

Research Article

Vulnerability of Trees to Climate Events in Temperate Forests of West Germany

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An improved understanding of the spatiotemporal climate/growth relationship of our forests is of particular importance for assessing the consequences of climate warming. A total of 67 stands of beech (*Fagus sylvatica* L.), pedunculate oak (*Quercus robur* L.), sessile oak (*Quercus petraea* (Matt.) Liebl.), Scots pine (*Pinus sylvestris* L.), and spruce (*Picea abies* Karst.) from sites located in the transition zone from the lowlands to the low mountain ranges of West Germany have been analysed. A combination of pointer year and cluster analysis was used to find groups with similar growth anomaly patterns over the 1941–2000 period. Shifted reaction patterns especially characterise differences in the growth behaviour of the clusters. These are controlled by different reactions to the climate conditions in winter and spring and are determined by a complex system of forcing factors. Results of this study reflect the enormous importance of the length of the growing season. Increasing the duration of the vegetation period climate warming can change the climate/growth relationship of trees, thereby confounding climate reconstructions which use tree rings. Since forcing factors have been detected that are more important than the tree species, we recommend the application of growth-specific approaches for the analysis of tree species' vulnerability to climate.

1. Introduction

Whereas tree growth at the timberline is mostly limited by only one specific dominant factor [1], growth of temperate forest regions is influenced by a multitude of biotic and abiotic factors [2–4]. This is caused by predominant temperate climate conditions and the fact that mostly native tree species are growing in the range of their natural distribution areas [5]. Nevertheless, climate control is still a crucial forcing factor for annual tree-ring growth in lower altitudes [3]. The 20th century warming trends are extraordinary [6] and steady since the late 1970s [7] and have lengthened the duration of the growing season [8]. An increase of severe climate extremes such as heat waves is inherent with these [9], whereas changes in precipitation and dryness extremes are less clearly linked [10]. However, a better understanding of the spatiotemporal climate/growth relationships, including the identification of the environmental drivers, is of particular importance [11–13] to understand climate-induced changes in forest

productivity with regard to different tree species and site characteristics. Previous studies have shown that analyses of tree-ring width at lower elevation sites are suitable for climatological interpretations [4, 12, 14–17]. Comprehensive network analyses have been made by Neuwirth et al. [12] investigating the interannual climate/growth relationship of temperate and humid forest stands within a wide region of mid-latitude Europe. Covering an altitudinal range of 10–2300 m a.s.l., the investigation area is affected by strong environmental gradients, leading to a comparison of temperate with limiting conditions [12]. To further enhance comprehension of the complex climate/growth relationship in temperate forests, Schweingruber and Nogler [18] recommended the analysis of tree growth at a more regional scale. Friedrichs et al. [4] investigated slight variations in oak growth within relatively homogeneous growth patterns on a regional scale. Homogeneous subsets caused by smaller environmental gradients could be identified by grouping splined tree-ring series. Babst et al. [19] detected 15 groups with

