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Effects of Climate Change on Scots Pine (*Pinus sylvestris* L.) Growth across Europe: Decrease of Tree-Ring Fluctuation and Amplification of Climate Stress

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Abstract: From an economic perspective, Scots pine (*Pinus sylvestris* L.) is one of Europe's most important tree species. It is characterized by its wide ecological adaptability across its natural range. This research aimed to evaluate the forest structure, productivity and especially radial growth of heterogenous pine stands in 16 research plots in the Czech Republic, Poland, Spain and Great Britain. The study assessed the tree-ring formation and its relationship to climate change for each country, using 163 dendrochronological samples. The stand volume of mature pine forest ranged between 91 and 510 m^3 ha^{-1}, and the carbon sequestration in the tree biomass was 40–210 t ha^{-1}. The stands had a prevailing random distribution of trees, with a high vertical structure close to selection forests (forest stands with typical very diverse height, diameter and age structure). Spectral analyses showed a substantial decrease in fluctuations in the tree-ring index and a loss in natural growth cyclicity in the last thirty years. The results also evinced that mean air temperature was the most important factor influencing the radial growth compared to precipitation totals. Pine thrives in precipitation-stable locations, as shown by the results from Great Britain. The conclusions of this study confirm the fundamental effect of ongoing global climate change on the dynamics and growth of pine forests in Europe.

Keywords: close-to-nature management; forest structure; stand diversity; timber production; carbon sequestration

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1. Introduction

Climate change in the form of increasing frequency and intensity of long-term droughts, heat waves and other extreme weather events negatively affects forest stands worldwide [1,2]. Climate models for the 21st century predict an increase in the average annual temperature by another 1.5 °C over the next decade, while precipitation will decrease radically [3]. Other scenarios show that the maximum temperature may increase by up to 2.5 °C [4]. In addition, the frequent occurrence of droughts and forest fires [5] decreases the vitality of trees or directly results in the disruption of entire forest stands [6].

Scots pine (*Pinus sylvestris* L.) occupies a dominant position in more than half of European forests [7]. It is considered as one of the tree species most affected by climate change [8–14]. In several alpine areas, drought has already been reported as a major cause of Scots pine decline in the second half of the 20th century [15,16]. Pine stands suffer considerably from climatic fluctuations, manifested by an unbalanced distribution of wet and dry periods [9,11–13,17]. This has a direct negative impact on the photosynthetic activity of pines [18,19], their cambial growth [20], and their overall resistance against bark beetles [6,21], fungal pathogens [22] and mistletoe (*Viscum album* L.) attack [23–25]. Dry periods also increase the risk of forest fires in pine forests [26]. The vulnerability to various disturbances likely increases with the homogenization of forest stands [27,28].

Changes in management and silvicultural approaches are needed to increase the resilience of forest stands [29–31]. It is accepted that the greater use of natural processes and increased spatial, species and genetic diversity are the main principles of adaptive forest management [32]. In structurally differentiated stands, we generally expect higher stability and an improvement in the possibility of a physiological response to climatic variations [33–35]. Furthermore, refs. [2,8] confirm the influence of the provenance of Scots pine on its adaptability to climate change. Refs. [36,37] point out the relationship between nutrient balance and availability in combination with drought response. Some authors report the essential role of species composition in the drought stress process [38–40] as well as in individual growth trends or habitat conditions [41]. Concerning vulnerability to climate change impact, refs. [42,43] confirm the dependence of tree size, while [44] discuss the influence of competition between tree individuals.

In most of Europe, the productive silviculture of pine forests is mainly based on clear cutting or shelter systems. This reflects the ecological requirements of Scots pine as a light-demanding tree species with a tendency to create asymmetric crowns in lower stand densities [45]. The resulting homogenous even-aged forest stands usually require subsequent manipulation of stand density by thinning to increase their resistance to damaging factors [46–49]. Although close-to-nature forest management methods have been used for more than 100 years [50], there are still significant knowledge gaps in the silviculture of structurally differentiated pine stands. Stands with higher structural differentiation allow low-intensity management and are expected to better adapt to climate change [28,51–55].

Climate change negatively affects tree growth, while recent years indicate the phenomenon of a divergence problem between drought with high temperature and irregular precipitation distribution in Europe. The beginning of this divergence can be considered as starting from the 1980s [56,57].

This research evaluates production, structural and especially dendrochronological parameters of heterogenous Scots pine forest stands in the Czech Republic (CZ), Spain (SP), Poland (PL) and Great Britain (GB). The specific objectives of this study were to determine (i) the stand forest production parameters, biomass potential and carbon sequestration of pine stands in four different countries across Europe; (ii) the spatial pattern, structural differentiation and total diversity of tree layers; (iii) the dynamics of radial growth and cyclicity of the tree-ring width index of Scots pine from the 1951 to 2016 in two periods before and during the more noticeable dynamic climate change using the threshold year of 1986; and (iv) the effect of climatic factors (temperature and precipitation) on radial growth in relation to climate change.

2. Materials and Methods

2.1. Study Areas

This study evaluated Scots pine stands in four locations in four European countries representing different climatic and geographic zones: the Czech Republic (CZ), Spain (SP), Poland (PL) and Great Britain (GB) (Figure 1). The forest stands from the Czech Republic are located in the Western Bohemia Uplands; the studied forest stands in Spain are located in the central part of the Sierra de Guadarrama; the study area in NE Poland is in the northwest of the city of Nowogoród, in the catchment of Narew River; and the Scots pine stands in Great Britain are located in the sub-central part of the Scottish Highlands, on the south shore of Loch Rannoch, within the Black Wood complex of native pine stands [58,59] in the Tummel Valley, Perthshire. The studied pine forests represent heterogeneous stands due to close-to-nature management (CZ—Czech Republic, PL—

Poland, ES—Spain) or natural dynamics without interventions (GB—Great Britain) for several decades. In the case of the Black Wood of Rannoch, the last extensive felling occurred in 1940–1941, when only the best trees were removed [59]. Before World War II, the harvesting of trees\occurred probably via selective logging [58]. In Spain, the stands represent one of the most productive Scots pine forests, with highly valued wood. Since the 1980s, an irregular shelterwood system has been applied, with a greater emphasis on the environmental functions and services of the forest [60,61]. Since 2013, the areas have been part of Sierra de Guadarrama National Park. A felling policy with different intensities was carried out on sites in CZ and PL, with close-to-nature management to support natural regeneration and create complex forest structures. In general, clear-cuts and further release cuts were rejected. The tree species composition is formed by monospecific Scots pine with mixed Norway spruce (*Picea abies* [L.] Karst.) (<5%) and silver birch (*Betula pendula* Roth.) (<5%). In terms of phytocoenology, the pine stands in Poland and the Czech Republic belong prevailingly to the vegetation association *Vaccinio vitis-idaeae-Quercetum* Oberdorfer 1957 and the vegetation association *Vaccinio myrtilli-Pinetum sylvestris* Juraszek 1928. According to [62], the Scottish pinewoods belong to the *Pinus-Hylocomium* type, while in Spain, the represented association is *Senecioni carpetani-Cytisetum oromediterranei* R. Tx. and Oberdorfer 1958 corr. Rivas-Martinez (ca. 1991).

