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Climate Response in Tree-Rings of Sawara Cypress [*Chamaecyparis pisifera* (Siebold & Zucc.) Endl.] in Poland

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Abstract: Sawara cypress [*Chamaecyparis pisifera* (Siebold & Zucc.) Endl.] is originally from Japan. It was introduced to Europe in the latter half of the 19th century (in England and Holland in 1861, and in Poland in 1864). The aim of this study was to examine the influence of climatic conditions on tree-ring width among Sawara cypress populations growing in Poland. Additionally, other indicators determining the growth-climate relationship for the studied tree species were investigated such as false rings, missing rings, or frost rings. Five stands of Sawara cypress from northwestern and central Poland were selected for study. Samples were taken from 97 trees, using Pressler borers at breast-height. Tree-ring widths were measured down to 0.01 mm. Climatic data came from weather stations located the nearest to the study plots. Tree-ring width in the studied populations of Sawara cypress varies (from 1.94 to 4.47 mm). The oldest Sawara cypresses grow in Glinna Arboretum and are nearly 130 years old. The youngest ones grow in Rogów Arboretum (67 years old) and Wirty Arboretum (58 years old). Ten regional pointer years, including six negative and four positive ones, were determined for local chronologies. Negative pointer years were associated with the occurrence of cold winters and water shortages in summer. Positive pointer years are mostly periods with a warm winter season, early and warm spring, and with high precipitation totals during summer months. Correlation and response function analysis corroborates the results yielded by pointer year analysis. False rings carry an additional information on pluvial conditions in the summer period, and frost rings are an aid in dating dendrochronological series and indicate the occurrence of both very cold winters and persistent ground frost occurrences in the spring period. In comparison to native conifers, the Sawara cypress can be regarded as a fast-growing species. The knowledge of acclimatization, growth rate, and growth-climate relationship may be useful, especially in the time of a rapidly changing climate, increasing human impact, and highly intensified invasion of insect and fungal species attacking native forest-forming taxa.

Keywords: dendrochronology; dendroclimatology; pointer years; false rings; frost rings

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Citation: Cedro, A.; Nowak, G.; Kowalewska-Kalkowska, H. Climate Response in Tree-Rings of Sawara Cypress [*Chamaecyparis pisifera* (Siebold & Zucc.) Endl.] in Poland. *Forests* **2021**, *12*, 967. https://doi.org/10.3390/f12080967

Academic Editor: Giovanna Battipaglia

Received: 18 June 2021
Accepted: 14 July 2021
Published: 21 July 2021

1. Introduction

The recent decades have been a period of unprecedented impact on natural environment, manifested for instance by climate change caused predominantly by human activity, the loss or degradation of numerous habitats that are deemed crucial for species survival, and by pathogen transmission into previously unaffected areas. Such pathogens can cause large damage among taxa that have not developed immunity. Such rapid changes cause extinction of numerous taxa and their withdrawal from previously occupied areas. In such conditions, previously underappreciated plant or animal taxa, and marginal or introduced species, may increase in both their natural and economic significance. It is therefore important to enhance our understanding of the ecology of all taxa, especially those that retain high immunity and resilience despite changing environmental conditions. In Poland, one such taxon is the Sawara cypress.

The Sawara cypress [*Chamaecyparis pisifera* (Siebold & Zucc.) Endl.] of the Cupressaceae family, is originally from Japan in the mountainous regions of Honshu Island, between 35° and 38° N [1]. Although in its original habitat it reaches 50 m in height and 2 m in trunk diameter, in Europe it is considerably smaller. It is an evergreen, long-lived, slow-growing tree, with a cone-shaped loose crown with flat branches. The trunk is straight, visible to the top. The bark is red brown. As the tree ages, the bark exfoliates in the form of long belts. The scales are almost of equal length, and (in comparison to all false cypress taxa) are the most pointed and taper over the longest distance. Scales are dark green, glossy, with a distinct white, waxy texture visible on the underside, resembling a small butterfly or a bow (these are not lines). Cones are small (six to eight mm in diameter) light green before maturing (resembling the seeds of pea *Pisum sativum* L.), and brown following maturation [2–6]. Sawara cypresses prefer sun-lit stands that are shielded from wind. They prefer fertile, slightly acidic or neutral, and especially permeable substrata (they grow poorly on calcareous soils). Sawara cypress trees are frost-resistant, but when growing in an unsheltered area and exposed to strong winds small twigs may freeze. The Sawara cypress is rarely infected by diseases or attacked by pests [3].

In Japan, the Sawara cypress was often planted around shrines, in parks and in gardens. It was carried to Europe as late as the latter half of the 19th century. In England and Holland, it was introduced in 1861, and in Poland it was first noted in 1864, in the Botanical Garden of the Jagiellonian University in Kraków [5].

In silvicultures, the Sawara cypress is not an economically significant species. It is often used, however, as a decorative tree in green spaces. Its use as a decorative tree is significant as there are few gymnosperm species in the indigenous flora. In green spaces, it is represented by both the type and numerous cultured varieties. According to Tumiłowicz [7], in contemporary Poland three species of false cypress were studied as prospective silvicultural taxa: *Chamaecyparis lawsoniana* (A.Murray) Parl., *Ch. obtusa* (Siebold & Zucc.) Endl. and *Ch. pisifera* (Siebold & Zucc.) Endl. Silvicultures were established in the late 19th century by A. Schwappach, mostly in northern and western Poland. Tumiłowicz [7] reports that of these three false cypress species, the best results were obtained for the Sawara cypress.

Human-induced progressive climatic changes and habitat transformations make a negative impact on conservation of biological diversity, for instance via the accumulation of a thick layer of slowly decaying leaves. In the future, these changes may cause modifications in silviculture. Introducing alien plants into forests has led to settling of invasive taxa (mostly trees). Notably, not all alien taxa become settled in forest gatherings, and few of them are capable of establishing self-sustaining populations. It is important to seek new, non-invasive taxa that will enable maintaining appropriate forest resources in a multi-year perspective [8–10].

