic) signal in the indexed chronology [44]. The significance of the differences between the mean values of the TRW, MS, $r_{bt}$, EPS and SNR of the provenance trials was tested by Tukey's HSD test [38].

### 2.3. Grouping of Provenances and Climate–Growth Relationships

A principal component analysis (PCA) was used to reveal the common radial growth patterns of European larch, described by 60 indexed chronologies of larch provenances. This method was applied in earlier dendroclimatic studies [45–47]. The radial growth indices were converted into a new set of variables (principal components) calculated from the covariance matrix of the original data. The yearly component scores calculated by the PCA represented the common variations of the radial growth indices of larch provenances for the period 1971–2015. In our analysis, we took into account the first three principal components that had eigenvalues $\geq$1. The component loadings indicated the relationships between the chronologies and the new factors—the principal components. This is because the loading $a_{ij}$ was equal to the correlation coefficient between a given original variable—the indexed chronology (i)—and a given principal component (j) [38]. The graph of the positions of the 60 chronologies vs. the component loadings illustrated the form of grouping of the indexed chronologies (the larch provenances examined here) with regards to the new factors. For each provenance trial, a similar PCA was performed on the 20 indexed chronologies of larch provenances growing there.

In order to make sure that it was mostly the climate factor that described the first three principal components, 60 series of the correlation coefficient describing the climate–radial growth relationships in the studied larch provenances were included in the PCA. Each series consisted of 26 correlation coefficients, which were calculated for the indexed provenance chronologies, as well as the mean monthly air temperatures and monthly precipitation totals for 13 consecutive months, starting from September of the previous year and ending with September in the year of tree ring formation (in all, $2 \times 13 = 26$ climatic variables) for the period of 1970–2015. The PCA was performed using STATISTICA 13 software (Krakow, Poland) [48].

Identification of the first three principal components (PC1, PC2 and PC3) distinguished during the PCA of the indexed chronologies of the larch provenances was based on Pearson's correlation and a multiple regression (response function) analysis of the yearly component scores (i.e., independent variables), as well as the monthly air temperatures and precipitation totals from the previous September to the current September for the period of 1970–2015. The calculations were carried out using RESPO software (Tucson, AZ, USA), which removes the collinearity of the climatic variables with the aid of the PCA [49]. The results of these analyses were further compared with the correlation coefficients between the climatic parameters and the local indexed chronologies for the provenance trials and, also, with the regression coefficients for the climatic parameters and the mean indexed chronologies of the two groups of provenances at each provenance trial.

## 3. Results

### 3.1. Statistics of the Chronologies

The TRW chronologies of the provenances growing during the three provenance trials displayed a falling linear trend with respect to tree aging and a similar medium-term variation in the period of 1970–2015 (Figure 2a). The highest mean TRW values were recorded for the provenances at the SI provenance trial and varied from 2.80 to 4.01 (Table 3). The lowest mean TRW values were noted for the provenances at BL (2.43–3.43). At KR, the mean TRW values ranged from 2.70 to 3.35. The differences between the mean TRW for the provenance trials were significant ($p < 0.05$). The indexed provenance chronologies possessed a stabilized variation and a mean value close to 0. The coefficients

of the first-order autocorrelation for all the chronologies (0.10–0.37) were insignificant ($p < 0.01$).

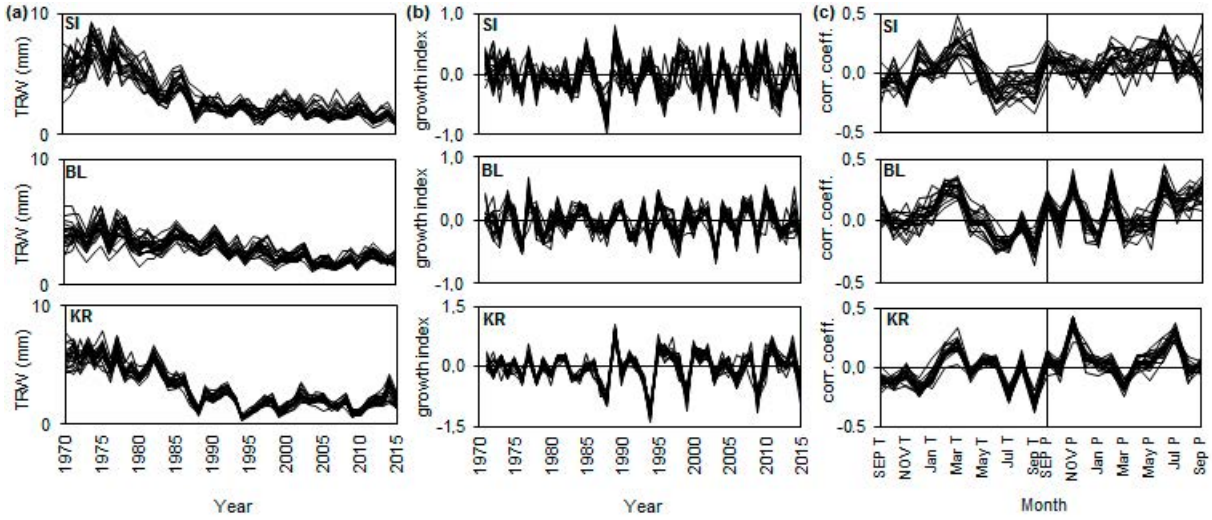



**Figure 2.** Mean tree ring width (**a**) and indexed (**b**) chronologies of the larch provenances and a series of correlation coefficients (**c**) for the provenance trials in Siemianice (SI), Bliżyn (BL) and Krynica (KR), as calculated between the indexed chronologies and mean monthly air temperature (T) and total monthly precipitation (P) for 13 consecutive months from September of the previous year (SEP) to September of the year of tree ring formation (Sep).