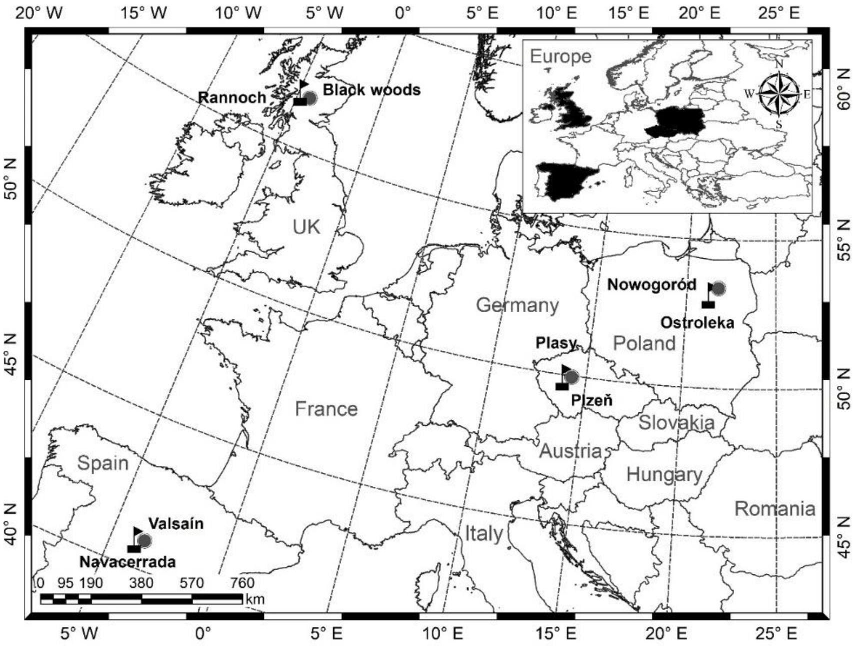

Figure 1. Location of research plots (dots) and adjacent location of sites for which meteorological data were derived (flags).

In Table 1, all research plots (RPs), with their location and overview of basic site parameters, are listed; other basic climate characteristics for all study areas are shown in Table 2. Climatic regions of the study areas were determined according to the Köppen–Geiger climate classification [63]. Long-term climate characteristics for all study areas were focused on two periods—Period 1: 1951–1985 and Period 2: 1986–2016. The division into two periods was implemented to cover the growth of pine before the most intense climate changes and during climate changes. The rationale for splitting this time series was the growth divergence of tree rings caused by higher average temperatures, leading to increased growth variability and the emergence of the "divergence" issue, where tree-ring growth does not mirror climate fluctuations with the same trend [64–66]. The period of the onset of divergence can be considered the period from the 1980s, when a gradual temperature increase began, with precipitation levels remaining around the same threshold, leading to divergence between these observed factors [56]. In our study, the cutoff for the onset of climate change is set at 1986, marking the period of the beginning of divergence and also half of the period of our observed climate data. When comparing these periods, air temperature in the growing season increased in all studied countries meanly by 0.95 °C, and no changes were observed for the overall precipitation (mean increase by 1.8 mm for all countries; decrease only in the case of Great Britain). The April to September growing season was an intentional choice of a seasonal window, aimed to reduce variability in the start and end of the growing season. The data assessed within this timeframe represents the nearest real vegetation period shared across all research plots (Figure 2).

Table 1. Location and overview of basic site parameters of research plots.

RP ID	Country	GPS Latitude (WGS84)	GPS Longitude (WGS84)	Altitude (m)	Slope	Expo-Sure	Soil Type
CZ_1	Czech Republic	49°54′35.653″ N	13°11′59.617″ E	600	-	-	Gleyic Podzol
CZ_2	Czech Republic	49°54′15.779″ N	13°12′30.546″ E	580	4°	E	Gleyic Podzol
CZ_3	Czech Republic	49°54′19.548″ N	13°12′17.456″ E	600	4°	E	Gleyic Podzol
CZ_4	Czech Republic	49°55′37.037″ N	13°14′16.646″ E	580	4°	E	Gleyic Podzol
SP_1	Spain	40°49′2.102″ N	3°59′8.730″ W	1580	11°	SE	Cambisol—Ferric Luvisols
SP_2	Spain	40°48′56.365″ N	3°58′58.343″ W	1670	13°	SE	Cambisol—Ferric Luvisols
SP_3	Spain	40°48′52.132″ N	3°58′44.223″ W	1780	20°	SE	Cambisol—Ferric Luvisols
SP_4	Spain	40°48′58.747″ N	3°58′55.331″ W	1670	17°	SE	Cambisol—Ferric Luvisols
PL_1	Poland	53°19′12.130″ N	21°40′19.159″ E	130	-	-	Arenic Podzol
PL_2	Poland	53°19′25.408″ N	21°40′17.895″ E	130	-	-	Arenic Podzol
PL_3	Poland	53°19′17.887″ N	21°39′46.918″ E	130	-	-	Arenic Podzol
PL_4	Poland	53°19′23.354″ N	21°39′13.084″ E	130	-	-	Arenic Podzol
GB_1	Great Britain	56°40′29.170″ N	04°20′51.520″ W	250	4°	NW	Gleyic Podzol
GB_2	Great Britain	56°40′29.170″ N	04°20′51.520″ W	250	4°	NW	Gleyic Podzol
GB_3	Great Britain	56°40′19.748″ N	04°20′32.942″ W	280	4°	NW	Gleyic Podzol
GB_4	Great Britain	56°40′19.748″ N	04°20′32.942″ W	280	4°	NW	Gleyic Podzol

Table 2. Long-term climate characteristics for all study areas (Period 1: 1951–1985; Period 2: 1986–2016).

	Czech Republic	Spain	Poland	Great Britain
Köppen–Geiger climate classification	Dfb	Csb	Dfb	Cfb
Annual average air temperature (°C)	7.95	6.55	7.34	5.67
Growing season average air temperature (°C)	13.98	9.02	14.18	11.30
Growing season average air temperature: Period 1 (°C)	12.63	8.79	13.73	10.68
Growing season average air temperature: Period 2 (°C)	13.64	9.29	14.68	12.03
Annual average total precipitation (mm)	492.28	1325.71	553.18	1552.24
Growing season average total precipitation (mm)	351.22	553.51	340.57	445.38
Growing season average total precipitation: Period 1 (mm)	350.66	533.08	325.24	478.06
Growing season average total precipitation: Period 2 (mm)	351.87	577.35	357.94	407.27

Notes: Köppen–Geiger climate classification: Cfb—oceanic climate; Csb—Warm-summer Mediterranean climate; Dfb—humid continental climate.

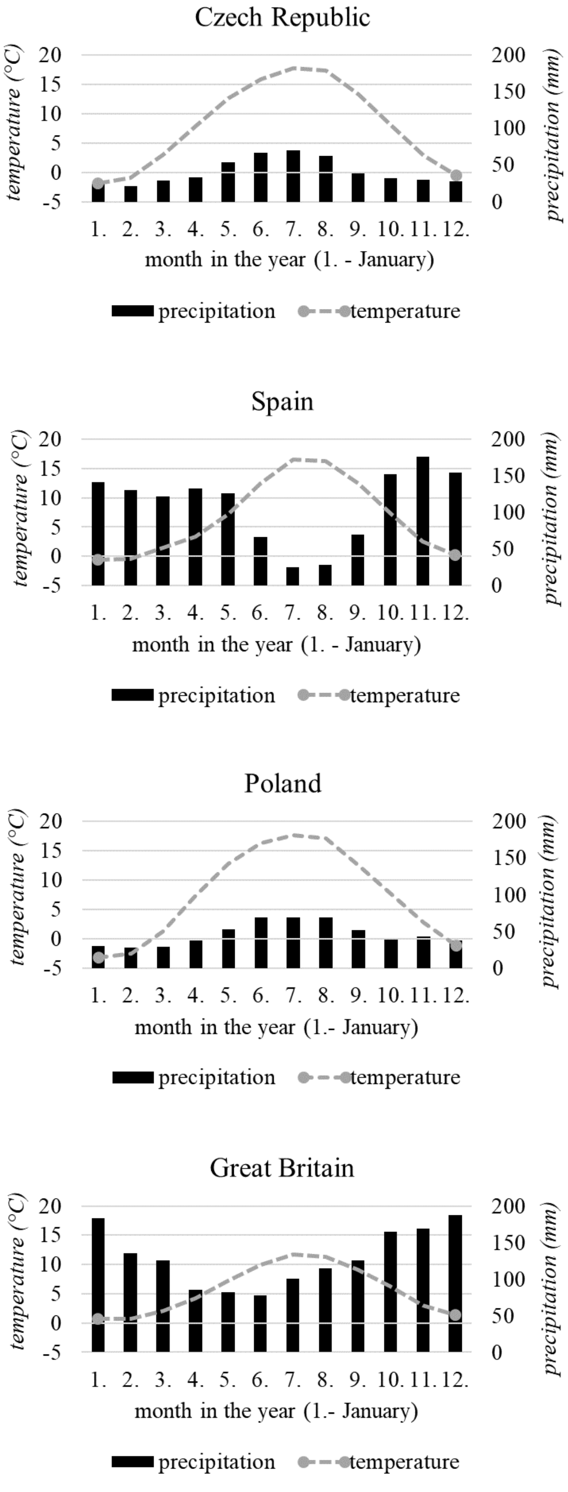

Figure 2. Average air temperatures (°C) and average total precipitation (mm) in individual months for the period 1951–2016 for the monitored countries: Czech Republic, Spain, Poland and Great Britain.