Dendrochronological studies on Sawara cypresses are very rare due to the restricted area of natural occurrences, and a low number of trees introduced outside Japan (and consequently the small area they occupy). In Japan, dendrochronological analyses are used for reconstructing (e.g., tree stand composition; earthquakes and associated avalanches [11]; numbers of days with rain [12,13]; rate of young tree growth (based on tree-ring width and wood density) [14]; or examining the spring process of cambium activation depending on temperature conditions [15,16]). Dendrochronological analyses from outside the natural *Ch. pisifera* occurrence area are few, often published many years ago, or give only fragmentary information (e.g., only tree-ring width).

The aim of the present study was to examine the influence of climatic conditions on tree-ring width in *Ch. pisifera* populations growing in Poland (central Europe). Additionally, other indicators determining the growth-climate relationship for the studied tree species were considered (false rings, missing rings, or frost rings).

2. Material and Methods

2.1. Study Area

Five Sawara cypress stands located in northwestern and central Poland were selected for this study. The stands are in fact plots. Three are located within arboreta, and two are located within state forests (Figure 1, Table 1).

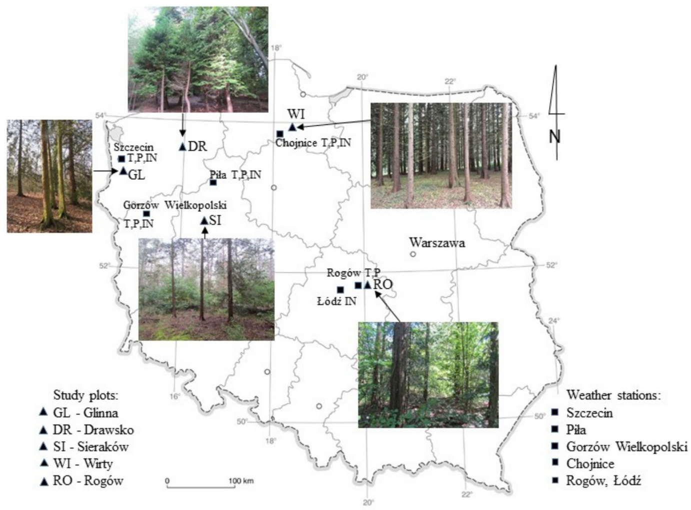

Figure 1. Study plot location. T, temperature; P, precipitation; IN, insolation.

Table 1. List of study plots and basic information.

Lab. Code	Name	Habitat	Geographic Coordinates		Altitude a.s.l. (m)	No. of Trees	No. of Samples	No. of Tree-Rings
			ϕ (N)	λ (E)				
GL	Glinna	arboretum	53°17′	14°43′	68	12	17	1563
DR	Drawsko	forest	53°52′	15°82′	115	21	39	2665
SI	Sieraków	forest	52°65′	16°09′	48	23	46	3322
WI	Wirty	arboretum	53°89′	18°37′	131	21	25	1192
RO	Rogów	arboretum	51°49′	19°53′	194	20	40	2572
					Σ	97	167	11,314

The Glinna Arboretum (GL) is located within Gryfino State Forest District, in the southwestern part of Bukowe Hills, at the boundary between Wełtyń Plain and Pyrzyce-Stargard Plain. The arboretum is surrounded by morainic hills covered by beech forest. The microclimate is exceptionally favorable. In conjunction with the Atlantic climate of Western Pomerania, this enables numerous shrub and tree taxa that are vulnerable to frost to be grown in this area. It is a fresh forest habitat conforming to the Pomeranian beech forest type. Glinna is the westernmost study site. No information on seed provenance is available, and the trees are likely remnants of a tree nursery that existed here previously.

Drawsko Pomorskie (DR) is located within the Drawsko Lake District. Sawara cypress trees were planted as an admixture together with yellow pine *Pinus ponderosa* Douglas ex C.Lawson and grand fir *Abies grandis* (Douglas ex D.Don) Lindl., in a pine forest.

The Forest District Sieraków (SI) is located within Noteć Forest. The plot was established in a fresh mixed forest habitat, where Sawara cypress grows as an admixture along giant cedar *Thuja plicata* Donn ex D.Don.

The Wirty Arboretum (WI) is the northernmost study site. An experimental plot was established here in 1958 in a fresh mixed forest habitat. 110 trees were planted then on an area of 0.1 ha. Of these, 37 specimens up to 31 m high and displaying a breast-height diameter of 18–64 cm remain as of early 2021.

The Rogów Arboretum (RO) is located within WULS-SGGW (Warsaw University of Life Sciences–Szkoła Główna Gospodarstwa Wiejskiego) Forest Experimental Station, in central Poland. The plot covers 0.21 ha. It was established in 1954, from seeds obtained from the Wirty Arboretum (sown in 1948).

2.2. Tree-Ring Data

Samples were collected using Pressler borers from breast level (~1.3 m above ground level). In the laboratory, samples were mounted on boards and dried, and subsequently sliced with a knife until a clear view of tree-rings and ring boundaries was obtained. Additionally, samples were smeared with chalk in order to enhance the ring boundaries. Tree-ring widths were measured using a binocular microscope, down to 0.01 mm, using Dendrometer software [17]. All abnormalities in ring structure were noted during measurements, especially false rings which largely hinder sample measuring and cross-dating. Skeleton plots were generated for the radii in order to correctly identify false rings. Following this, tree-ring sequences were dated using classical cross-dating methods, and local chronologies were compiled [18,19]. Dating and cross-dating accuracy was tested using Cofecha program, part of DPL software package [20,21]. EPS index (Expressed Population Signal) was calculated for each chronology. This determines how representative the measured sequences are relative to a response variability range of a population [22].

In order to identify and describe statistical trends in spatial and temporal variability of the local chronologies compiled in this work, the basic measures of assemblage structure description were used, obtained according to the formulae included in the paper by Nicholas [23]. In order to depict the measures of position, dispersal and asymmetry, box and whisker plots were generated, featuring a box showing the position of the lower and upper quartile, and whiskers indicating the lowest and highest values. The median position was indicated within the box.

Mutual relationships between local chronologies were analyzed based on Pearson's linear correlation coefficient [24]. Its significance at $\alpha = 0.05$ level was assessed using Student's *t*-test. Principal component analysis (PCA) [25] was employed in order to verify the detected patterns and relationships. Bartlett's sphericity test [26] was applied to determine whether the use of PCA was justified. The Cattell criterion [27] was applied to identify essential modes to be retained so that the underlying data structure could be described.