**Table 3.** Chronology statistics for sample populations of larch provenances growing during the provenance trials in Siemianice (SI), Bliżyn (BL) and Krynica (KR).

| No | Name of Provenance | Mean TRW (mm) ** | | | MS | | | $r_{bt}$ | | | EPS | | | SNR | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SI | BL | KR | SI | BL | KR | SI | BL | KR | SI | BL | KR | SI | BL | KR |
| 1 | Myślibórz | 3.40 | 3.22 | 3.19 | 0.25 | 0.23 | 0.27 | 0.70 | 0.67 | 0.57 | 0.98 | 0.98 | 0.96 | 45.7 | 39.8 | 26.5 |
| 2 | Pelplin | 3.35 | 2.43 | 3.12 | 0.27 | 0.26 | 0.35 | 0.56 | 0.63 | 0.75 | 0.96 | 0.95 | 0.98 | 25.7 | 19.0 | 58.7 |
| 4 | Płonne | 2.96 | 2.86 | 3.08 | 0.26 | 0.25 | 0.32 | 0.60 | 0.69 | 0.69 | 0.97 | 0.98 | 0.98 | 30.4 | 43.4 | 43.5 |
| 6 | Tomkowo | 2.81 | 2.97 | 3.03 | 0.28 | 0.20 | 0.34 | 0.58 | 0.56 | 0.74 | 0.97 | 0.96 | 0.98 | 28.1 | 24.9 | 56.7 |
| 7 | Czerniejewo | 2.80 | 2.72 | 2.84 | 0.27 | 0.22 | 0.34 | 0.54 | 0.61 | 0.69 | 0.96 | 0.97 | 0.98 | 23.7 | 31.2 | 45.1 |
| 8 | Rawa | 3.05 | 2.77 | 3.00 | 0.25 | 0.18 | 0.34 | 0.55 | 0.68 | 0.81 | 0.96 | 0.98 | 0.99 | 24.5 | 43.3 | 87.2 |
| 9 | Grójec | 3.69 | 2.70 | 2.70 | 0.22 | 0.19 | 0.31 | 0.47 | 0.71 | 0.69 | 0.95 | 0.98 | 0.98 | 17.9 | 48.0 | 43.6 |
| 10 | Marcule | 3.50 | 3.00 | 3.35 | 0.26 | 0.19 | 0.31 | 0.61 | 0.59 | 0.73 | 0.97 | 0.97 | 0.98 | 31.6 | 29.3 | 54.4 |
| 11 | Skarżysko | 3.18 | 3.16 | 2.96 | 0.24 | 0.20 | 0.31 | 0.60 | 0.65 | 0.63 | 0.97 | 0.97 | 0.97 | 30.5 | 37.5 | 34.0 |
| 12 | Bliżyn | 2.95 | 2.84 | 2.97 | 0.23 | 0.18 | 0.32 | 0.38 | 0.72 | 0.66 | 0.93 | 0.98 | 0.97 | 12.4 | 51.4 | 38.1 |
| 13 | Chełmowa | 3.44 | 3.43 | 2.84 | 0.23 | 0.19 | 0.31 | 0.67 | 0.53 | 0.78 | 0.98 | 0.96 | 0.99 | 41.2 | 22.8 | 72.0 |
| 14 | Moskorzew | 3.08 | 3.08 | 2.87 | 0.25 | 0.20 | 0.33 | 0.55 | 0.52 | 0.48 | 0.96 | 0.96 | 0.95 | 24.9 | 21.9 | 18.5 |
| 16 | Hołubla | 4.01 | 2.68 | 3.24 | 0.29 | 0.19 | 0.34 | 0.63 | 0.57 | 0.81 | 0.97 | 0.96 | 0.99 | 34.3 | 26.3 | 83.7 |
| 18 | Krościenko | 2.94 | 2.80 | 2.82 | 0.32 | 0.21 | 0.37 | 0.75 | 0.63 | 0.77 | 0.98 | 0.97 | 0.99 | 61.0 | 34.7 | 66.3 |
| 19 | Pilica | 3.14 | 2.80 | 2.92 | 0.31 | 0.21 | 0.35 | 0.72 | 0.63 | 0.69 | 0.98 | 0.97 | 0.98 | 51.2 | 34.7 | 46.3 |
| 20 | Prószków | 3.35 | 2.54 | 2.89 | 0.27 | 0.20 | 0.34 | 0.54 | 0.59 | 0.68 | 0.96 | 0.97 | 0.98 | 23.0 | 29.3 | 42.8 |
| 21 | Henryków | 3.38 | 2.67 | 3.21 | 0.26 | 0.19 | 0.30 | 0.67 | 0.56 | 0.70 | 0.98 | 0.96 | 0.98 | 39.9 | 25.1 | 47.4 |
| 22 | Kłodzko | 3.24 | 2.76 | 3.12 | 0.27 | 0.22 | 0.30 | 0.55 | 0.64 | 0.65 | 0.96 | 0.97 | 0.97 | 24.1 | 35.4 | 24.6 |
| 23 | Szczytna | 3.00 | 3.07 | 2.78 | 0.31 | 0.20 | 0.32 | 0.55 | 0.71 | 0.72 | 0.96 | 0.98 | 0.98 | 24.1 | 48.2 | 51.6 |
| 24 | Kowary | 3.74 | 2.94 | 3.03 | 0.27 | 0.21 | 0.30 | 0.49 | 0.60 | 0.66 | 0.95 | 0.97 | 0.98 | 18.9 | 30.2 | 38.4 |
| | Mean for provenance trial | 3.25 * | 2.87 * | 3.00 * | 0.26 * | 0.21 * | 0.32 * | 0.59 | 0.62 | 0.69 * | 0.96 | 0.97 | 0.98 | 30.7 | 33.8 | 49.0 * |

TRW—tree ring width. MS—mean sensitivity. $r_{bt}$—mean between-tree correlation. EPS—expressed population signal. SNR—signal-to-noise ratio. * Significant ($p < 0.05$) differences between the means of the provenance trials and the means of the other sites. ** All shown statistics, except for the TRW, were calculated for the chronologies of the growth indices.