2.2. Data Collection

Field-Map technology (IFER-Monitoring and Mapping Solutions Ltd., Jílové u Prahy, Czech Republic) was used to determine the tree layer structure and production parameters in RPs (Research Plots) in 2015–2016. Four 50 × 50 m (0.25 ha) RPs were established in each country (Czech Rep., Spain, Poland and Great Britain; a total of 16 RPs). The positions of all individuals of the tree layer with a diameter at breast height (DBH) ≥ 8 cm were recorded. The height of trees, height of the live crown base and the crown projection were measured in at least four directions perpendicular to one another. The diameter of tree layer individuals was measured by a Mantax Blue metal caliper (Haglöf, Långsele, Sweden) with an accuracy of 1 mm, and heights were measured using a Vertex laser hypsometer (Haglöf, Sweden) with an accuracy of 0.1 m.

Dendrochronological samples were taken from codominant and dominant trees, according to the classification described by [67], for significant growth response (compared to subdominant and suppressed trees) [68]. We collected a total of 163 dendrochronological samples, with a minimum of 34 samples on the research plot and a maximum of 47, with one sample drilled from a single tree. The core samples were taken with Pressler auger at BH (Breast Height), perpendicular to the axis of the tree along/against the slope. The dendrochronological samples were glued to boards and carefully ground and polished, so that it was possible to measure the distances between the annual rings, as polishing also highlights the anatomical structure of the annual rings. The tree-ring width was measured (accuracy 0.01 mm) using an Olympus binocular magnifying glass on a LinTab measurement table and registered using the TSAP-Win software (version 4.64, RINNTECH, Heidelberg, Germany).

Climatic data for the Czech Republic were obtained from the Czech Hydrometeorological Institute (CHMI)—meteorological station Kralovice (49°58′54.522″ N, 13°29′38.331″ E; altitude 318 m; distance to RPs 22.4 km); for Poland from the Institute of Meteorology and Water Management (IMGW)—meteorological station Ostrołęka (53°04′59.9″ N 21°34′00.3″ E; altitude 94 m; distance to RPs 27.2 km); for Great Britain from the Met Office Integrated Data Archive System—the gridding process accounts for effects such as latitude, longitude, altitude, coastal influence, and the effect of urban land through the use of normalization with respect to monthly 1961–1990 climate normals, and in the case of some variables a regression model [69]. For more details about the construction, see [70]. Climatic data for Spain were obtained from the State Meteorological Agency (AEMET)—meteorological station Puerto de Navacerrada (40°47′18.863″ N, 4°0′12.158″ W; altitude 1860 m; distance to RPs 3.1 km).

2.3. Data Processing

The basic structure, diversity and production characteristics of the tree layer were evaluated by the SIBYLA Triquetra 10 forest growth simulator [71]. For the evaluation of the spatial pattern, the aggregation index [72] was calculated. Structural diversity was evaluated by the Arten-profile index [73], diameter and height differentiation [74], crown differentiation, vertical diversity and total stand diversity [75] (see Table 3). The stand volume of pine was calculated according to [76]. Tree biomass was derived from the above-ground biomass (stem, branches and needles) and below-ground biomass (roots and snags). The above-ground biomass of pine in dry matter was derived from the model from [77]. The biomass of pine roots was calculated using a model from [78]. The content of carbon (C) in pine trees was calculated following the research of [79] using the unit content of elements in 10 mg kg^{-1} of dry matter. The relative stand density index (SDI) [80] and the canopy closure [81] were observed for each plot.

Dendrochronological analysis was performed in R (version 4.3.1) software [82]. Each dendrochronological tree-ring series were detrended through a two-step process. First, a negative exponential detrending function was applied, followed by a 67% insertion cubic smoothing spline detrending, as per the 'dplR' instructions, to the original tree-ring series. [83,84]. Detrending removes the age trend by preserving low-frequency climate signals [85–88]. The time frame of the dendrochronological data was divided into two periods (Period 1: 1951–1985, Period 2: 1986–2016) to evaluate the Scots pine response to changing climatic conditions. The DendroClim 2002 program was used to analyze dendrochronological curves with monthly climatic data, using the 'response and correlation' function from April of the preceding vegetation season to September of the current vegetation season [89]. Spectral analyses and a Simple Linear Correlation (Pearson r) table were used for the indexed (detrended) radial growth of Scots pine, using Statistica 13 software [90].

The calculation was conducted with the 'Single Furier (Spectral) Analysis' function for the evaluation of fluctuations in tree-ring growth variability, using the output 'Periodogram' plot by 'Period' [90].

Table 3. Overview of indices describing the stand diversity and their common interpretation.

Criterion	Quantifier	Label	Reference	Evaluation
Horizontal structure	Aggregation index	R (C&Ei)	Clark and Evans (1954) [72]	mean value $R = 1$ (random distribution); aggregation $R < 1$; regularity $R > 1$
Vertical structure	Arten-profile index	A (Pri)	Pretzsch (2006) [73]	range 0–1; balanced vertical structure $A < 0.3$, inhomogeneous structure $A = 0.3–0.6$, multi-layered structure $A = 0.6–0.9$, selection forest $A > 0.9$
	Vertical diversity	S (J&Di)	Jaehne and Dohrenbusch (1997) [75]	low $S < 0.3$, medium $S = 0.3–0.5$, high $S = 0.5–0.7$, very high diversity $S > 0.7$
Structure differentiation	Diameter dif.	TMd (Fi)	Füldner (1995) [74]	range 0–1; low $TM < 0.3$, medium $TM = 0.3–0.5$, high $TM = 0.5–0.7$, very high differentiation $TM > 0.7$
	Height dif.	TMh (Fi)		
	Crown dif.	K (J&Di)	Jaehne and Dohrenbusch (1997) [75]	low $K < 1.0$, medium $K = 1.0–1.5$, high $K = 1.5–2.0$, very high differentiation $K > 2.0$
Complex diversity	Stand diversity	B (J&Di)	Jaehne and Dohrenbusch (1997) [75]	monotonous structure $B < 4$, even structure $B = 4–6$, uneven structure $B = 6–8$, diverse structure $B = 8–9$, very diverse structure $B > 9$

The dendrochronological indices were computed using the tutorial methods of [83,84]. The detrended ring-width data of Scots pine were used to calculate the EPS (expressed population signal). The EPS indicates the reliability of a chronology as a fraction of the joint variance of the theoretical infinite tree population. We used the 'EPS cutoff' to increase the quality of dendrochronological data, and therefore, the time series was shortened to the time period 1951–2016 for all variants so that $\text{EPS} > 0.85$ [83,84]. This time period was defined as the intersection of data availability due to the availability of comparable precipitation and temperature forecasts. We also calculated the SNR (signal-to-noise ratio), which evaluates the signal strength of chronology and R-bar (inter-series correlations) [86,91]. The indicators EPS, SNR, R-bar, and AR1 were computed using the 'dplr' guidelines [83,84], which are based on standard principles of dendrochronology [85,86,91]. Information on dendrochronological indicators can be found in Table 4.