The TCS program [28] was used to calculate pointer years for local chronologies and Gl coefficient (Gleichläufigkeitswert) [29]. Pointer years were those years during which >90% of the studied trees displayed the same growth trend relative to the preceding year. In negative years (−), there was a reduction in ring width, and in positive years (+), there was in increase in ring width [30,31]. Years during which the same growth trend occurred in four or five chronologies simultaneously were deemed regional pointer years. These were established only for the common period covered by all five local chronologies (1969–2018). In order to facilitate pointer year comparison among all five chronologies, pointer years were presented as dimensionless values, following the formula:

$$\frac{\text{growth per year in a given pointer year}}{\text{multi} - \text{year average growth per year}} - 1$$

Thus, positive values were higher than multi-year mean growth per year, and negative values were lower than multi-year mean growth per year.

Residual chronology (RES) was compiled using Arstan software [20,21,32], emphasizing short-term variability and eliminating long-term trends and autocorrelation by applying a two-phase detrending technique, by fitting either a modified negative exponential curve or a regression line with negative or zero slope [18,33]. This was subsequently used for correlation and response function analysis [24,34], performed using the Respo program which is part of DPL software package [20,21]. In these analyses, mean air temperature, monthly precipitation sums, and monthly insolation from 16 months (from June of the year preceding growth (pJUN) to September of the growth year (SEP)) were correlated with residual chronology. In every case, multiple regression determination coefficient (r^2) was calculated, determining the strength of the relationship between the analyzed features (Respo program included in the DPL package) [21].

Climate data utilized in this study came from Institute of Meteorology and Water Management-National Research Institute (IMGW-PIB) weather stations located the nearest to the respective study plots and from the WULS-SGGW Forest Experimental Station (Table 2).

Table 2. List of weather stations providing data for dendroclimatological analyses, and their distances from the study plots.

Station	No.	Geographic Coordinates		Altitude a.s.l. [m]	Temperature (No. of Years)	Precipitation (No. of Years)	Insolation (No. of Years)	Distance and Direction from Study Plot
		φ (N)	λ (E)					
Chojnice	12235	53°42′	17°33′	172	1961–2018 (58)	1961–2018 (58)	1966–2018 (53)	WI, 55 km on WSW
Szczecin	12205	53°24′	14°37′	1	1948–2020 (73)	1948–2020 (73)	1965–2020 (56)	GL, 12 km on NE
Gorzów Wlkp.	12300	52°45′	15°17′	72	1948–2020 (73)	1948–2020 (73)	1965–2020 (56)	SI, 53 km on W
Piła	12230	53°08′	16°45′	72	1949–2020 (72)	1951–2020 (70)	1973–2020 (48)	DR, 65 km on E
Rogów	WULS-SGGW Forest Experimental Station	51°49′	19°53′	190	1962–2019 (58)	1962–2019 (58)	-	RO, <1 km
Łódź	12465	51°44′	19°24′	187	-	-	1966–2019 (54)	RO, 35 km on E

3. Results

3.1. Ringwidth Chronologies

Our dendrochronological analysis was based on a total of 167 cores collected from 97 trees, which yielded over 11,300 measured tree-rings. The oldest Sawara cypresses grow in the Glinna Arboretum (as few as 12 individuals); they are nearly 130 years old (the longest sequence involves 122 tree-rings). The plot at Glinna was established in the last decade of the 19th century, which is the reason why such a low number of trees survive. Trees from the plot in Drawsko were planted at the turn of the 19th century. The oldest sequences here include 116 and 115 tree-rings, and the estimated age of the trees was 125 (1896–2020) and 123 years (1898–2020), respectively. At this plot, however, the population is diverse with respect to age; of the studied trees, seven are >100 years old, 7 trees are 50–100 years old, and 7 trees are young individuals, younger than 50 years. The plot at Sieraków comes from the third decade of the 20th century. The longest sequence includes 82 tree-rings, and it is thus considered to span 1939–2020. These trees are of similar age, and similar with respect to height and breast-height diameter. The trees growing in Rogów and Wirty arboreta are the youngest. The longest sequence obtained from Rogów is 67 years long (1953–2019), and the longest sequence from Wirty represents 58 years (1961–2018). The trees are of similar age, having been planted in the 1950s.

The compiled local chronologies differ slightly from the longest sequences obtained for individual trees with respect to length. The longest chronology was obtained for the DR plot. It spans 89 years (1932–2020), and the shortest chronology (spanning only 50 years) was compiled for the WI plot (1969–2018). The number of individual sequences for each year of the chronology is ≥10, and EPS index is >0.85, which enables the chronologies to be used for investigating the growth-climate relationship. The broadest tree-ring widths were observed in the trees from Wirty Arboretum (4.47; up to 7.1 mean growth per year per tree). The narrowest ring widths were observed in the trees from Sieraków (1.94 mm; Table 3). No missing rings were found in the analyzed tree-ring sequences.

The local chronologies are highly convergent (Figure 2, Table 4). The highest Student's t-test values were obtained for the pair of chronologies RO-WI (5.92), and the lowest–for WI-GL (2.59). Gl coefficient value was the highest for the pair DR-RO (76%), and the lowest, as in the case of t value, for WI-GL (60%) (Table 4).

Table 3. Basic statistics of standard and index (residual) Sawara cypress local chronologies.

Lab. Code	Total Chronology		EPS > 0.85										
	No. of Years	Time Span	No. of Years	Time Span	No. of Samples	Mean TRW (min−max) (mm)	Measured Chronology			Residual Chronology			EPS
							SD	1AC	MS	SD	1AC	MS	
GL	122	1899−2020	75	1946−2020	12	2.44 (1.05−3.12)	1.55	0.59	0.43	0.36	−0.9	0.39	0.94
DR	116	1905−2020	89	1932−2020	17	2.01 (1.20−3.28)	1.03	0.61	0.37	0.27	−0.12	0.36	0.92
SI	82	1939−2020	75	1946−2020	21	1.94 (1.22−2.48)	1.16	0.63	0.39	0.29	−0.11	0.28	0.93
WI	58	1961−2018	50	1969−2018	15	4.47 (3.02−7.10)	2.05	0.53	0.34	0.26	0.09	0.29	0.87
RO	67	1953−2019	58	1962−2019	20	2.99 (1.97−3.66)	1.63	0.59	0.43	0.31	−0.07	0.38	0.95

Abbreviations: TRW, tree-ring width; SD, standard deviation; 1AC, first order autocorrelation; MS, mean sensitivity; EPS, Expressed Population Signal.