The mean sensitivities of the provenances studied here differed. The MS was the lowest for the provenances growing at BL, where values ranged from 0.18 to 0.26 (Table 3). BL is located in an upland area with a warmer climate than at KR but cooler than that at SI. The trees at BL were not too often exposed to extreme climatic changes. The radial

growth sensitivity was the highest for the provenances at KR, which experience the cold and humid climate of the Carpathian Mountains. MS at KR varied from 0.27 to 0.37, and for each provenance at that site, was significantly ($p < 0.05$) higher than at the other two sites (Table 3). At SI, the MS was also relatively high (0.22–0.32) and higher than at BL. At the three provenance trials, the values of $r_{bt}$ varied from 0.38 to 0.81. This indicator was significantly ($p < 0.05$) higher for the provenances at KR than at SI and BL. This means that the degree of homogeneity of the tree radial growth reactions was the highest in the mountain climate. As a consequence of the high $r_{bt}$ and the relatively large number of sampled trees (20), the EPS attained very high values for each provenance (0.93–0.99) (Table 3). The representativeness of all the indexed provenance chronologies was therefore high. The SNR values were the highest for the provenances at KR, so their chronologies possessed the strongest high-frequency (climatic) signal. The provenances from KR differed significantly ($p < 0.05$) in SNR from those growing at SI and BL. Table 3 shows that the values of the $r_{bt}$, MS, EPS and SNR recorded for the provenances were highly diverse during each provenance trial.

### 3.2. Grouping of Provenances

The provenances were grouped using the PCA of the indexed chronologies; these illustrated the interannual variability in the magnitude of the radial growth indices as a response of the trees to the climatic conditions (Figure 2b). The first three principal components explained 81% of the total variance of the 60 indexed chronologies (Figure 3). PC1 most effectively explained the variance of the mean radial growth indices of the provenances. The positions of the chronologies in relation to the loadings of PC1 indicated that it served to integrate the chronologies obtained. All the chronologies correlated positively ($p < 0.05$) with PC1, which explained 44% of the variance among the chronologies (Figure 3). Based on the PCA, there was a clear separation of the chronologies into three groups, representing three different environmental conditions. The indexed chronologies from SI correlated positively ($p < 0.05$) with PC2 (Figure 3). The chronologies obtained for BL correlated poorly and positively with PC2, while those for KR correlated negatively with PC2 ($p < 0.05$). The indexed chronologies for BL correlated positively ($p < 0.05$) with PC3, and the chronologies for SI correlated negatively with PC3 ($p < 0.05$), whereas the chronologies for KR correlated poorly and negatively with PC3. PC2 and PC3, respectively, explained 22% and 15% of the variance among the chronologies.

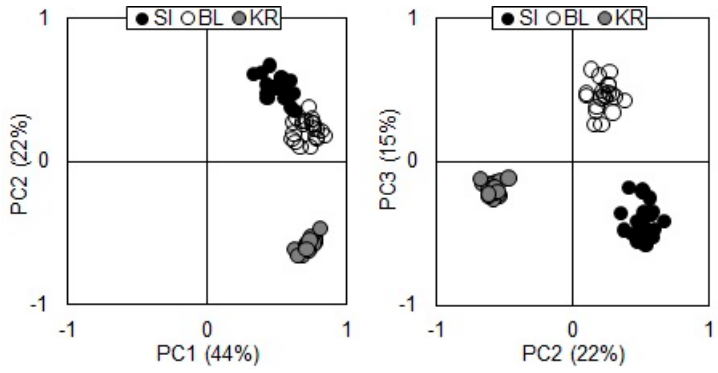



**Figure 3.** Grouping of the indexed chronologies of the larch provenances (see Figure 2b) in relation to the loadings of the principal components: PC1, PC2 and PC3. The parentheses provide the percentages of the total variances of the chronologies explained by their individual principal components.

The results of the PCA performed on the indexed chronologies (Figure 2b) and the series of correlation coefficients obtained from the climate–growth analysis (Figure 2c) yielded the same groupings of provenances, so only the results of the PCA conducted on the chronologies are presented in Figure 3. The similarities and differences in the patterns

of the radial growth variations of the provenances were the result of their responses to the local climatic conditions during the provenance trials.

Next, the PCA of the indexed chronologies for each separate provenance trial was performed (Figure 4a–c). The provenances were divided into two groups relative to PC2 but not by the region of origin of European larch. Each group contained the chronologies from the Polish lowlands, uplands and mountains. The compositions of the groups in the three provenance trials were different.