Table 4. Characteristics of tree-ring chronologies of Scots pine for the period 1951–2016 in research plots.

Country	No. Trees	Age Mean	Sampling Year	Increment (mm)	Increment Min–Max (mm)	Std.	R-Bar	SNR	EPS
Poland	40	125	2016	1.25	0.67–2.44	0.618	0.234	9.005	0.900
Czech Republic	42	132	2015	0.95	0.47–1.61	0.494	0.247	11.186	0.917
Spain	47	119	2015	1.33	0.73–1.92	0.664	0.314	19.172	0.950
Great Britain	34	117	2016	2.22	0.82–4.85	1.017	0.385	8.254	0.887

Notes: No. Trees—number of trees; Age mean—mean sample age in years; Sampling year—year of dendrochronological sampling; Increment—average annual increment in tree-ring width; Increment min–max—the range of minimum and maximum growth of the tree ring; Std.—standard deviation; R-bar—inter-series correlation; SNR—signal-to-noise ratio; EPS—expressed population signal.

The analysis of negative pointer years (NPYs) was performed according to [92,93]. For each tree, the pointer year was set as an extremely narrow tree ring that does not reach 40% of the increment average from the four preceding years. The occurrence of the negative year was proven if a strong reduction in increment occurred at least in 20% of the trees on the plot.

Principal component analysis (PCA) in CANOCO 5 [94] was used to analyze the relationships between timber production, stand structure and diversity on RPs and also radial growth (tree-ring width index) and climate factors (temperature and precipitation) in relation to climate change for all countries. Data were log-transformed, centered and standardized before the analysis. The results of PCA were exported into the form of an ordination diagram. The situation map was made in ArcGIS 10 software (Esri, Redlands, CA, USA).

3. Results

3.1. Stand Structure and Production

The DBH and height range was 18.2–50.4 cm and 10.88–27.36 m, respectively, across all RPs (Table 5). The number of trees was in the range from 144 trees ha^{-1} on RP GB_1 to 768 trees ha^{-1} on PL_1. Similarly, the highest basal area (47.6 m^2 ha^{-1}) and stand volume (510 m^3 ha^{-1}) was observed on RP PL_1 with the highest stocking (SDI). The highest ever carbon sequestration (210 t/ha) was also found at PL_1. This index, influencing the overall production of the stand, ranged between 0.31 and 0.93. In terms of average values for all RPs and countries, the average basal area reached 30.6 m^2 ± 10.7 SD, stand volume 303 m^3 ha^{-1} ± 129 m^3 ha^{-1} and carbon sequestration in biomass 123 t ha^{-1} ± 52 SD. Overall, the average annual radial growth in Table 4 best reflects the production in each RP. The highest increment was recorded in GB (2.26 mm), followed by SP (1.33 mm), and PL (1.25 mm), with the lowest mean annual increments recorded in CZ (0.95 mm).

Table 5. Basic stand characteristics on RPs in the Czech Republic (CZ_1–CZ_4), Spain (SP_1–SP_4), Poland (PL_1–PL_4) and Great Britain (GB_1–GB_4).

RP	DBH (cm)	H (m)	v (m^3)	N (trees ha^{-1})	BA (m^2 ha^{-1})	V (m^3 ha^{-1})	HDR	SDI	CC (%)	BIO (t ha^{-1})	Carbon (t ha^{-1})
CZ_1	25.8	17.15	0.439	596	31.2	261	66.5	0.62	75.8	213	111
CZ_2	18.2	16.95	0.215	424	11.0	91	93.1	0.26	59.2	76	40
CZ_3	23.2	15.22	0.372	368	15.5	137	65.6	0.33	47.6	110	58
CZ_4	34.5	25.43	1.061	316	29.6	335	73.7	0.48	62.4	236	124
SP_1	28.2	16.13	0.663	556	34.7	369	57.2	0.68	74.9	286	150
SP_2	27.4	14.19	0.496	752	44.5	373	51.8	0.88	75.8	293	154
SP_3	24.9	14.55	0.436	740	36.1	323	58.4	0.74	81.5	257	135
SP_4	24.7	10.88	0.335	676	32.2	227	44.0	0.67	76.4	180	94
PL_1	28.1	19.73	0.664	768	47.6	510	70.2	0.93	84.1	401	210
PL_2	27.6	18.92	0.683	716	42.8	489	68.6	0.85	74.7	381	200
PL_3	31.7	19.68	0.973	384	30.2	374	62.1	0.55	69.0	281	147
PL_4	38.0	27.36	1.496	304	34.5	455	72.0	0.60	69.0	346	181
GB_1	43.6	15.39	1.326	144	21.4	191	35.3	0.35	56.4	144	75
GB_2	50.4	19.12	1.928	196	39.0	378	37.9	0.61	77.3	282	148
GB_3	34.8	13.02	0.826	248	23.5	205	37.4	0.41	70.8	159	83
GB_4	29.7	14.28	0.571	232	16.1	132	48.1	0.31	62.2	105	55

Notes: DBH—mean quadratic diameter at breast height; H—mean height; v—mean stem volume; N—number of trees per hectare; BA—basal area; V—stand volume; HDR—height to diameter ratio; SDI—stand density index; CC—canopy closure; BIO – biomass in dry matter; Carbon – carbon sequestration in biomass.

3.2. Diversity of Tree Layer

The horizontal structure of the tree layer was random in most RPs, aggregated in the case of three RPs and regular on PL_4. The vertical structure shows a monotonous to very high diversity, approaching a selection forest. According to both evaluation indices, vertical diversity reached the highest values in Spain. On the other hand, the lowest vertical diversity was on the RPs in Great Britain. Similarly, the highest diameter, height and crown differentiation was observed in the case of plots in Spain. However, the structure differentiation of stands was generally low to medium for all RPs. Total diversity, describing the complex diversity of forest stands, raged from B = 3.936 on RP GB_2 (monotonous structure) to B = 7.051 on CZ_1 (uneven structure) (Table 6).

Table 6. Diversity of tree layers on permanent research plots in the Czech Rep. (CZ_1–CZ_4), Spain (SP_1–SP_4), Poland (PL_1–PL_4) and Great Britain (GB_1–GB_4).

RP	Horizontal Structure	Vertical Structure	Vertical Diversity	Diameter Differen.	Height Differen.	Crown Differen.	Total Diversity
CZ_1	1.119	0.369	0.795	0.314	0.207	1.868	7.051
CZ_2	0.957	0.455	0.827	0.300	0.228	1.993	6.684
CZ_3	1.078	0.383	0.742	0.254	0.206	1.618	5.346
CZ_4	1.104	0.674	0.484	0.200	0.125	1.101	5.134
SP_1	0.926	0.904	0.903	0.428	0.372	1.568	5.274
SP_2	0.943	0.789	0.875	0.327	0.243	1.926	5.548
SP_3	0.904	0.909	0.829	0.392	0.303	1.603	5.032
SP_4	0.797A	0.967	0.814	0.339	0.234	2.642	6.046
PL_1	1.079	0.398	0.786	0.367	0.227	1.791	5.995
PL_2	1.075	0.499	0.720	0.355	0.256	1.506	5.210
PL_3	0.875	0.631	0.812	0.423	0.351	2.142	6.124
PL_4	1.191R	0.168	0.805	0.217	0.136	2.095	5.957
GB_1	0.799A	0.251	0.781	0.391	0.252	1.535	4.823
GB_2	0.863	0.469	0.432	0.269	0.122	1.705	3.936
GB_3	0.655A	0.425	0.834	0.400	0.252	1.797	6.279
GB_4	0.811	0.487	0.737	0.324	0.201	1.956	6.166

Notes: A/R—statistically significant ($p < 0.05$) for horizontal structure (A—aggregation, R—regularity).