Table 4. Convergence of Sawara cypress local chronologies as measured with t and Gl (%) values.

t/Gl	GL	DR	SI	WI	RO
GL	X	4.19	5.49	2.59	3.27
DR	63	X	5.36	4.10	5.03
SI	67	73	X	4.62	3.86
WI	60	65	75	X	5.92
RO	62	76	74	65	X

Abbreviations: t, Student's *t*-test value; Gl (%), coherence coefficient Gleichläufigkeitswert.

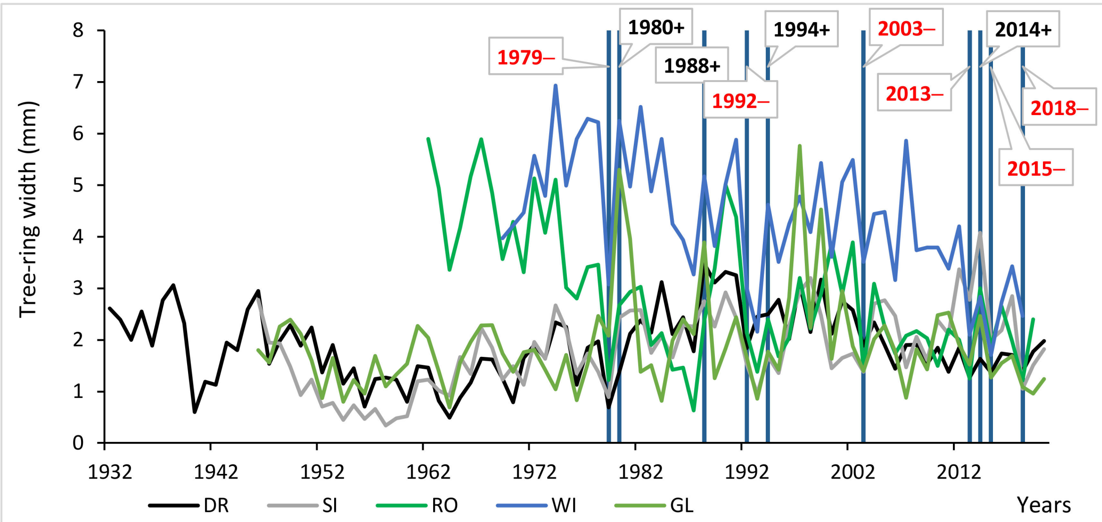

Figure 2. Local Sawara cypress chronologies (DR, SI, RO, WI and GL), and regional pointer years (blue bars; + denotes positive and – denotes negative pointer years).

The high convergence of local chronologies is corroborated by their box and whisker plot representations (Figure 3). This plot additionally shows some differences among the chronologies. In contrast to the remaining chronologies, the distribution of Glinna (GL) chronology variability based on indexed data displays the largest span of data, their highest diversity, a strong positive asymmetry, and a narrow distribution.

Analysis of correlations between indexed tree-ring widths shows most of the variables to be significantly correlated at $\alpha = 0.05$ level. Bartlett's sphericity test [26] shows the value χ^2 (63.5) to be higher than the critical value $\chi^2 = 18.31$ ($\alpha = 0.05$ and 10 degrees of freedom), thus proving that PCA was capable of detecting and describing the data set structure. Two of the principal components (PCs) indicated by the analysis were found to explain 71.4% of total variance. A resultant 2D scatter plot shows that the chronologies for Rogów (RO), Wirty (WI), Sieraków (SI) and Drawsko (DR) are strongly correlated with the first PC (loadings below −0.7). The chronology for Glinna was found to be strongly correlated with the second PC (Figure 4). That the distribution of GL chronology differs from those for the remaining plots may be due to definitely milder climatic conditions prevailing in northwestern Poland.

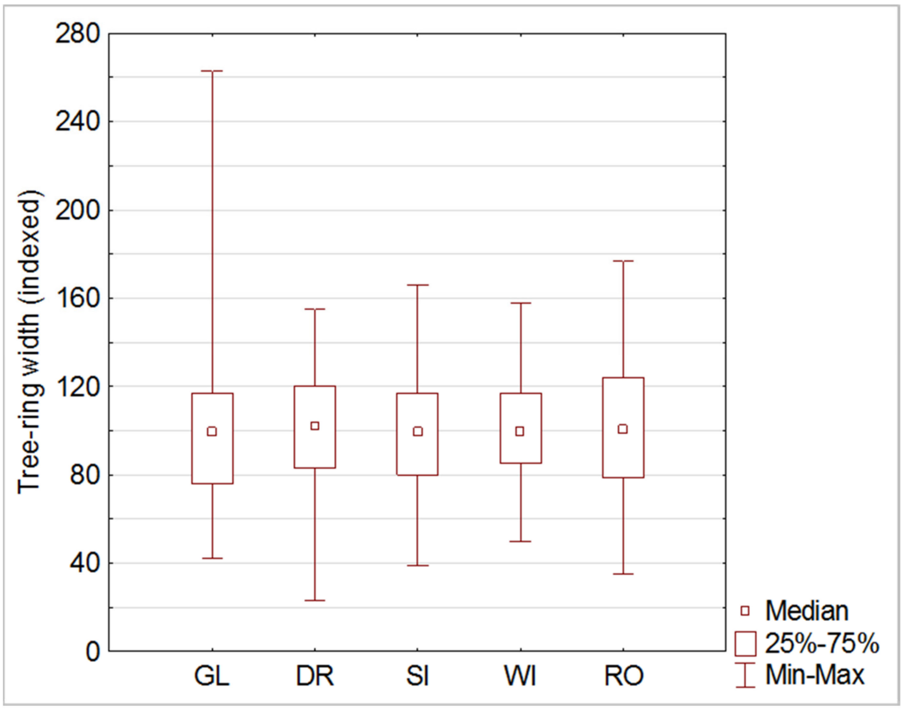

Figure 3. Box and whisker plot presenting descriptive measures for tree-ring width (indexed). Boxes show the position of the lower and upper quartile, and whiskers represent the minimum and maximum values.