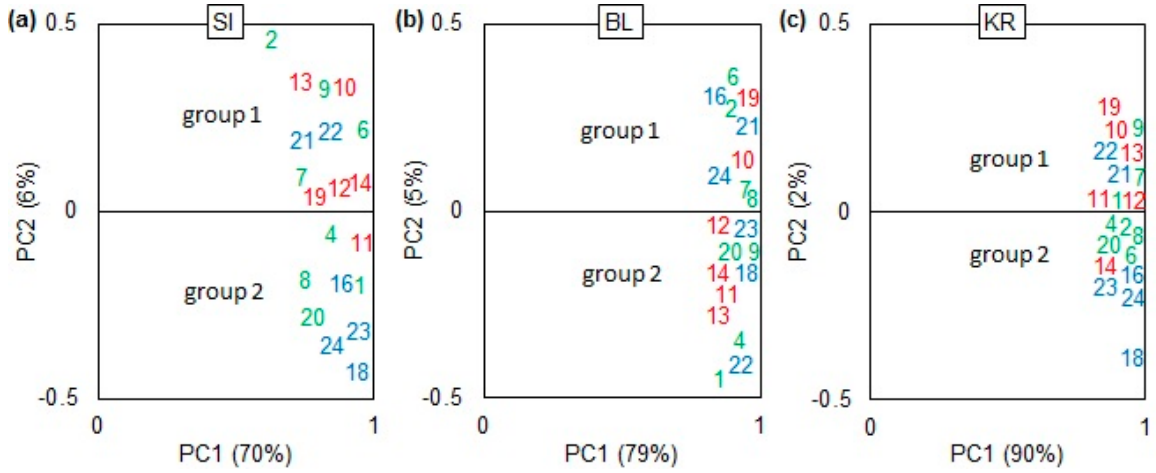



**Figure 4.** Grouping of the indexed chronologies of the larch provenances (see Figure 2b) from the provenance trials at Siemianice—SI (**a**), Bliżyn—BL (**b**) and Krynica—KR (**c**) in relation to the loadings of PC1 and PC2. The parentheses provide the percentages of the total variances of the chronologies explained by the individual principal components. The provenances that originated from Polish lowlands are marked in green, uplands in red and mountains in blue.

### *3.3. Growth–Climate Relationships in Provenance Trials*

The correlation analysis conducted between the yearly scores of PC1 and the climatic data revealed significant positive relationships between the radial growths of the provenances growing in the three provenance trials and the mean monthly air temperatures in February and March; the total precipitation in February, June and July in the year of tree ring formation and, also, the precipitation in November of the previous year (Figure 5a). The PC1 scores were negatively related to temperature in July and September in the current year. The PC2 scores correlated significantly ($p < 0.05$) with temperature in the previous December and June in the current year. In turn, the PC3 scores correlated significantly ($p < 0.05$) with precipitation in the current September (Figure 5a). The climatic variables described by PC2 and PC3 differentiated the radial growth patterns of the provenances growing during the three provenance trials.

These results were verified by correlating the climatic variables with the mean indexed chronologies developed for the provenance trials at SI, BL and KR (Figure 5b). These three chronologies correlated positively with temperature in the current February and March and with precipitation in the previous November and current February, June and July. The SI, BL and KR chronologies were negatively correlated with temperature in the current July and September. These relationships tallied with the results of the correlation analysis for PC1 (see Figure 5a,b). The results of the correlation analysis of PC2 and PC3 were also confirmed (see Figure 5a,b). The radial growths of the provenances at KR were negatively associated with temperature in the previous December but positively so at SI and BL. The radial growths of the trees responded positively to temperature in June at KR but negatively during the other provenance trials. At BL, the magnitude of the annual radial growth was clearly positively related with precipitation in the current September. Moreover, the provenance growths at SI and KR were not responsive to precipitation during this month (Figure 5b).

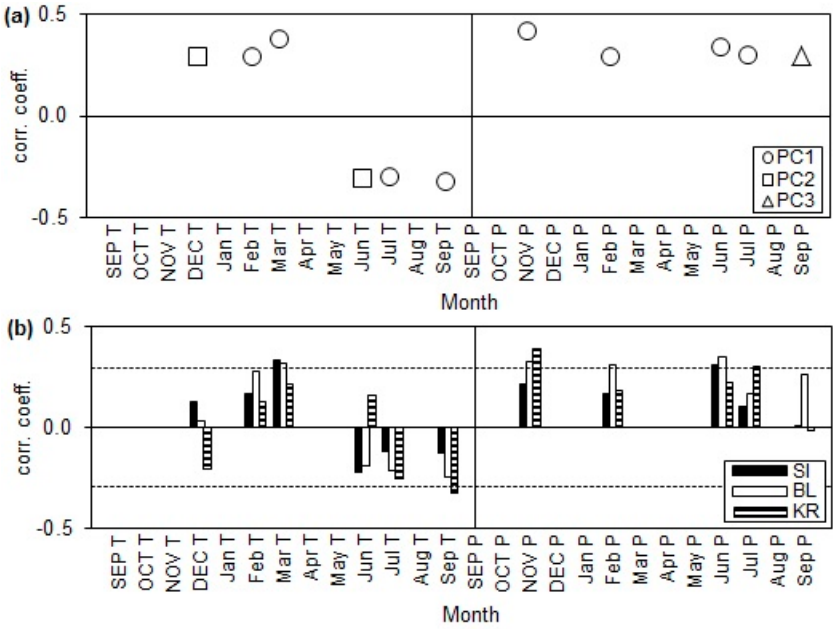



**Figure 5.** Significant correlation coefficients ($p < 0.05$) between the yearly scores of PC1, PC2 and PC3 and the mean monthly air temperatures (T) and total monthly precipitations (P) from the previous September (SEP) to the current September (Sep) for the period of 1971–2015 (**a**). Correlation coefficients between the mean indexed chronologies for the provenance trials in Siemianice (SI), Bliżyn (BL) and Krynica (KR) and the above-mentioned climatic data. The 95% confidence level—dashed lines (**b**).

### *3.4. Interpopulational Variability of Radial Growth Responses of Provenances to Climatic Conditions at the Provenance Trials*

In the case of SI, the response function analysis indicated that PC1 correlated significantly ($p < 0.05$) and positively with temperature in October of the previous year, and March and April, and, also, with precipitation in November of the previous year, and February, March, July and August, but negatively with temperature in June (Figure 6a). In turn, PC2 correlated significantly ($p < 0.05$) and positively with temperature in November and December of the previous year and, also, with precipitation in September in the year of tree ring formation but negatively with temperature in July.

To verify the results for two principal components, a response function analysis for the climatic parameters and mean indexed chronologies of groups 1 and 2 was carried out (see Figures 4a and 6a). The mean chronologies of both groups of provenances correlated significantly ($p < 0.05$) and positively with temperature in October of the previous year, and March and April, but negatively with temperature in June (Figure 6a). They also correlated significantly ($p < 0.05$) and positively with precipitation in November of the previous year and February, March, June and August. We found identical significant correlations for PC1. This indicated that all the provenances at SI responded similarly to the climatic variables described by PC1.