3.3. Interactions between Production, Structure and Diversity

The PCA results are presented in an ordination diagram in Figure 3. The first ordination axis explains 31.2% of data variability, the first two axes combined explain 61.3% and the first four axes 87.2%. The x-axis illustrates the canopy closure and stocking (stand density index), and the y-axis represents the mean height and aggregation index with total diversity. Tree characteristics (tree volume, diameter, height) were positively correlated with the aggregation index (tendency to regularity), while these parameters were negatively correlated with structural diversity indices. Total diversity and crown differentiation decreased with the increasing mean height and diameter of trees. Stand volume was positively correlated with the carbon sequestration in biomass, basal area, stocking and canopy. Vertical structure and structural (height and diameter) differentiation increased with the increasing number of trees. The aggregation index was the lowest explanatory variable in the ordination diagram. Differences between all studied parameters (stand characteristics, structural diversity indices) in the ordination diagram in Figure 3 were remarkable for countries, as symbols (■ from each record were relatively distant from one another, except for Great Britain and the Czech Republic (similarity between the two countries). The lower part of the diagram was typical for stands with high structural and overall diversity, while the upper part of the graph represents areas with a high production potential and carbon sequestration.

3.4. Dynamics and Spectral Analysis of Radial Growth

The detrended ring-width chronologies in Figure 4 show that the difference between Periods 1 and 2 is mainly in the growth variability continuity of the curves. The period 1951–1985 was characterized by more significant fluctuations in detrendable growth than in Period 2; however, a slight exception is the samples from Great Britain, where both periods are almost identical. The most incoherent growth took place in Period 1 in Poland and Spain. Samples from the Czech Republic in Period 1 show smaller differences compared to plots from Poland. The later Period 2 shows a gradual synchronization of the growth of Scots pine across all studied habitats, especially in the period since 2000.

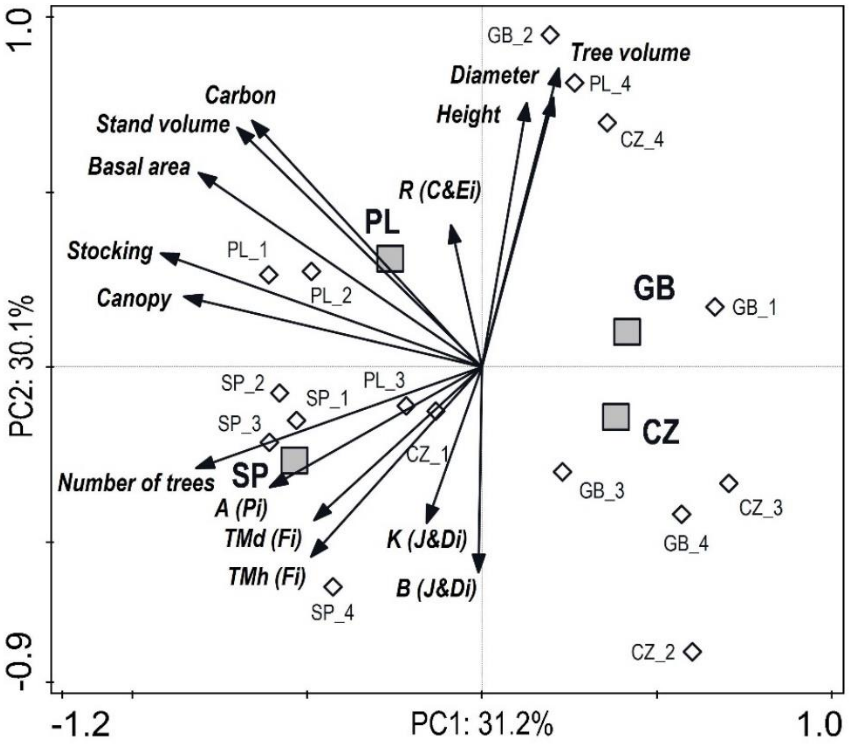

Figure 3. Ordination diagram focused on the species and environmental variables shows results of the principal component analysis of relationships between stand characteristics (Stand volume, Carbon—sequestration in biomass, Tree volume, Basal area, Diameter, Height, Number of trees, Canopy closure, Stocking—stand density index), structural diversity (R (C&Ei), A (Pi), TMd (Fi), TMh (Fi), K (J&Di), B (J&Di); see Table 3), and countries (CZ—Czech Republic, PL—Poland, GB—Great Britain, SP—Spain). Symbols indicate ■ countries and ◇ permanent research plots (label: country + number of plot).

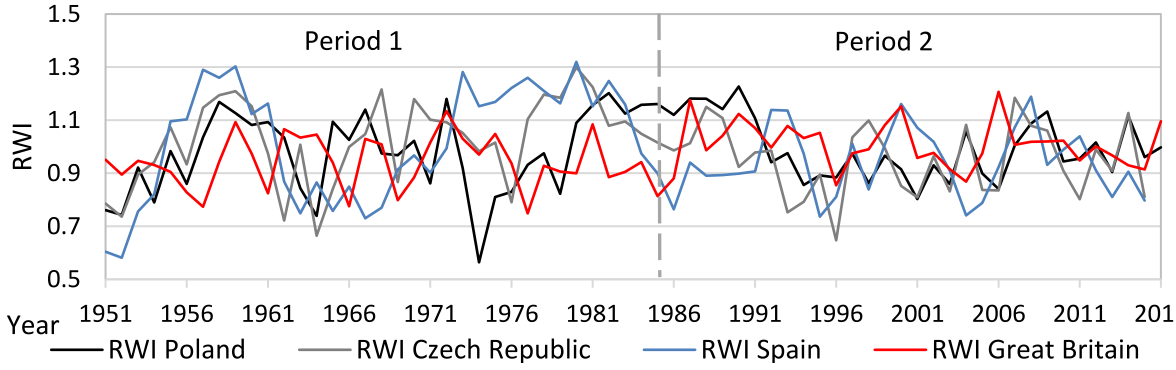

Figure 4. Detrended ring-width chronologies of Scots pine in Periods 1 and 2. Period 1 for 1951–1985, and Period 2 for 1985–2016. RWI means ring-width index.

In terms of NPYs, in Spain, extreme radial growth decline was seen in 1963, 1986, 1995 and 2004; in the conditions of the Czech Republic, these were the years 1962 and 1996. In Poland, a significant decline in increase was observed in 1964 and 1974. No NPYs were observed for Great Britain.

The spectral analyses of detrended data in Figure 5 show that there is a difference between Period 1 and Period 2, chiefly in the 'Periodogram values', where in Period 1 there are higher values than in Period 2. Larger data values in the 'Periodogram values' suggest more differences between cycles. Areas in Spain go through the most visible cyclical fluctuations during Period 1, where Scots pine has the most significant cycles from 8 to 34 years according to the periodogram values. In contrast, the smallest cyclical fluctuations are in areas in Great Britain, where the 'Periodogram values' are the lowest of our variants, and there is not much difference between Periods 1 and 2. Overall, Period 1 shows the greatest cyclical fluctuations at all research sites. In contrast, Period 2 shows smaller cycles in the radial growth of pine, as confirmed by Figures 4 and 5.