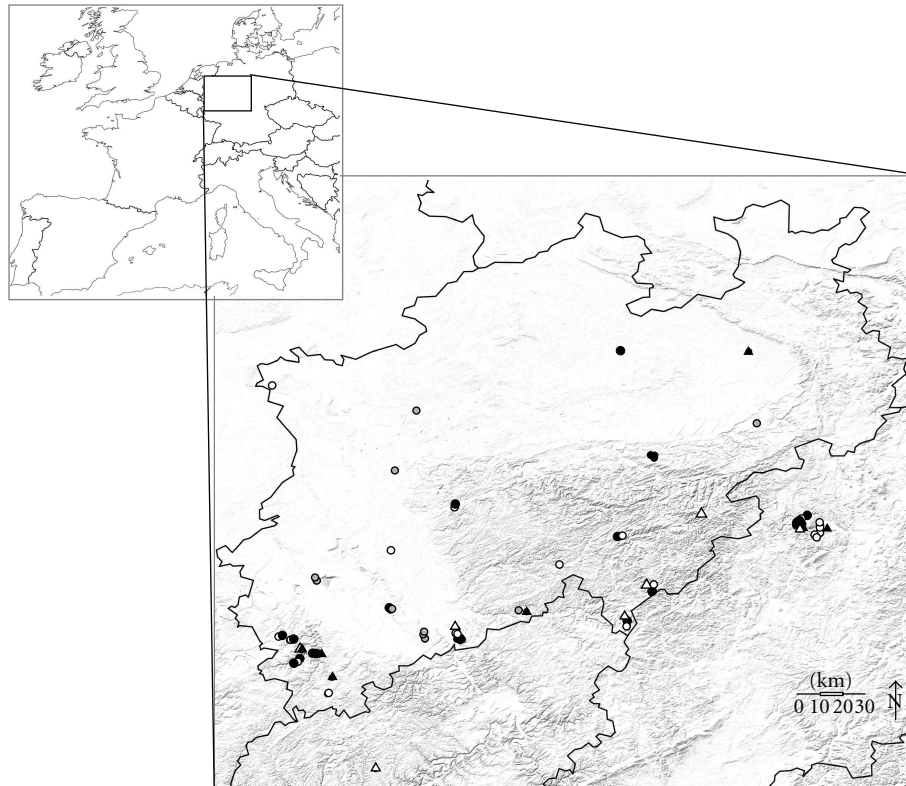


FIGURE 1: Topographical situation of the research area and location of the investigated sites. Black circles denote beech stands, grey circles pedunculate oak stands, white circles sessile oak stands, black triangles Scots pine stands, and white triangles spruce stands.

similar high-frequency growth variability due to temperature and precipitation anomalies for a supraregional network covering the European continent. Lacking from previous studies is an analysis of multispecies growth anomalies within single years as a response to abrupt changes in climatic conditions on a regional scale.

Pointer years are an accepted tool to analyse high-frequency changes in radial tree growth, which are primarily climatologically induced. They can be interpreted as expressions of rapid environmental changes [20]. Since trees are optimally adapted to their site-specific environmental conditions [5, 18], positive pointer years reflect optimal growth conditions [12], with almost all growth factors close to optimum [21]. Extreme environmental conditions lead to reductions of tree-growth [20]. Negative pointer years are a suitable method to detect single environmental factors, which deviate strongly from optimal conditions [21]. As such, our analyses are focused on evaluating negative pointer years, which can be seen as reactions to external disturbances. The pointer year analysis was conducted on the basis of measured tree-ring width values, in contrast to visual approaches described by Kaennel and Schweingruber [22].

The aim of this study is to detect forcing factors for the climate/growth relationships of different tree species in temperate forests. The analysis is based on a multispecies tree ring network of beech (*Fagus sylvatica* L.; FASY), pedunculate oak (*Quercus robur* L.; QURO), sessile oak (*Quercus petraea* Matt Liebl.; QUPE), Scots pine (*Pinus sylvestris* L.; PISY), and

spruce (*Picea abies* Karst.; PCAB), covering the transition of the lowlands to the low mountain ranges of West Germany. In line with this investigation, a particular approach was applied, combining pointer year analysis with cluster analysis.

2. Material and Methods

2.1. Research Area and Tree-Ring Data. The research area is situated 6.2–9.1°E and 50.1–51.9°N and covers the transition from the lowlands to the low mountain ranges of West Germany (Figure 1). Climatic conditions of the region are characterised by northwesterly atmospheric flows [23]. They are predominantly homogeneous with some local differentiations, such as a tendency to more oceanic conditions in the western area and more continental conditions in the eastern parts of the research area. The mean annual temperature over the 1961–1990 period was 9.0°C with a minimum of 0.83°C in January and a maximum of 17.1°C in July. The average annual precipitation was 816 mm, ranging from 53 mm in February to 79 mm in July. The length of the growing season was shortened with increasing altitude and latitude [8, 24].

The dataset contains 67 sites of a continuously extended dendroecological network [4, 16, 17, 25–27] including stands of beech, pedunculate oak, sessile oak, Scots pine, and spruce. Sites range in altitude from 40 to 710 m a.s.l. and represent a variety of gradients (0–45°) and aspects. Soil analyses detect cambisols and luvisols as predominant soil types which are also typical for temperate forest regions in West

Germany [28]. The available water capacity ranges from low (60–110 mm) to very high (>240 mm) (Table 1).

Tree-ring series were prepared using standard procedures [29, 30]. Tree-ring widths were measured with a programme for tree-ring analyses (Time Series Analysis and Presentation; TSAP) in a resolution of 1/100 mm followed by synchronising the series carried out with TSAP [31] and a programme which is used to control the quality of the cross-dating and the tree-ring chronologies (COFECHA) [32]. Tree-ring series were averaged to site chronologies and afterwards to tree-species as well as cluster chronologies. The chronology of all sites including cluster 1 corresponds to the master chronology across all sites.