We also found differences between the groups. The chronology of group 1 correlated significantly ($p < 0.05$) and positively with temperature in November and December of the previous year, and with precipitation in September in the year of tree ring formation, but negatively with temperature in July. For group 2, opposite signs of the regression coefficients were noted (Figure 6a). The provenances from groups 1 and 2 were therefore variably sensitive to the climatic variables represented by PC2.

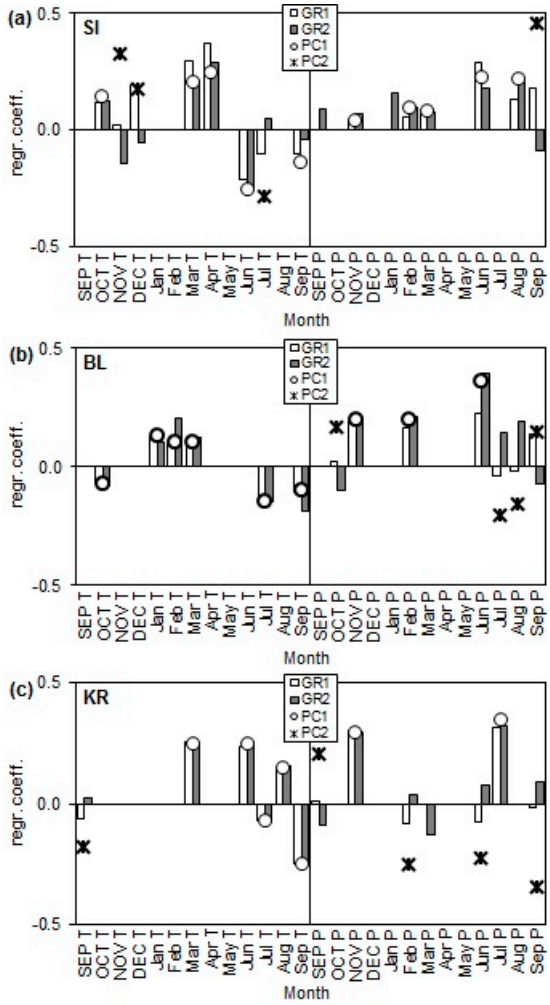



**Figure 6.** Significant ($p < 0.05$) multiple regression (response function) coefficients calculated for the yearly scores of PC1 and PC2 and the mean indexed chronologies of the larch provenances from groups 1 (GR1) and 2 (GR2) for the provenance trials in Siemianice—SI (**a**), Bliżyn—BL (**b**) and Krynica—KR (**c**). Independent variable were the mean monthly air temperature (T) and total monthly precipitation (P) from the previous September (SEP) to the current September (Sep) for the period of 1971–2015.

In the case of BL, PC1 correlated significantly ($p < 0.05$) and positively with temperature in January, February and March and with precipitation in November of the previous year, and February and June, but negatively with temperature in October of the previous year and June and September in the year of tree ring formation (Figure 6b). PC2 correlated significantly ($p < 0.05$) and positively with precipitation in October of the previous year and in September of the current year but negatively with precipitation in July and August.

The results of the response function analysis for the group 1 and 2 chronologies and the climatic parameters corresponded with the results of the previous analysis (see Figures 4b and 6b). The chronologies of both groups correlated significantly ($p < 0.05$) and negatively with temperature in October of the previous year and July and in September of the year of tree ring formation (Figure 6b). In addition, they correlated significantly ($p < 0.05$) and positively with precipitation in November of the previous year, and February and June, and with temperature in January, February and March. All the provenances at BL were similarly sensitive to the climatic variables described by PC1.

The provenances in both groups reacted differently to the climatic variable represented by PC2. The chronology of group 1 correlated significantly ($p < 0.05$) and positively with precipitation in October of the previous year and in September of the current year but

negatively with precipitation in July and August. The opposite signs of the regression coefficients were noted for group 2 (Figure 6b).

In the case of KR, PC1 correlated significantly ($p < 0.05$) and positively with temperature in March, June and August, and with precipitation in November of the previous year and July, but negatively with temperature in July and September of the current year (Figure 6c). In turn, PC2 correlated significantly ($p < 0.05$) and negatively with temperature in September of the previous year, and with precipitation in February, June and September in the year of tree ring formation, but positively with precipitation in September of the current year. These results coincided with the results of the response function analysis for the mean indexed chronologies of groups 1 and 2 and the climatic parameters (see Figures 4c and 6c). The chronologies of both groups correlated significantly ($p < 0.05$) and positively with temperature in March, June and August but negatively with temperature in July and September in the year of tree ring formation. They correlated significantly ($p < 0.05$) and positively with precipitation in the previous November and the current July. These results show that all the provenances growing during this provenance trial responded similarly to the climatic variables represented by PC1.

The chronology of group 1 correlated significantly ($p < 0.05$) and negatively with temperature in the previous September and with precipitation in February, June and September in the year of tree ring formation but positively with precipitation in the previous September. The opposite radial growth responses to these climatic elements were found for group 2 (Figure 6c). The two groups of provenances reacted differently to the climatic variables described by PC2.

These highlighted supra-regional climatic elements corresponded with those of the local nature, to which the all the provenances growing during the individual provenance trials exhibited similar radial growth sensitivity (see Figures 5 and 6).