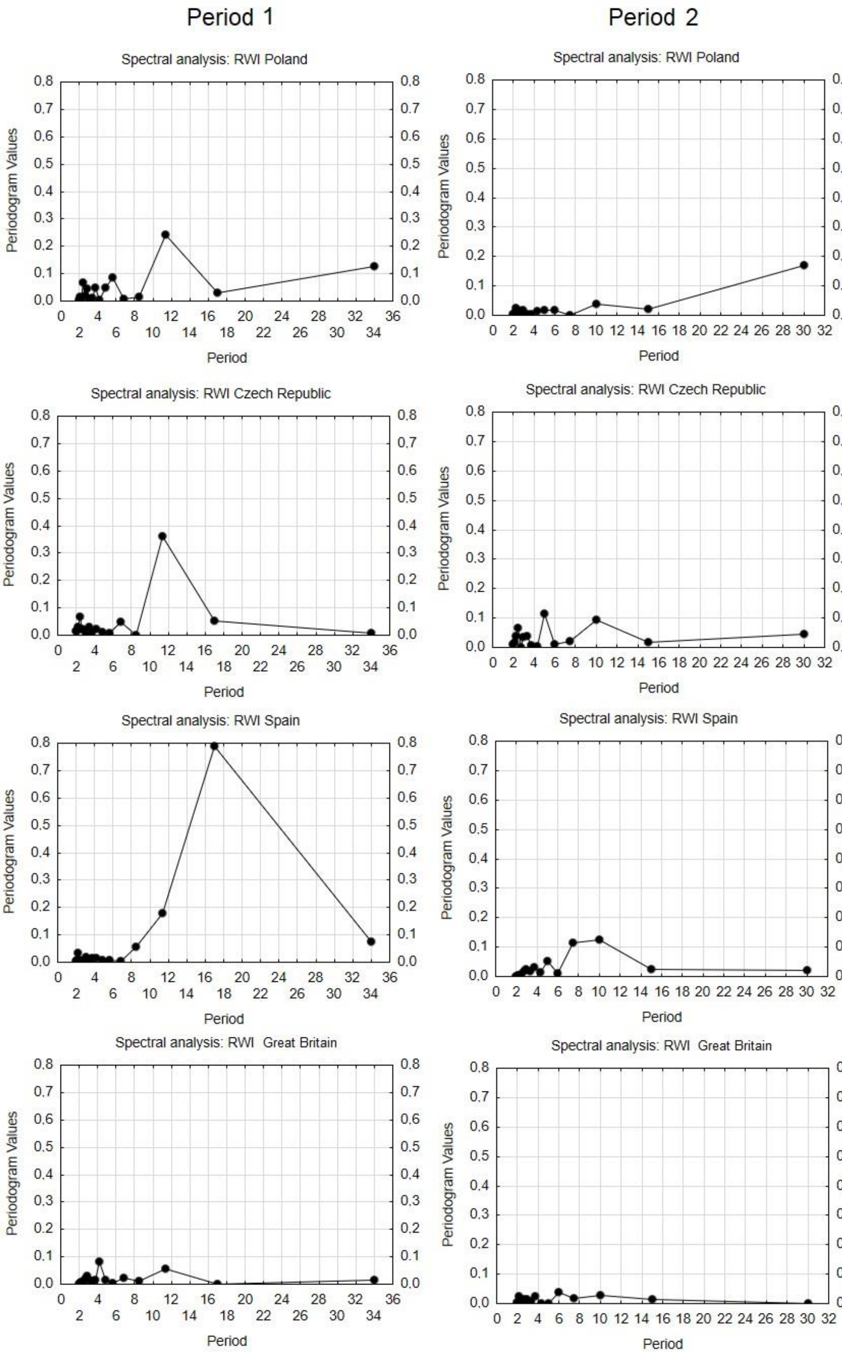

Figure 5. Spectral analysis 'Periodogram' of RWI for Poland, Czech Republic, Spain and Great Britain in Periods 1 and 2. Period 1 is calculated for 36 cases (1951–1985), and Period 2 is calculated for 32 cases (1986–2016). RWI means ring-width index.

Cyclical fluctuations of detrendable growth in the Czech Republic and Poland share nearly the same 'Periodogram values'; in the Czech Republic, there are slightly higher differences between growth cycles than in Poland. The same growth periods in the Czech

Republic and Poland also occur, with 11-year cycles in Period 1 having the greatest value. In Period 2, the 5- and 11-year cycles are more pronounced. In contrast to Poland, the 30-year cycles are more pronounced for the Czech Republic in Period 2, according to the periodogram values, in contrast to Period 1. Furthermore, there are 4- and 11-year cycles in Great Britain in Period 1, but in Period 2, there are fewer 6-year cycles. In Period 2, 7- to 10-year cycles are the highest in Spain. Overall, it can be said that in six variants of eight, there are 11-year periods.

3.5. Effect of Temperature and Precipitation on Radial Growth

Correlation coefficients (Table 7) describe the correlations between the ring-width index and average temperature and precipitation sums in the vegetation season and average annual temperature and annual precipitation sums. The correlations between the temperatures and ring-width index do not show statistically significant values ($p < 0.05$). However, the highest correlation with temperatures can be seen in the Czech Republic for temperatures in the vegetation season (r = −0.29) in Period 1. Spain shows a high correlation with temperature in the vegetation season in Period 2 (r = −0.27). Tree rings of pine show a higher correlation of annual temperature compared to temperatures in the vegetation season, which show lower correlations, with the two exceptions already mentioned above. Precipitation totals have mostly negative correlations with the ring-width index, but all statistically significant values are positive. Higher correlations are shown in vegetation season precipitation with tree-ring growth. Significant correlations are for Period 1 tree-ring growth with precipitation in the vegetation season (r = 0.40) and annual precipitation (r = 0.38). Spain also shows a significant correlation, where Period 2 is positively correlated with precipitation in the vegetation season (r = 0.39). The most negative correlations between precipitation and the growth of tree rings are evident for values from Great Britain. Correlations between growth in Periods 1 and 2 tend to be negative. These correlations are positive in the case of the average annual temperature for locations in Poland, and only slightly negative in the Czech Republic. The correlation trend for precipitation totals is also negative between Periods 1 and 2, except for Spain, where values show a transition from lower correlations to higher positive correlations.

Table 7. Correlation coefficients of ring-width index (RWI) with temperature in the vegetation season, annual temperature, seasonal precipitation and annual precipitation. Values in bold are statistically significant ($p = 0.05$).

Plot Name	Time Period/Year	Temperature in Veg. Season	Annual Temperature	Precipitation in Veg. Season	Annual Precipitation
RWI Poland	Period 1/1951–1985	0.03	0.15	0.21	−0.02
	Period 2/1986–2016	0.01	0.18	−0.01	−0.12
RWI Czech Republic	Period 1/1951–1985	−0.29	−0.01	**0.40**	**0.38**
	Period 2/1986–2016	−0.07	0.19	−0.13	−0.06
RWI Spain	Period 1/1951–1985	−0.07	0.12	0.02	−0.16
	Period 2/1986–2016	−0.27	−0.16	**0.39**	−0.02
RWI Great Britain	Period 1/1951–1985	0.09	0.16	−0.26	−0.27
	Period 2/1986–2016	−0.03	−0.07	−0.23	−0.09

Comparing both time periods, the radial growth of pine was more affected by monthly air temperature and the overall precipitation in the second period across all RPs (Figure 6). Overall, a higher number of significant correlation coefficient ($p < 0.05$) months affecting growth were found, in six cases in the second period (eight significant values for all plots,). In one case in the first period, we observed less frequent significant correlation values with temperature on all plots (six significant values) for temperatures in CZ, and in one case, equalized for temperatures in Spain. Generally, precipitation had a lower effect (12 significant correlation coefficients in different months—12 months) on radial growth in all research plots than temperature (16 months). Both studied climate factors had the same effect on radial growth in the previous year (April to December—14 significant moths), such as in the current year (January to September—14 significant moths). The climate in August of the current year had the highest effect on radial growth (4× significant values).