The four parameters Gleichläufigkeit, NET, Rbar, and EPS were calculated on the basis of the undetrended chronologies as measures of homogeneity for each site, tree-species and cluster chronology. The Gleichläufigkeit is a sign test of the synchronous year-to-year changes of a single series [3] whereas NET is a combination of the Gleichläufigkeit and the coefficient of variation and additionally supplies information about the growth level of the series. Small NET values indicate high signal strength of the mean tree-ring chronology with a maximum of 0 [33]. A threshold of 0.7 was defined for Gleichläufigkeit and a threshold of 0.8 was used for NET [33]. The interseries correlation Rbar and the expressed population signal (EPS) are based on the correlation coefficient between the single series and were calculated over 30 years, lagged by 15 years. EPS is a function of Rbar and the series replication. EPS values increase with sample size and interseries correlation [34] and should remain above the commonly applied threshold of 0.85 [35]. Site chronologies were considered to be homogeneous when at least two parameter values satisfied the defined thresholds.

2.2. Climate Data. To investigate climate/growth relationship, gridded ($0.5^\circ \times 0.5^\circ$) datasets of monthly temperature and precipitation series [36] were used. The climate data from all grid points covering the research area were averaged and prepared as anomalies with respect to the 1961–1990 reference period. Climate data were classified using thresholds of $\pm 1z$, $\pm 1.5z$, and $\pm 2z$ to divide them into “hot,” “very hot,” and “extremely hot” as well as “cold,” “very cold,” and “extreme cold,” respectively.

2.3. Methods. The detection of stands with similar growth behaviour in single years within the multi-tree-species network was carried out over the 1941–2000 period and combined two different techniques, a pointer year and a cluster analysis.

To emphasize annual growth reactions in answer to extreme environmental conditions, comparable values for extreme growth years were calculated after Cropper [37]. Raw tree-ring series were standardized by using a 13-year moving average and calculating ratios. Afterwards a z -transformation was applied to normalise these values resulting in the Cropper series with a mean of 0 (μ) and a standard deviation of 1 (σ).

Cluster analysis was performed to detect sites showing similar increment patterns due to climatic influences,

modified by the site's ecologic conditions [4, 17, 38, 39]. Site-specific Cropper series were grouped, stepwise, using hierarchical cluster analysis. To induce a clear separation of the resulting clusters, Ward's method was applied, using the squared Euclidian distance as a measure of similarity [17, 40]. The intergroup variance was then maximised while the intragroup variance was minimised [39]. An indicator for determining the number of clusters was a jump in the squared Euclidian distance between two steps of the cluster analysis, bigger than all those preceding [41].

For each cluster, the so-called cluster plots were calculated by averaging all corresponding site-specific Cropper series. Years with values above $+1\sigma$ and below -1σ were defined as pointer years of which these years, reflected by at least 80% of the sites of a cluster, were defined as “characteristic” for the cluster. Characteristic pointer years were classified with respect to standard deviation (σ) units. Anomalies larger than $\pm 1\sigma$ were defined as “weak,” $\pm 1.28\sigma$ as “strong,” and $\pm 1.645\sigma$ as “extreme” pointer values. Attributes such as tree species or site ecological aspects appearing only by one of the clusters which were combined in the following grouping step were defined as differentiating criteria. For each grouping step, characteristic pointer years for corresponding clusters as well as differentiating criteria have been detected. For each cluster and for each tree species, a specific variance value of growth anomalies was calculated, by averaging the Cropper value variances per year over the 1941–2000 period (VaC).

Analysis of the climate/growth relationship of each group was carried out by interpreting cluster-characteristic growth anomalies with the corresponding climatic conditions. To maximise the quality of the interpretation of the cluster-specific climate/growth relationship, only these climatic influences could be used with high probability, which could be detected in several cluster-specific pointer years [21]. Growth reactions due to the same climatic impact occurring in one cluster in the same year as the climatic event and in another cluster one year later were defined as shifted reactions.