## 4. Discussion

### *4.1. Chronology Statistics*

This study indicates that the various European larch provenances from Poland growing in the cold, moist climate of the provenance trial at KR, situated in a montane zone (790 m a.s.l), and in the warm, dry climate of SI, situated in a lowland area, were more sensitive to the climate than those at BL, which lies in an upland area. The climate at BL was the weakest trigger for European larch. We showed that the more extreme the climatic conditions, the stronger the trees' radial growth responses to their pressures. The mean sensitivities for larch provenances growing at KR were very high (>0.30), except for provenance No. 1 (0.27), the origin of which was in Northwestern Poland. Lower MS values than at KR were obtained in a local indigenous European larch population in the Polish Carpathians (0.19–0.26) and the Sudety Mountains (0.19–0.30) [50,51]. The mean sensitivity was also found to be relatively high in European larch populations growing in the mountain climate of the Alps: 0.23–0.28 [23], 0.315–0.375 [17], 0.26–0.37 [18] and 0.29 [26]. Having examined various tree species in different climatic zones in the USA, Sakulich [52] concluded that values of MS > 0.3 should be considered high. Thus, the larch provenances from other regions of Poland growing at KR must have been subject to the pressures of the harsh mountain climate. The MS values for the provenances at BL resembled those for the local indigenous larch populations growing in the uplands of Central Poland [22]. Hence, the studied larch provenances from various parts of Poland growing in the uplands were as sensitive to the climate as the local larch populations. As in the case of sensitivity, the homogeneity of the interannual radial growth reactions ($r_{bt}$) and climatic signal (SNR) were the greatest in the larch provenances at KR. This indicates that the mountain climate, which is severe in comparison to the other provenance trials, strongly unified the short-term growth responses of European larch trees. The wide divergence of MS, $r_{bt}$, EPS and SNR values during each provenance trial show that the climatic sensitivity of the larch provenances, the homogeneity of the European larch tree radial growth reactions, the representativeness of the provenance chronologies and the climatic

signal strengths in them were not connected with the regions of origin of these European larch trees.

### 4.2. Common Radial Growth Responses of the Larch Provenances Growing at Three Provenance Trials

The results of our research show that the first principal component can be treated as the multi-provenance variable that described the supra-regional climatic elements that determined the radial growth of European larches, regardless of the region in which they grew. A shorter growing season, high air temperatures in mid- and late summer, insufficient precipitation in the first half of summer and, also, little precipitation in the previous late autumn and the current mid-winter adversely affected the radial growth of all the larch provenances during the three trials.

Our results indicate that the longer the winter, the smaller the magnitude of the annual radial growth of European larch during all three provenance trials, a relationship that was most evident in the lowlands (SI) and uplands (BL). European larch in the mountains (KR) starts growing much later and the growing season is shorter, so the radial growth in European larch is limited by the length of the growing season, which is mainly dependent on its starting date. The earlier trees break dormancy; the more rapid the development of foliage, the sooner the cambium starts to divide [53–55]. A positive relationship between the temperature in February and the radial growth of European larch was found only at some sites in the Alps [16]. A negative relationship between the winter temperature and the tree ring widths of European larch growing at the provenance trial in Puławy (Central Poland) was found by Oleksyn and Fritts [28] and Oleksyn et al. [29]. These growth reductions intensified during a period of increased air pollution, but the authors did not explain this phenomenon. In turn, the mountain populations of European larch at the provenance trial in Sękocin, which experience the warmer lowland climate of Central Poland, required strong overcooling in the winter [13]. A similar relationship was found by Wilczyński and Wertz [56] for European larch in the Central Polish uplands. Many researchers have indicated the importance of the high mean March temperatures for the formation of tree ring widths in European larch growing in the Alps [14–16], the Carpathians [11], the Polish uplands [22,56] and the Central Polish lowlands [24,25,29].

Abundant precipitation in February supplies water to the soil for the upcoming growing season. European larch requires more precipitation to intensify the radial growth at BL than at the other two provenance trials. This may be the result of the specific soil conditions prevailing at BL, because the shallow, compact clay-loam layer in the soil impeded the movement of water deep into the soil. Other studies have not shown a significant relationship between the current February precipitation and radial growth in European larch.

The air temperature in the summer was negatively associated with European larch radial growth at the three provenance trials. Similar results were obtained in the lowlands of Latvia [57] and Poland [24]. However, the radial growth of European larch at KR was positively related to temperature in June. In mountain areas, the importance of temperature to tree growth rises with the increasing elevation [42]. Some researchers argue that European larch growing in a cold climate at high elevations is more sensitive to shortages of warmth than in warmer regions [18,20,23]. Our study has indicated that the temperature in September of the current year was also an important factor affecting the tree ring width of larch provenances at the three provenance trials. Thus, the radial growth of European larch lasts until the end of September. This was also demonstrated by Moser et al. [58] for European larch growing in the Alps. High summer air temperatures may lead to water shortages in the soil and limit the growth of trees [26,59,60]. With rising air temperatures and falling relative humidity during the growing season, the formation of foliage and intensifying vascular cambium activity lead to extensive transpiration in trees [61,62]. The water balance of trees is then upset, and photosynthesis decreases in intensity. The magnitude of the annual radial growth of European larch growing at SI and BL was more strongly related to precipitation in June than at KR. The reverse

was the case with precipitation in July: this month is the period of intensive cambium division in trees in mountain areas, which require water and warmth, whereas, in the lower altitude, areas this takes place at already in June. Abundant precipitation in the summer causes the intensive flow of nutrient-containing water to cambium cells. The high water pressure exerted on a cell wall deforms the cambium cells, thereby inducing their faster growth [60–62]. Large supplies of water in June and July are especially necessary, because European larch forms most of its cambium cells during this period [58]. In turn, precipitation in July and August was positively associated with the radial growth of all the European larch provenances growing during the provenance trial in Rogów in the Central Polish lowlands [10]. The high level of precipitation in June was found to be significant in the formation of tree ring widths in European larch in various parts of this species' distribution range [21,27,57,63,64]. Moreover, abundant precipitation in July was also important in various regions of Europe [14,24,26,65], but excessive precipitation in June [17,18] and July [23] weakened the radial growth of European larch growing close to the tree line in the Alps. These results concur with Fritts's [42] claim that, with the increasing elevation, the importance of precipitation during tree growth decreases.