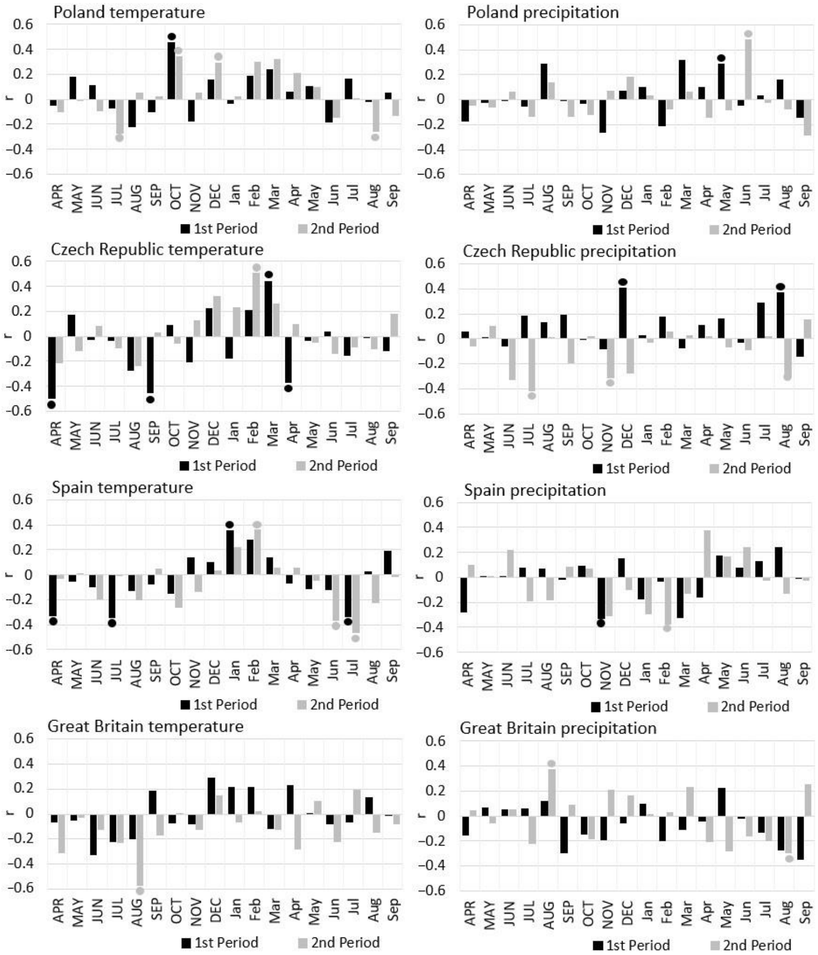

Figure 6. The correlation coefficients of ring-width index values for Scots pine monthly temperatures and precipitation from April (capital letter) of the previous year to September of the current year (lowercase letter). Values are divided into Period 1 (1951–1985) and Period 2 (1986–2016). Statistically significant values ($p < 0.05$) are marked with a round/circle symbol.

In terms of individual countries, the lowest influence of climate factors on radial growth was recorded in Great Britain (3 significant months), followed by Poland (6 months; Figure 6). Conversely, the most sensitive pine forest to climate factors was in the Czech Republic (10 months) and in Spain (9 months). In Poland, the main limiting factor for radial growth was low temperature from October to December of the previous year, while in the case of the Czech Republic it was the period from February to March of the current year. In Spain, the main limiting factor for growth of pine was low temperature from February to March together with high temperature in June and July of the current year. Precipitation and temperature in August of the previous year played a major role in the case of Great Britain.

Interactions between the radial growth of pine and climate factors (temperature and precipitation) in different periods are presented by PCA in an ordination diagram in Figure 7 for all countries and both periods. All four ordination axes explain 71.1–79.2%, while in all cases (except the Czech Republic), there was a higher explanation of climate factors in relation to ring-width index in the second period. The diagram shows that the influence of climatic factors (precipitation vs. temperature) and its intensity on radial growth has changed over time. Radial growth was more affected by climate factors in the second period in all four countries.

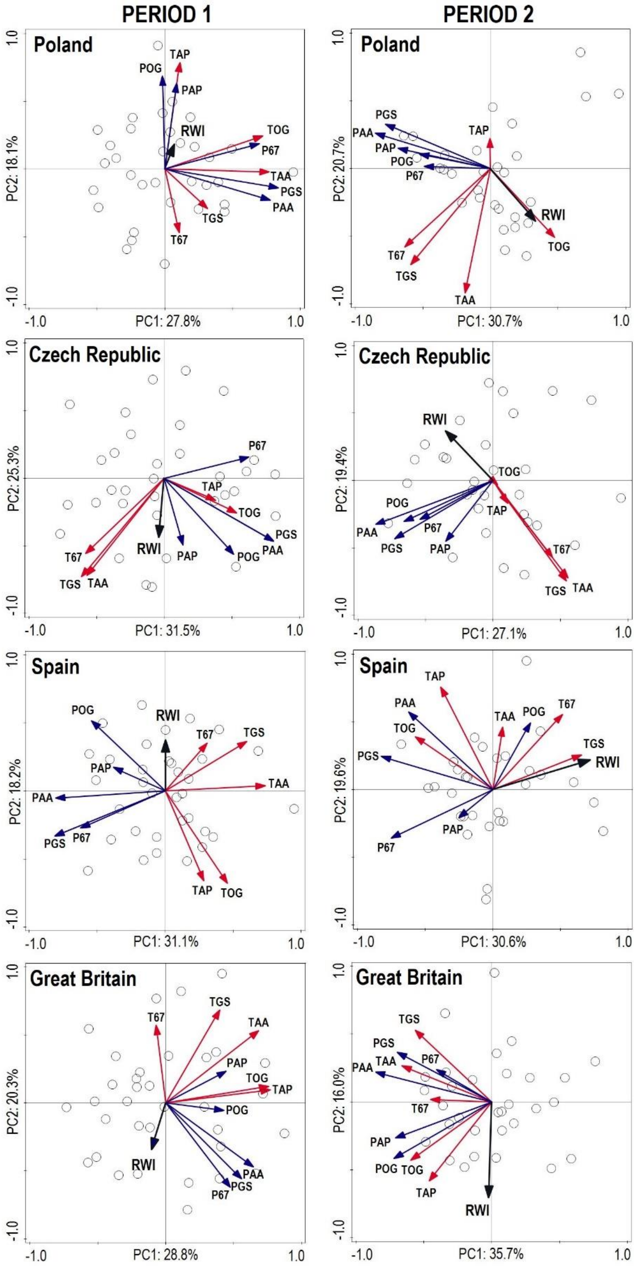

Figure 7. Ordination diagrams focused on the species and environmental variables show results of the principal component analysis of relationships between radial growth of pine (black color: RWI), temperature indicators (red color: TAA—annual temperature of the current year, TAP—annual temperature of the previous year, TGS—temperature in growing season of the current year, TOG—temperature outside growing season, T67—temperature in June and July of the current year) and precipitation indicators (blue color: PAA—annual precipitation of the current year, PAP—annual precipitation of the previous year, PGS—precipitation in the growing season of the current year, POG—precipitation outside growing season, P67—precipitation in June and July of the current year). Values are divided into Period 1 (1951–1985) and Period 2 (1986–2016) and countries (Czech Republic, Poland, Great Britain, Spain). Symbol ○ indicates years.

4. Discussion

4.1. Stand Production

The stand volume of the studied heterogenous pine forests covered a broad range, from 91 to 510 m^3 ha^{-1}, and a basal area from 11 m^2 ha^{-1} to 47.6 m^2 ha^{-1}. The stand summary characteristics were variable in each country. The high variability of stand characteristics was also confirmed in other studies, both from the conditions of native Scots pine woodlands and from managed stands [58,95,96]. The lowest production parameters were observed on RP CZ_2, CZ_3 and GB_4, with natural dynamics since the 1940s [57]. Comparable stand volumes (88–176 m^3 ha^{-1}) were observed in semi-natural pine stands in the Czech Republic [96]. On the other side, [97] showed very high volumes of monospecific pine stands, of 714 m^3 ha^{-1}, and even 874 m^3 ha^{-1} for mixed ones. The authors of [98] reported similar results from pure pine stands, with a volume of up to 714 m^3 ha^{-1}.