3. Results

3.1. Homogeneity. The parameters Gleichläufigkeit, NET, Rbar, and EPS confirm the homogeneity of all analysed site chronologies (Table 1). Chronology statistics for cluster 1 refer to the overall homogeneous growth behaviour within the research area, reflected by values of NET, Gleichläufigkeit, Rbar, and EPS, which suffice the recommended thresholds (Table 2; for detailed information about the clusters, see Figure 2 and subsection Structure of the clusters). Mean parameter values for the cluster-specific chronologies are superior to these for the species-specific chronologies throughout. Only the mean EPS value is slightly lower for the cluster-specific chronologies, since EPS values are calculated including series replication. Regarding the chronology parameters as well as the VaC values for a single tree species and clusters, a better differentiation is effected at the cluster level.

Whereas coniferous trees show the highest NET and nearly the highest VaC values, the eastern coniferous cluster

TABLE 1: Geographical position and attributes of the investigated stands.

Site	Longitude	Latitude	Species	Elev.	Asp.	Grad.	AWC	<i>n</i>	AGR	<i>s</i>	GLK	NET	Rbar	EPS	Clu
1	7.0472	50.6706	QURO	185	15	2	4	12	181	70	0.78	0.62	0.53	0.92	8
2	7.0472	50.6700	QURO	185	15	2	4	12	198	60	0.79	0.51	0.52	0.92	8
3	7.0372	50.6836	QURO	165	20	2	4	14	190	63	0.78	0.55	0.57	0.95	8
4	6.4194	50.9272	QURO	105	0	0	4	16	222	73	0.77	0.58	0.50	0.91	8
5	6.4239	50.9169	QURO	103	0	0	3	16	171	61	0.79	0.58	0.57	0.95	8
6	6.8031	51.0447	QUPE	45	180	2	3	14	235	97	0.77	0.66	0.44	0.91	8
7	6.7975	51.3147	QURO	40	0	0	3	15	236	83	0.78	0.59	0.26	0.84	8
8	7.8864	51.9069	QURO	60	0	0	4	17	162	55	0.78	0.57	0.57	0.96	8
9	8.9681	51.1708	QUPE	290	135	30	1	16	149	50	0.79	0.55	0.45	0.93	9
10	7.2492	50.6694	QUPE	370	320	40	2	18	147	69	0.73	0.74	0.36	0.91	9
11	7.2475	50.6703	QUPE	375	180	45	n/a	16	152	59	0.74	0.64	0.47	0.93	9
12	7.2217	50.6836	QUPE	280	150	20	n/a	7	178	77	0.81	0.59	0.47	0.81	9
13	6.3250	50.6653	QUPE	320	340	15	3	10	143	47	0.70	0.63	0.44	0.87	9
14	6.5656	50.4400	QUPE	560	90	5	3	13	149	55	0.75	0.63	0.31	0.84	9
15	6.2794	50.6806	QUPE	460	0	0	1	13	149	59	0.76	0.65	0.54	0.93	9
16	6.3992	50.6244	QUPE	400	300	40	3	14	151	45	0.81	0.48	0.50	0.93	9
17	6.3603	50.5708	QUPE	500	150	15	2	13	128	36	0.78	0.49	0.49	0.92	9
18	8.1175	50.7272	QUPE	450	19	40	2	16	116	49	0.78	0.65	0.50	0.90	9
19	8.2269	50.8661	QUPE	440	180	25	1	14	118	39	0.81	0.53	0.65	0.96	9
20	6.8439	50.7917	QURO	155	240	5	2	12	300	95	0.80	0.52	0.61	0.95	9
21	7.7169	50.9825	QUPE	385	270	15	3	12	190	76	0.78	0.63	0.48	0.92	9
22	7.1111	51.2297	QUPE	260	230	30	1	14	167	73	0.80	0.66	0.61	0.94	9
23	6.0631	51.7503	QUPE	50	180	3	3	11	108	31	0.78	0.50	0.51	0.93	9
24	8.0228	51.1028	QUPE	470	130	35	1	16	133	49	0.79	0.58	0.56	0.93	9
25	8.6736	51.5831	QURO	295	350	2	3	11	188	67	0.76	0.61	0.21	0.67	9
26	7.5303	50.7933	QURO	175	290	15	n/a	8	207	66	0.75	0.58	0.57	0.90	9
27	8.9619	51.1694	FASY	340	360	45	n/a	13	173	92	0.80	0.75	0.55	0.90	10
28	8.9669	51.1703	FASY	310	150	30	n/a	15	178	70	0.78	0.64	0.51	0.94	10
29	9.0117	51.1936	FASY	280	180	35	n/a	13	140	68	0.80	0.70	0.58	0.92	10
30	8.9583	51.1672	FASY	420	345	3	n/a	16	152	47	0.84	0.48	0.66	0.97	10
31	7.2361	50.6628	FASY	230	270	10	n/a	16	297	120	0.73	0.69	0.47	0.91	11
32	7.2489	50.6689	FASY	360	320	40	n/a	14	232	82	0.75	0.63	0.51	0.92	11
33	7.2469	50.6700	FASY	340	160	45	n/a	17	160	65	0.80	0.63	0.55	0.94	11
34	6.3250	50.6653	FASY	320	340	15	3	16	207	85	0.76	0.66	0.44	0.90	11
35	6.4569	50.6086	FASY	530	315	15	1	16	99	34	0.77	0.58	0.50	0.94	11
36	6.4900	50.6061	FASY	470	60	10	1	15	209	60	0.83	0.47	0.63	0.96	11
37	6.2794	50.6806	FASY	440	45	1	1	13	230	84	0.78	0.60	0.49	0.91	11
38	6.3597	50.5711	FASY	490	150	15	2	14	149	47	0.82	0.51	0.57	0.94	11
39	6.3611	50.5717	FASY	480	150	10	2	15	149	51	0.79	0.56	0.57	0.95	11
40	8.1186	50.7289	FASY	500	140	30	n/a	16	182	58	0.80	0.54	0.55	0.95	11
41	8.2253	50.8656	FASY	440	180	25	1	18	188	61	0.79	0.56	0.53	0.94	11
42	6.8439	50.7917	FASY	155	240	5	2	10	420	141	0.82	0.54	0.52	0.91	11
43	7.1111	51.2300	FASY	260	330	30	1	12	195	65	0.79	0.56	0.48	0.90	11
44	8.0222	51.1022	FASY	455	130	40	1	15	185	61	0.77	0.58	0.54	0.94	11
45	8.1422	51.4425	FASY	350	310	8	2	19	157	56	0.77	0.59	0.49	0.94	11
46	8.1297	51.4469	FASY	360	280	3	2	19	156	56	0.74	0.63	0.42	0.92	11
47	8.1297	51.4469	FASY	350	140	3	n/a	10	151	48	0.79	0.54	0.49	0.89	11
48	6.8489	51.5633	FASY	65	30	1	1	15	172	70	0.80	0.62	0.53	0.94	11
49	9.0842	51.1564	QUPE	350	180	30	1	13	138	45	0.82	0.50	0.57	0.93	12
50	9.0842	51.1572	QUPE	365	180	20	1	6	88	40	0.81	0.63	0.60	0.90	12
51	9.0842	51.1581	QUPE	380	180	25	1	7	139	38	0.82	0.43	0.58	0.90	12