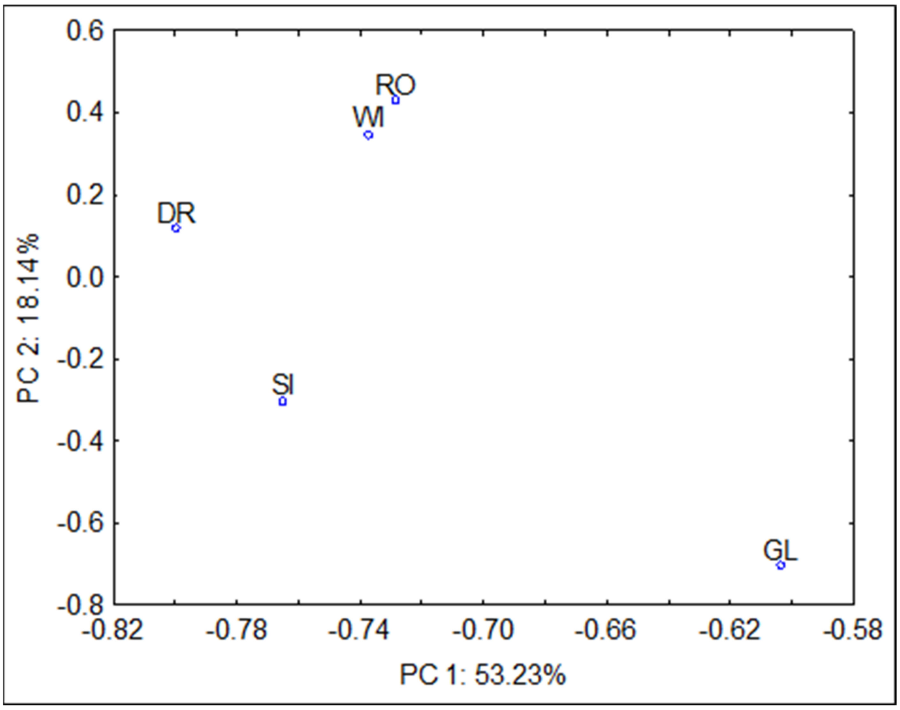

Figure 4. Loading scatter plot for PC1 (principal component 1) versus PC2 (principal component 2), along with percentage of total variance explained by PC1 and PC2.

3.2. Correlation and Response Function

Correlation and regression analysis indicates three periods of growth-climate relationship: late winter/early spring, the summer months, and summer/early autumn of the preceding growth season (Figure 5). The highest values, exclusively positive (statistically significant) for the correlation and regression coefficient, were obtained for February and March (late winter/early spring). Higher than average air temperatures, higher precipitation totals, and high insolation through this period favor a wide tree-ring formation in the following growth season. At the GL plot, the growth-climate relationship for February and March is the weakest. In May, negative values of the analyzed coefficients are noted for air temperature (RO, DR, SI and GL). The summer months (June and July) display positive correlation and regression values for atmospheric precipitation, and negative values for insolation. Again, the weakest relationships are noted in these months for the GL population. The third period of strong growth-climate correlation are summer and early autumn of the preceding growth season. Moderate insolation, low temperatures and higher than usual precipitation favor the formation of wide tree-rings in the following year. These correlations are the strongest for the GL plot, and are non-existent for RO. r^2 coefficient for air temperature reaches the highest value for DR (50%), and the lowest value for WI (17%). For precipitation, the maximum value is noted for RO (34%), and the minimum value for WI (15%). r^2 for insolation has the highest values for the SI population (32%), and the lowest value for that at DR (11%) (Figure 5a–e).

3.3. Pointer Years

A total of 170 pointer years were determined for local chronologies, including 95 characterized by a decrease in tree-ring width relative to the preceding year (i.e., negative pointer years) and 75 with an increase in tree-ring width relative to the preceding year (i.e., positive pointer years). Over the period between 1969 and 2018, a high convergence of pointer years occurred only in 10 years (i.e., the same trend in growth in at least 4 out of 5 analyzed local chronologies). These include six regional negative pointer years (1979−, 1992−, 2003−, 2013−, 2015− and 2018−), and four regional positive pointer years (1980+, 1988+, 1994+ and 2014+) (Figures 2 and 6). Figure 6 shows indexed tree-rings against multi-year average values during negative (negative values) and positive (positive values) pointer years. Two years stand out among these data: 1980, with the largest tree-ring width increase (with a maximum in Glinna), and 1979, with the lowest tree-ring width increase (with a minimum in Rogów).

Negative pointer years are associated with the occurrence of cold winters and cool autumns, and with insufficient rainfall in the summer period. Positive pointer years are periods most commonly with a warm winter season, early and warm spring, and with high precipitation sums in summer months (Table 5).