The biomass of RP pine stands varies from 71 to 401 t ha^{-1}, and carbon sequestration from 40 to 210 t ha^{-1}. The high productive potential and carbon sequestration of Scots pine compared to other native or introduced tree species have also been documented in several studies in Europe [99–101]. According to [100], Scots pine stands show significantly higher values of carbon sequestration compared to spruce, Douglas fir or larch tree. Conversely, [102] and [29] state that in the conditions of European beech forests, carbon sequestration is up to twice as high as in the case of Scots pine stands, with a higher primary production. The highest increment of codominant and dominant trees in our case is evident in Great Britain (average annual increment in tree-ring width of 2.22 mm), the lowest in the Czech Republic (0.95 mm), while intermediate increment rates were evidenced in Spain (1.33 mm) and Poland (1.25 mm). The highest carbon sequence was recorded in Poland stands, probably due to the larger volume of recorded RPs. The stand volume has a positive effect on tree-stand biomass, which is related also with tree-stand age and height [103].

4.2. Stand Structure

The horizontal structure of the tree layer individuals was random in most RPs, aggregated in the case of three RPs, and regular only in the case of one plot PL_4. The authors of [27] confirm that in Scots pine stands with a limited regime of silvicultural interventions, an aggregated distribution of trees is visible, while in typical production forests the distribution of individuals is regular. The random horizontal structure of individuals in heterogeneous stands was also shown by [95], where younger trees formed in such stand aggregations, while older individuals were distributed regularly. Based on the spatiotemporal analysis, [104] observed in uneven-aged Scots pine-dominated forests a shift from a random to a clumped pattern of pine trees with forest ageing, while for oak trees, the spatial pattern developed toward uniform structures.

The vertical structure was relatively low in the case of Great Britain and high in the case of Spain, with values typical for selection forests. This is also the case for the diameter, height and crown differentiation. However, the structural differentiation of stands was generally low to medium for most RPs. Higher structural differentiation of Scots pine stands in Spain can be explained by the typical mountain environment, management history [59,60] and significant pine mortality due to climate change in the entire Valsaín region, including the studied site [61]. According to studies dealing with water stress [15,105], we can assume that the lack of moisture was the reason for significant changes in the structure of pine stands also in this case. The study in [106] mentions that diameter differentiation is significantly higher in heterogeneous stands, but based on [73], the diameter differentiation in RPs (index values 0.200–0.428) was low to medium. The same applies to the height differentiation (index values: 0.122–0.372). For example, the authors of [107] claim that height differentiation in heterogeneous stands with a limited economic regime tends to be significantly greater. However, in their conclusions based on comparable conditions, [106] mentions a similar range of height differentiation in Scots pine stands as in our study. The crown differentiation index amounted to 1.101–2.642, indicating low to high differentiation [74]. These values are comparable to [27].

4.3. The Effect of Climate on the Radial Growth of Pine

We found a significant effect of climatic factors on radial growth, where temperature and precipitation affected pine growth significantly more in the second period (1986–2016) of ongoing climate change compared to the first one (1951–1985). Climate change is behind the widespread dieback of pine forests in almost all of Europe. The main abiotic factors causing pine dieback are the lack of precipitation and the increase in temperature [8–13,108–110]. Dry periods also greatly affect the radial growth of Scots pine. Low correlation coefficients (r = 0.3 to −0.3) were observed between monthly precipitation values and temperature and tree-ring growth. The lowest radial growth was observed in pine trees at sites in Great Britain. A minimal correlation between the increment and precipitation is reported, for example, by a study from Sweden; [111] claims that, on the contrary, it is the temperature that significantly affects the radial growth of pine. The results show the negative impact of rainfall on pine trees in Spain, where there is an uneven distribution of precipitation during the vegetation season. Their study also mentions the effect of temperature on the radial growth of pine. While warming has a noticeable negative impact on growth [110], statistically, the authors are not able to confirm this effect. The absence of correlations between precipitation and temperature and the increase of tree-ring width at sites in Great Britain can be partly explained by the presence of the Gulf Stream, which ensures a significant warming of the western shores of Europe, especially in winter, thus maintaining a mild climate [112] and reducing the frequency of extreme weather fluctuations [113]. However, we are aware that the possibility of influencing the growth of trees by the Gulf Stream can be called into question by the location of the research sites, i.e., inland with an altitude of 250–280 m a.s.l.

Overall, concerning all the investigated sites, monthly precipitation showed less significant correlation with increment than monthly temperatures, except for the locations in Great Britain, where more significant correlations with precipitation were found. This finding is surprising given the claims of other authors [114], who found in the climatic conditions of Great Britain that temperature has a greater influence on the increment than the total precipitation. Similarly, [114] and [115] report that the lack of precipitation affects the diameter increment of pine trees. The results of our study confirm that temperature is the main factor determining the radial growth of pine, which is shown by the higher correlations of monthly temperatures to radial growth. However, it is also necessary to add that the growth of Scots pine, as well as other trees, could also be affected by air pollution in the last century [116–118].

4.4. Cyclic Tree-Ring Growth of Pine Trees

Spectral analyses showed a difference between Period 1 and Period 2. A substantial decrease in fluctuations in the tree-ring index and loss in the growth cyclicity of pine was observed in the second period, likely affected by ongoing climate change. The explanation for this phenomenon may be a smaller effect of winter temperatures on pine, which was described in Estonia [119]. Moreover, the effect of winter temperatures is positively correlated with pine RWI at three research sites, with the exception of the UK research plot.

The high-frequency oscillations in 2 to 7 years on Scots pine might be associated with the frequent changing in the temperature and precipitation [120,121]. However, these high-frequency signals in RWI are lesser compared to the lower oscillations (larger RWI cycles). Moreover, it was shown that in six out of eight cases, in the spectral analyses for the research plots, there was a repetition of a 9- to 11-year period. This cycle can be linked with the influence of the solar cycle that has been described for precipitation and temperature across Europe [122,123] and can be observed in the tree-ring series of many tree species. The 11-year growth cycle has been recorded on forest tree rings throughout Europe, on European beech, for example, in the Czech Republic, Italy [124–126], and Bulgaria [127]. Scots pine forests also reflected solar cycles, for example, in western Russia [87,88,120]. The solar cycle is involved in weather that is either stale or changeable [122,128]. Overall, the cyclical processes of radial growth of pine may vary, but across the results, it is the aforementioned 11-year cycle that can be found as a common factor in our results.

5. Conclusions

Scots pine forests representing a close-to-nature management approach (Czech Republic, Poland and Spain) and semi-natural forests in Great Britain showed high diversity and vertical structure. These forest stands also reached high potential in terms of carbon sequestration and biomass productivity. In all study sites, close-to-nature management and natural development have led to high variability of stand structures, which is desirable for increasing the resilience of forest stands. Tree-ring analyses from all four countries showed a difference in the fluidity of radial increment curves in Period 1 (1951–1985) and Period 2 (1986–2016). Data reveal the presence of 11-year growth cycles in Period 1, while Period 2 was characterized by the prevailing loss of these cycles. On the contrary, the effect of climate factors and stress was significantly higher in Period 2 compared to Period 1. The results also partially confirm that temperature is the main factor influencing the radial growth of pine, rather than precipitation totals. Locations in Great Britain are an exception, where a mild relationship between precipitation and temperature and tree growth was recorded. Scots pine thrives in sites with balanced precipitation and moderate temperatures, characteristic of an oceanic climate. The highest average annual increment of dominant and codominant trees in Great Britain also demonstrated this. Scots pine's reaction to climatic variables was more sensitive in Mediterranean and continental climate conditions. Forest management affects the structural and production characteristics of pine stands, and the growth of pine itself changes as a result of climate change, including climate resistance and cyclicity dynamics.

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