TABLE 1: Continued.

Site	Longitude	Latitude	Species	Elev.	Asp.	Grad.	AWC	<i>n</i>	AGR	<i>s</i>	GLK	NET	Rbar	EPS	Clu
52	9.0761	51.1561	QUPE	400	215	10	n/a	13	140	40	0.84	0.43	0.58	0.92	12
53	9.0769	51.1556	QUPE	390	150	20	n/a	10	165	46	0.81	0.46	0.59	0.93	12
54	6.8731	50.1236	PCAB	470	255	8	n/a	22	492	19	0.74	0.70	0.58	0.96	13
55	7.2128	50.7122	PCAB	170	70	5	n/a	17	251	104	0.74	0.71	0.41	0.91	13
56	6.4917	50.6056	PCAB	470	60	25	n/a	15	144	79	0.75	0.81	0.43	0.91	13
57	8.1133	50.7311	PCAB	520	45	5	n/a	16	210	71	0.79	0.57	0.45	0.92	13
58	8.2261	50.8661	PCAB	440	180	25	1	7	205	84	0.79	0.63	0.49	0.86	13
59	8.4408	51.1997	PCAB	710	340	10	n/a	14	242	109	0.76	0.71	0.42	0.88	13
60	9.0844	51.1569	PISY	360	180	20	n/a	13	113	41	0.80	0.56	0.50	0.92	14
61	8.9872	51.1553	PCAB	340	315	30	n/a	12	168	63	0.80	0.59	0.46	0.90	14
62	8.9897	51.1572	PISY	350	270	40	n/a	12	104	34	0.84	0.50	0.58	0.94	14
63	6.4919	50.6058	PISY	490	210	20	n/a	15	164	70	0.74	0.73	0.30	0.85	15
64	6.5783	50.5083	PISY	490	270	35	n/a	11	107	40	0.73	0.69	0.45	0.90	15
65	6.4769	50.6067	PISY	415	280	30	n/a	13	126	45	0.77	0.60	0.43	0.90	15
66	7.5697	50.7867	PISY	275	260	30	n/a	14	195	106	0.71	0.91	0.45	0.91	15
67	8.5839	51.8875	PISY	110	330	0–5	n/a	9	136	49	0.73	0.67	0.40	0.84	15