The results of our study showed that there was a significant, positive relationship between precipitation in the previous November and the radial growth of all the European larch provenances studied at each provenance trial. A high November precipitation mediated the growth of European larch the most strongly at KR in the following year and the weakest at SI. European larch at KR required more precipitation than at the other two provenance trials, because they were growing in a highly skeletal soil on the upper part of a slope, off which rainwater quickly flows. The trees growing at BL required more precipitation than at SI, because the shallow, compact clay-loam layer prevents water from percolating deep into the soil [34]. Serre [14] also found a significant relationship between November precipitation in the previous year and the radial growth of European larch growing in the Alps, but we failed to find such an association in any of the other dendrochronological studies on this species. The significant relationships between November precipitation and the radial growth of European larch in the following year can be explained as follows: if the soil in autumn is rich in water and the weather is also sufficiently warm, conifers continue to develop their root systems [66]. European larches in the Alps utilize soil water stored in late autumn so that they can grow intensively in the spring [26]. Moreover, when the soil contains large supplies of water, the trees are more resistant to winter frost [67].

### *4.3. Differences in Radial Growth Responses between the Larch Provenances at the Individual Provenance Trials*

At SI (lowland), two groups of larch provenances can be distinguished with regards to the second principal component. PC2 was correlated with temperature in November and December in the previous year and July and with precipitation in September in the current year (Figure 6a). It follows that both groups of provenances reacted differently to these climatic elements.

Temperature at the beginning of winter (November and December) was negatively associated with radial growth in the following year in larch provenances mostly from the Carpathians, the higher parts of the Sudety Mountains and Northern Poland (group 2; see Figure 4a) in that it caused the trees to harden off before the winter. By contrast, it was positively related with the radial growth of larch provenances mostly from Central Poland and the lower parts of the Sudety Mountains (group 1; see Figure 4a). Holzer [68] claims that the resistance to low winter temperatures in trees originally from a harsh mountain climate and growing in a mild lowland climate is genetically determined.

At SI, the July temperature was negatively related to the radial growth of European larch from the Polish uplands and North-central lowlands and, also, from the lower parts of the Sudety Mountains (group 1). These provenances originated from areas where the mean summer temperature is lower by at least 1 °C than at SI, so they may not have adapted to hotter summers during this provenance trial. The provenances from the Carpathians and the higher parts of the Sudety, as well as provenances 1, 4, 8 and 11 (group 2) growing

at SI, responded positively to high early summer temperatures by increasing the radial growth. In the case of the mountain provenances, this relationship may be genetically determined. For example, European larch growing in the French and Austrian Alps [15], the Italian Alps [17,18,23], the Swiss Alps [19,69] and the Slovakian Tatras [20] also formed wide tree rings in years with a warm beginning to the summer. Koprowski [24] and Jansons et al. [57] stated that European larch growing in the lowlands of Poland and Latvia reacted negatively to high temperatures in the early summer by decreasing the cambium activity.

At BL (upland), the factor differentiating the radial growth pattern of the larch provenances was precipitation in October of the previous year and in July–September of the current year (Figure 6b). The previous October's precipitation was positively related to the magnitude of the annual radial growth of European larch mainly from Northern Poland, the Świętokrzyskie Mountains and the higher parts of the Sudety and Carpathian Mountains (group 2; see Figure 4b) but was negatively associated with the growth of the other provenances from very different parts of Poland (group 1; see Figure 4b). A water deficit in the autumn inhibits tree root growth [66]; tree shoots then harden off and enter winter dormancy earlier. No previous dendroclimatological studies have shown a significant relationship between precipitation in the previous October and the radial growth of European larch.

At BL, the larch provenances from group 2 were also more sensitive to a deficiency in precipitation in the midsummer (July and August) than those from group 1. This difference may have a genetic background, since the group 2 provenances originated in regions with high levels of precipitation. In the specific soil type at BL (clay-loam layer), it is these provenances in particular that are vulnerable to drought. However, a too-cold and moist September could cause the end of radial growth of the north and mountain provenances too early.

The factors differentiating the radial growth pattern of larch provenances growing in the mountains (KR) were temperature and precipitation in the previous September and precipitation in February, June and September in the year of tree ring formation. The temperature at the turn of the summer and autumn in the previous year was positively related to the magnitude of the annual radial growth of the larch provenances, mainly from the Carpathians, the higher parts of the Sudety and North-central Poland (group 2; see Figure 4c). At low temperatures and under short day conditions, vegetative buds reach small sizes and tree shoots take longer to harden off [70], so they become more sensitive to the frequent early frosts in KR, especially in September [71]. On the other hand, the temperature in the previous September was negatively associated with the radial growth of European larch from the Świętokrzyskie Mountains, North-west and Central Poland and the lower parts of the Sudety Mountains (group 1; see Figure 4c). Many studies indicate a high resistance to early frosts in larch provenances from the Świętokrzyskie Mountains growing during provenance trials in various parts of Europe [5–9]. This resistance is therefore largely genetically determined. Similar relationships were found for European larch in the Alps [14], Central Poland [28], the Carpathian Foothills [65] and Latvia [57].

The European larch provenances from group 1 responded negatively to high levels of precipitation in the previous September by increasing their radial growth; this abundant precipitation was probably due to thick cloud cover. European larch forms generative buds in September [72]. Long hours of sunshine in September reduce the number of flower buds and, thus, the number of cones on the trees in the following year [73]. In turn, abundant fruition weakens the radial growth [74]. The positive effects of abundant precipitation in this month on the mountain provenances from group 2 are hard to explain. Their trees may be genetically coded to end radial growth faster, so it requires further study.