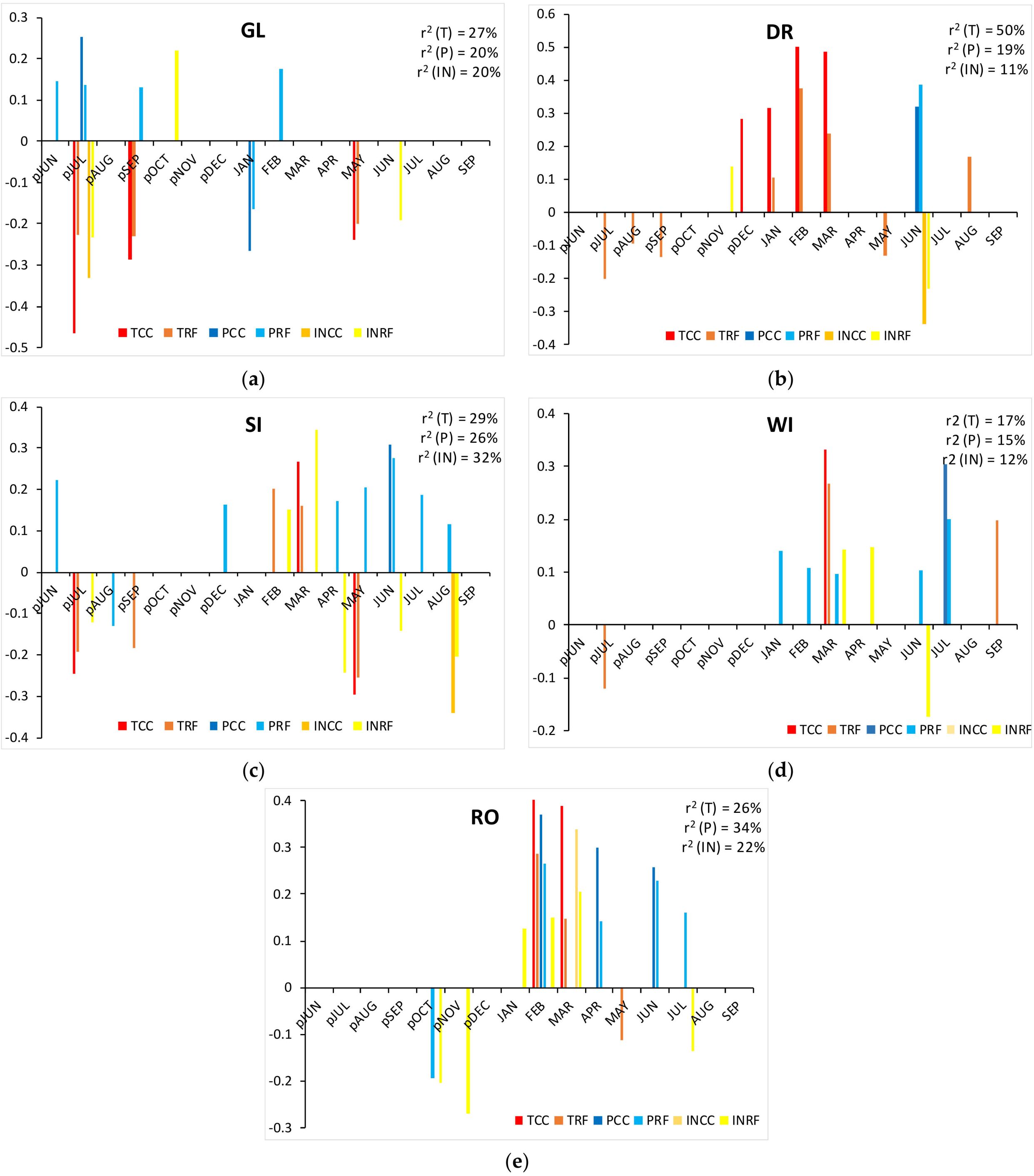

Figure 5. Results of correlation (CC) and response function (RF) analyses for Sawara cypress chronologies in (**a**) Glinna, (**b**) Drawsko, (**c**) Sieraków, (**d**) Wirty, (**e**) Rogów for temperature (T), precipitation (P) and insolation (IN). Bars denote significant values ($p \leq 0.05$); p, preceding year; r^2, multiple regression determination coefficient.

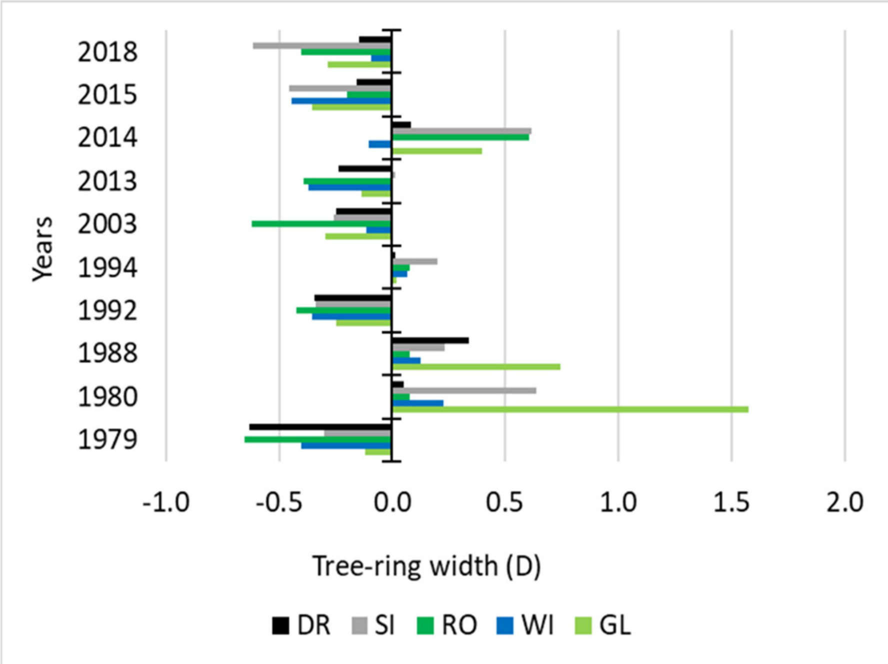

Figure 6. Tree-ring width (D) during regional pointer years (converted to dimensionless values).

Table 5. Regional pointer years, + denotes positive and − denotes negative pointer years.

Year	Chronologies	Meteorological Conditions
1979−	DR, SI, RO, WI	Cold winter, late and cold spring, rather dry year with insufficient rainfall in summer months
1980+	DR, SI, RO, WI, GL	Rather cool winter, cool summer, humid year, high precipitation totals in June and July, lower than average insolation, especially in summer
1988+	DR, SI, RO, WI, GL	Warm winter, rather cool summer, humid year, in June and July precipitation higher than average, low number of hours of sunshine in summer months
1992−	DR, SI, RO, WI, GL	Warm winter, hot summer, very dry year, spring and summer months with insufficient rainfall and high insolation
1994+	SI, RO, WI, GL	Except for February, winter and spring rather warm, warm summer, annual precipitation close to average, no large deficits of rainfall in summer
2003−	DR, SI, RO, WI, GL	Cold winter, very dry year, spring and summer months with low precipitation sums and high insolation
2013−	DR, RO, WI, GL	Cold winter, cold early spring, locally low precipitation sums and high insolation in summer
2014+	DR, SI, RO, GL	Warm winter and early spring, hot July, humid year, spring and summer with no rainfall deficits, insolation varied by region
2015−	DR, SI, RO, WI, GL	Warm winter, higher than average temperatures, rainfall considerably lower than average in summer months, high insolation in summer
2018−	DR, SI, WI, GL	Cold winter, cold early spring, dry year, lower than average precipitation noted in summer, very high insolation values, especially in summer