Elev.: elevation, Asp.: aspect [°], Grad.: gradient [°], AWC: available water capacity: 1 = low (60–110 mm); 2 = mean (110–170 mm); 3 = high (170–240 mm); 4 = very high (>240 mm); n/a: not applicable, *n*: number of trees per site, AGR: average growth rate, *s*: standard deviation, GLK: Gleichläufigkeit, NET: parameter of signal strength, Rbar: interseries correlation (calculated over 30 years lagged by 15 years), EPS: expressed population signal (calculated over 30 years lagged by 15 years), Clu: cluster.

TABLE 2: Chronology and Cropper's series statistics of cluster 1 (master chronology; including all sites), species-specific and cluster-specific chronologies.

	<i>n</i>	AGR	<i>s</i>	<i>v</i>	GLK	NET	Rbar	EPS	VaC
Cluster 1	63	1.70	0.80	0.47	0.73	0.74	0.38	0.97	0.57
QURO	10	1.71	0.44	0.25	0.84	0.41	0.55	0.90	0.40
QUPE	20	1.38	0.36	0.27	0.76	0.51	0.47	0.95	0.46
FASY	22	2.05	0.74	0.37	0.81	0.55	0.61	0.97	0.31
PCAB	7	2.19	1.29	0.57	0.81	0.76	0.55	0.90	0.49
PISY	7	0.93	0.35	0.37	0.81	0.57	0.36	0.79	0.46
Clu 8	8	1.71	0.33	0.19	0.86	0.34	0.70	0.93	0.35
Clu 9	18	1.45	0.42	0.29	0.77	0.53	0.51	0.94	0.45
Clu 10	4	2.02	0.45	0.22	0.89	0.33	0.64	0.87	0.15
Clu 11	18	2.05	0.78	0.38	0.82	0.57	0.65	0.97	0.28
Clu 12	5	1.27	0.27	0.21	0.94	0.28	0.85	0.97	0.10
Clu 13	6	2.29	1.37	0.58	0.81	0.77	0.56	0.87	0.46
Clu 14	3	1.14	0.40	0.35	0.89	0.46	0.64	0.84	0.28
Clu 15	5	0.93	0.41	0.43	0.82	0.61	0.38	0.75	0.42
x_Species	13	1.65	0.64	0.36	0.81	0.56	0.51	0.90	0.42
x_Clu	8	1.61	0.55	0.33	0.85	0.49	0.62	0.89	0.31

X_Species and x_Clu represent mean values for species-specific and cluster-specific chronologies. Values of *n*, AGR, *s*, *v*, GLK, NET, Rbar, and EPS are calculated on the basis of the undetrended chronologies. *n*: number of trees per site, AGR: average growth rate, *s*: standard deviation, *v*: coefficient of variation, GLK: Gleichläufigkeit, NET: parameter of signal strength, Rbar: inter-series correlation (calculated over 30 years lagged by 15 years), EPS: expressed population signal (calculated over 30 years lagged by 15 years). VaC: mean of the annual variance of the Cropper values per year over the 1941–2000 period calculated for the Cropper series.