The precipitation in February was negatively associated with the radial growth of the group 1 larch provenances. Thick and long-lasting snow cover in the mountains could extend the period of tree dormancy. However, precipitation at the end of the winter was positively related to the radial growth of European larches originating mostly from the Carpathians, the higher parts of the Sudety Mountains and Northern Poland (group 2). In

the case of the mountain provenances, this can be explained by the fact that they begin their physiological activity later [75], which makes them more resistant to the late frosts that are frequent in the mountains.

Precipitation at the beginning of the summer (June) was positively related to the magnitude of the annual radial growth of larch provenances mainly from the Carpathians, the higher parts of the Sudety Mountains and the North-central Polish lowlands (group 2) but negatively with the provenances from the uplands, the lower Sudety Mountains and the North-western Polish lowlands (group 1). In the case of the Northern Polish provenances, such a sensitivity to precipitation may be genetically determined, because local larch populations growing in the Baltic regions require a high level of precipitation at the beginning of the tree ring formation period [24,27,57]. On the other hand, the requirements of mountain larch provenances for substantial amounts of precipitation in the early summer are surprising. There is plenty of water in the mountains, but June is often a relatively cold month, with late frosts [71]. Hence, European larches growing in a cold climate at high altitudes are more sensitive to a shortage of heat during the period of intense cambium division and early wood formation [15–20]. Possible future rises in the air temperature and decreases in the precipitation in the summer [76,77] may pose a serious threat to the European larch in Poland, however. In the case of the upland's provenances, Szeligowski [10] also indicated their high drought resistance during other provenance trials, so it may be genetically determined.

At each of the three provenance trials (SI, BL and KR), precipitation at the end of the tree ring formation period (September) differentiated the radial growth patterns in the two groups of larch provenances. At SI, European larch from the uplands, North-central lowlands and the lower parts of the Sudety Mountains (group 1; see Figure 4a) formed wider tree rings when the precipitation was abundant in September. At Bliżyn, a similar relationship was found for some northern (Nos. 2 and 6), upland (Nos. 10 and 19), Carpathian (No. 16) and Sudety (Nos. 21 and 24) provenances from group 1 (see Figure 4b). At KR, this applied to European larch trees from the Central Polish uplands, the lower parts of the Sudety Mountains, the North-western Polish lowlands and, also, from Czerniejewo (group 2; see Figure 4c). Photosynthesis in coniferous trees can still occur at the beginning of autumn if it is warm enough and a sufficient supply of water is available. This process increases the amount of carbohydrates stored in trees, which will be consumed at the start of the new growing season [78,79]. Our study indicates that this form of storage may be used to support ongoing growth in tree rings in the current year. This was confirmed by the data provided by several researchers [58,80,81]. A so-called second leap of radial growth often occurs in European larch in September [82] when, after the water table has fallen during the summer, abundant precipitation at the end of this season raises it again. An inverse relationship between radial growth and precipitation in September was found in the remaining groups of larch provenances growing at SI, BL and KR (see Figure 4a–c). Most of them were originally from mountain areas, so the early completion of tree ring formation in them could be genetically determined [75], especially as cool temperatures often occur in combination with precipitation in the early autumn.

The differences in the radial growth patterns of European larch at the three provenance trials resulted from the climatic conditions prevailing there and, also, from the genetically coded sensitivity to the climatic conditions of the trees' areas of origin. Any exceptions to this rule may be due to the different primary origins of the trees. Only provenances Nos. 8, 9, 10, 11 and 12 were local native European larch populations (see Figure 1b), while the seed source stand of provenance No. 16 was established from seeds imported from the Sudety Mountains [83,84]. The origins of the other seed source stands are not known. It is believed that certain European larch stands in Northern Poland were established from seeds originating from the Sudety Mountains, but some larch trees growing in these mountains are an artificial hybrid between the local *L. decidua* subsp. *decidua* and *L. decidua* subsp. *polonica* from different parts of Poland [85].

## 5. Conclusions

Moving European larch trees to other habitats has consequences for them: they try to adapt to the new climatic conditions, transferring the genetic potential reflected in their radial growth response to the new climatic conditions. Through this provenance research on European larch trees, we obtained valuable information on how sensitive individual larch provenances are to the climate conditions prevailing during provenance trials located in different geographical–climatic regions of Poland. To some extent, this allowed us to predict the future radial growth responses of individual European larch provenances in the face of climate changes. It is expected that, despite ongoing global warming, drastic temperature drops in the winter will still occur in the future [75,76], so larch provenances highly tolerant towards low and high temperatures, which cause water deficits, will be the most desirable in forest plantations. In the lowlands (SI), the provenances from the Carpathians, the higher parts of the Sudety Mountains and Northern Poland seem to better tolerate low temperatures during the beginning of winter, but the provenances from the uplands, North-central lowlands and the lower parts of the Sudety Mountains seem to better tolerate high temperature during the hottest time of the radial growth period. The provenances from Northern Poland, the Świętokrzyskie Mountains and the higher parts of the Sudety and Carpathian Mountains seem less suited to the increasingly dry conditions of the upland areas (BL). In the montane zone (KR), the provenances from the uplands, North-western lowlands and the lower Sudety Mountains seem to better adapt to dry conditions during the beginning of the radial growth period. Apart from the aspects that differentiate the radial growth response of individual larch provenances, there are also supra-regional climatic elements, i.e., a short, warm and precipitation-rich winter, to which larches react in very similar ways, regardless of their places of origin and their new growing sites. These conditions bring the growing season forward, as the trees have guaranteed access to water stored in the soil during the winter. In the lowlands, uplands and mountains of Poland, the cool, humid summers promote the intensive growth of European larch cambium cells. Late-autumn precipitation is also important, as it supplies the soil with the water that the trees will need during the winter. In this way, a high growth potential (vitality) will be maintained into the next growing season. Knowledge of the intraspecific differences of the European larch in the context of its sensitivity to local climatic conditions can be a key regarding the directions in which the forest reproductive materials of this species can be transferred. In this case, however, knowledge of the origin of the larch trees going back several generations will be necessary.

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