3.4. False and Frost Rings

A characteristic feature of the Sawara cypress wood is the occurrence of a large number of tree-rings that involve considerable differences in late wood density. These zones often resemble separate tree-rings (false rings). The presence of false rings in the studied populations ranges from 1.71% (i.e., 44 rings) at RO to 8.49% (i.e., 282 rings) at SI. A high proportion of false rings was also observed at WT—6.71% (80 rings), and at

DR and GL, false rings constitute about 2–3% (57 and 46 rings, respectively). False ring distribution is shown in Figure 7, based on the WI population. Indicated in Figure 7 are only those years, in which at least two such rings occurred in separate trees. The highest number of false rings occurred in 1992 (in 10 trees), in 1989 and 1999 (in 7 trees), and in 2008 (in 6 trees). The year of false ring occurrence does not always match a pointer year (e.g., at WI: years 1978, 1987, 2000, 2002 or 2012). A negative pointer year often co-occurs with false ring occurrences in several trees (e.g., 1989, 1992, 1995 or 2008). However, in the studied population, positive pointer years (e.g., 1991 or 2016 for the WI population) are also noted in years with false ring occurrences. A detailed analysis of weather condition variations through the vegetation season indicated the occurrence of large precipitation deficits, and periods with no rainfall lasting up to several weeks in summer months in those years. Similar results were obtained for the remaining Sawara cypress populations in Poland studied here.

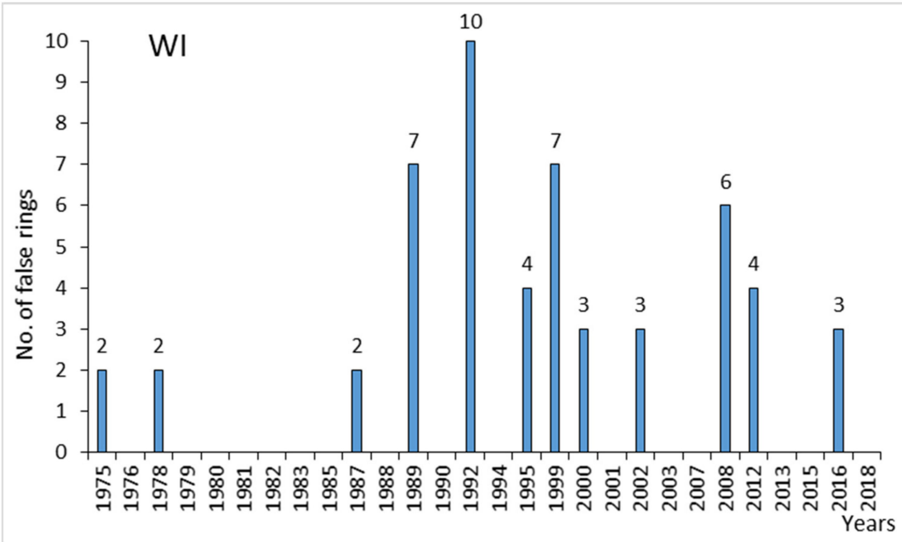

Figure 7. Number of false rings in Sawara cypress population at WI (shown are only false rings that occur in at least two trees in the same year).

54 frost rings, characterized by deformations to rays and wood cells at the late and early wood boundary, were also identified in the course of tree-ring measurements. The highest number of such deformations (30 frost rings, which accounts for 1.13% of all measured tree-rings) were noted for the DR plot. Nine frost rings were identified for both RO and SI, five frost rings for WI, and only one frost ring for GL. The majority of frost rings arise in juvenile wood. For the DR population, this was the case for 73% of frost rings; for RO, 78%, for SI, 67%, and for WI, 80%. The single frost ring found at GL dated from 1960, when the tree age was close to 80 years. The remaining frost rings occur in mature wood from the years 1930, 1940, 1943, 1944, 1948, 1957, 1960, 1968, 1971, 1979, 1983, 1986, and 1991. These deformations occur the most frequently in 1957 in the RO population (in as many as five trees), and in 1940 in the DR population (in four trees). The winters preceding the 1940 and 1957 vegetation periods were cold and long. In Rogów, negative mean monthly air temperatures were noted already in November and December 1956, and in 1957 minimum temperature dropped to −19.0 °C. In Gryfice (German Greifenberg, located about 70 km NW of the DR plot), in January and February 1940, monthly means were below −9 °C, and minimum temperature ranged as low as −27.6 °C. Ground frost occurrences in the discussed periods lasted very long, until May (in Rogów, Tmin = −2.4 °C was noted on 6 May 1957, and in Gryfice Tmin = −1.0 °C was noted in May 1940, no date specified).

4. Discussion

The tree-ring width in the studied populations of the Sawara cypress varied from 1.94 mm to 4.47 mm (Table 3). This is due, in part, to the variable age of the trees, and to contrasting habitative and culturing conditions (forest populations and arboreta). In comparison to the Baltic pine (*Pinus sylvestris* L.), northern Poland's dominant coniferous tree, and the European spruce (*Picea abies* (L.) H.Karst.), the tree occupying the second largest forest area, the average tree-ring width in Sawara cypress is broader [35–38]. However, the most frequent non-indigenous coniferous tree (the Douglas fir *Pseudotsuga menziesii* Franco) has broader tree rings [36]. In Japan, through the first 30 years of their lives, Sawara cypresses grow at a rate of 3.67 mm/year [14], and in Korea the grow at a rate of 1.84 mm/year and 3.97 mm/year [39].