14 shows much better values compared to spruce cluster 13 and Scots pine cluster 15. VaC is especially low for pedunculate oak and beech and the highest for spruce. At the cluster level, eastern oak cluster 12 shows the lowest VaC

value, followed by eastern beech cluster 10, low mountain range beech cluster 11, and lowland oak cluster 8. All evaluated parameters are most favourable for cluster 12, thereby revealing its comparatively high homogeneity. However, low

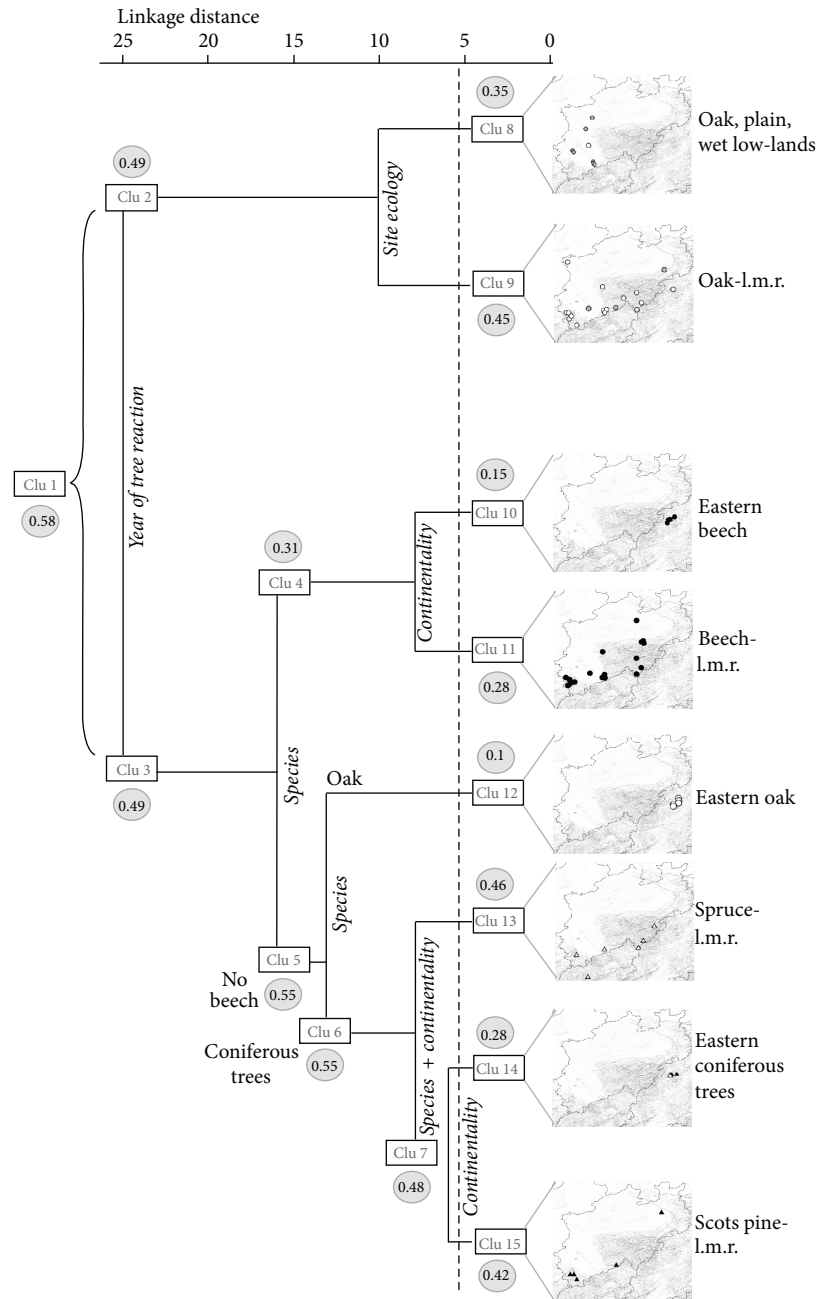


FIGURE 2: Dendrogram of the cluster analysis showing the relationship between the different clusters (Clu 1–15), ecological attributes, like tree species or topographical position, as well as differentiating criteria between the clusters (in italics); l.m.r.: low mountain ranges. Numbers in circles denote the cluster-specific mean variance over the annual variances of the Cropper values (VaC). Dashed line marks the linkage distance of five which was chosen for the selection of the final clusters (Clu 8–15). Maps show the topographical positions of the corresponding sites for each final cluster.

mountain range oak cluster 9 together with spruce cluster 13 shows the highest VaC values, Scots pine cluster 15 the lowest Rbar and EPS values.