The studied tree populations are characterized by highly convergent chronology (both visually and statistically). Only the population at Glinna (GL) differs in showing lower t and G1 values (Table 4), disparate descriptive statistics values (Figure 3), and principal component analysis results (Figure 4). This is most likely due to the location of the plot behind a range of hills, being in a morphological depression sheltered from strong and cold winds. The climate of this region in comparison to the remaining study plots is the mildest (especially the winters are shorter and warmer). Additionally, the proximity of a large forest complex makes a positive impact on air humidity and ground water level. A comparison of *Ch. pisifera* tree-ring width to climate (correlation and response function analysis) indicates three periods of such relationship: late winter/early spring (positive values for temperature and insolation), the summer months (positive values for precipitation, negative values for insolation and temperature), and the end of the preceding vegetation season (positive values for precipitation, and negative values for temperature and insolation). The population at Glinna (GL) displays slightly different growth-climate relationships. Here, the strongest links are those with the conditions from the end of the preceding growth season, while the relationships with the conditions in the current vegetation year are rather weak.

The analysis of pointer years, designation of regional years, and their links to weather conditions all corroborate the results of correlation and response function analysis. The main factors causing the decrease in tree-ring width in Sawara cypress populations (negative pointer years) were cold winters and insufficient rainfall in the summer period. The increase in tree-ring width (positive pointer years), however, took place in years with a warm winter period, early and warm spring, and with high precipitation sums in summer months.

In their natural habitat (in Japan), tree-ring widths in Sawara cypresses depend on temperature in spring (positive relationships), and on precipitation in summer months (negative relationships). There are also reports of a strong influence of anemobaric conditions on tree-ring width increase [12]. Other studies associate the tree-ring width with the number of rainy days between April and September, and use this relationship as a proxy for reconstructing the number of days of rain [12]. In Korea, Seo et al. [39] indicate the sensitivity of this tree species to drought. An important factor shaping the cambial activity of Sawara cypresses in Japan is late winter/early spring temperature. Periods of mean daily temperature > 13 °C lasting more than ten days can cause cambium activation and early growth of wood [16]. Rahman et al. [15] also identify temperature as the dominant factor in cambium reactivation.

Unfortunately, there are no dendrochronological studies on Sawara cypress from the present work's study area, nor from adjacent regions. Sawara cypresses growing in Eberswalde in Germany (a short distance from the Polish border) are frost-resistant, but are vulnerable to drought (especially longer periods with insufficient rainfall) and to strong winds [40]. Sawara cypresses from northern Poland, however, are vulnerable to freezing [7,41]. Following severe winters, Tumiłowicz [7] notes a decrease in tree-ring width in this region.

The presence of false rings in the Sawara cypress wood ranges from 1.71 to 8.49% of the measured tree-rings. The dating of these tree-ring anomalies, and the analysis of the conditions prevailing in the periods of their formation, carries an additional information on the conditions in which the studied trees have been growing (occurrences of dry, rainless periods in summer months i.e., June–September). Water availability during the vegetation season is also considered to be the main factor causing false ring formation in other species [42,43]. These data are corroborated by observations on Sawara cypresses cultured in Korea [39]. The trees were counted into two groups, fast-growing (with tree-rings about 4 mm wide) and slow-growing (<2 mm). They began cambium activity in April (1–21 April), and activity ceased between the 1st and 22nd of September. From April to early June, cypresses produced early wood. Then, in rainless periods (June–July), they frequently produced false rings (in the form of late wood). In July and August, following intense rainfall, there was another period of early wood formation, followed by yet another period of late wood cell production. The change in cambium activity (onset of early wood production or false ring formation) has been linked to daily precipitation sums, i.e., to high precipitation totals or rainless periods, respectively [39]. The presence of false rings, as well as the occurrence of missing rings and ambiguous ring boundaries in wood of other species of the Cupressaceae, are also confirmed in [44,45].

Over 50 frost rings were also identified in the studied trees. These deformations arise due to the formation of ice crystals in strongly hydrated xylem tissues when temperature drops below 0 °C during vegetation season, or in winter during very strong freezing events when water in soil freezes and is unavailable for plants [46]. Frost rings occur predominantly in juvenile wood (67–80% of frost rings noted here), which is also characteristic for other tree species [47–50]. Frost rings in the mature wood of Sawara cypress facilitate the dating of the series (especially in the case of false and missing ring occurrence). Also, they are associated with very cold and long winters, and long periods of ground frost occurrence (as was the case in 1940 and 1957). Tumiłowicz [7] designates the years 1929, 1940, and 1957 as characteristic years (i.e., displaying a decrease in tree-ring width in various false cypress species, including *Ch. pisifera*), and links their occurrence to unusually severe winters.

5. Conclusions

In comparison to indigenous coniferous trees, the Sawara cypress can be considered a fast-growing species. Populations of this taxon growing in northern Poland display a highly similar growth pattern. Only the population at Glinna shows slightly different statistical relationships due to its peculiar location and the mild climate of its environment. Dendroclimatic analyses indicate three periods of growth-climate relationship: late winter/early spring, the summer months, and the end of the preceding growth season. Warm winters, and warm and early springs cause an earlier onset for cambium activity and the formation of wider tree-rings. Long periods of ground frost occurrence and cold winters may be the reason for frost ring occurrence and the reduction in tree-ring width. High precipitation sums in summer months favor the formation of wide tree-rings, while droughts and rainless periods in summer cause a reduction in tree-ring width and/or false ring formation. Additionally, the conditions prevailing at the end of the preceding growth season influence cambium activity in the next growth season. Low temperature, low insolation, and high precipitation totals make a positive influence on the condition of trees.

Although *Ch. pisifera* occupies a small area in Poland, and has no economic significance, it is worthwhile to expand the study to include southern Poland and its adjacent regions. The knowledge concerning acclimatization, growth rate, or growth-climate relationship may be useful in the future, especially at a time of rapidly changing climate, increasing human impact on forests, and highly intensified invasion of insect and fungal species attacking native forest-forming taxa.

Author Contributions: Conceptualization, A.C. and G.N.; field collection A.C. and G.N.; data analyses, draft preparation, review, and editing, A.C., G.N. and H.K.-K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available in a publicly accessible repository. The data presented in this study are openly available in RepOD at https://doi.org/10.18150/D1ZDVB, accessed on 1 September 2021.

Acknowledgments: We gratefully acknowledge Wojciech Ożga for making available the data from the weather station in Rogów.

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

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