3.2. Structure of the Clusters. Each step of the cluster analysis results in the formation of clusters, combining sites with similar pointer year patterns. In general, VaC increases inversely with the number of clusters. In the following, 15

clusters will be described and interpreted. While the bigger clusters 1–7 are defined as succeeding clusters, cluster 8–15 are selected as final clusters. At a linkage distance of five, eight final clusters are differentiated, namely, three oak clusters (8, 9, 12), two beech clusters (10, 11), one spruce (13), one Scots pine (15), and one coniferous tree (14) cluster (Figure 2). Cluster 10, 12, and 14 are situated in the eastern part of the research area. Cluster 1 includes all investigated sites and

VaC is comparably high (0.58). One grouping step before, cluster 2 and 3 can be differentiated by their reaction pattern concerning the year of tree reaction. Both of them have a VaC value of 0.49. As parts of cluster 2, oak clusters 8 and 9 distinguish themselves by site ecological aspects. The oaks from plain wet lowlands (cluster 8) have a lower VaC value than those from low mountain range regions (cluster 9). One plain wet lowland site (site 23, Table 1) is classified into cluster 9. As parts of cluster 3, clusters 4 and 5 differ in tree species. Beech cluster 4 has a smaller VaC value than the mixed species cluster 5. As parts of cluster 4, eastern beech cluster 10 and low mountain range cluster 11 can be distinguished by continentality. As parts of cluster 5, clusters 12 and 6 are differentiated by tree species. Cluster 12 consists of eastern oaks and has the lowest VaC value of all groups (0.1). One eastern oak stand (site 9, Table 1) is classified into cluster 9. The variance value of coniferous tree cluster 6 is still high (0.55). One grouping step before, low mountain range spruce cluster 13 differs from cluster 7 in both tree species and continentality. Cluster 13 shows the highest VaC value of the final clusters. As parts of cluster 7, the eastern coniferous tree cluster 14 and the low mountain range Scots pine cluster 15 also distinguish themselves by tree species and continentality. Clusters 10, 12, and 14 are located east of 8°57'E, with VaC values comparably lower in relation to the more westerly-situated clusters.

3.3. Climatological Interpretation of the Characteristic Pointer Years. Characteristic pointer years are classified according to their main climatic conditions in six pointer year types (PYTs) characterised by (1) a hot previous year and a cold summer of the current year, (2) coldness + dryness, (3) coldness + wetness/lack of solar radiation, (4) a hot previous year and a hot and dry summer, (5) dryness in combination with drought in summer of the current year, and (6) dryness in spring, especially during a hot May. In addition to these typical attributes, further climatic criteria can be detected as having influenced the tree's reactions in these years (Figure 3).

Years of PYT 1 (previous year hot, summer of the current year cold) are 1947/1948, 1959/1960, 1984, 1996, and 2000. In 1947/1948, the whole previous year growing season is hot/extremely hot in combination with dryness during the previous summer. Winter 1947/1948 is extraordinarily warm and wet, with temperature anomalies exceeding values of +1z and precipitation anomalies of +2.09z (January). Current year's April is hot and below-average summer temperatures occur in June. The previous year growing season of 1959/1960 is dry/extremely dry, but temperature anomalies are clearly lower than those in 1947/1948. Winter temperatures are slightly above average. Summer coldness is detected in July, and August and October are extremely wet. 1984 is also characterised by very/extremely high precipitation values in previous year's May, both May and September in combination with coldness. Only previous year's June and August show extreme temperature values; summer coldness begins in May. Temperatures during winter months are slightly above average. Climate conditions in 1996 are also

dry/extremely dry from previous year's autumn until January, plus large parts of the growing season coupled with cold in winter, spring, May, and September. Previous year's temperature anomalies do not appear over the entire previous years' growing season. In 2000, the entire previous year's growing season is hot/extremely hot; below-average temperatures first occur in July.

1956, 1962/1963, 1973, and 1991 belong to PYT 2 (cold + dry).

1942, 1968, and 1981 are classified as PYT 3 (cold + wet/lack of solar radiation). Since high precipitation values were normally accompanied by lower temperatures and reduced solar radiation, positive precipitation anomalies in August 1941 and July 1942, August and September 1968, and June and July 1980, as well as in March, June, August, and October 1981, reflect a lack of solar radiation and lower temperatures in these months. In 1942, additional dryness in February and April is observed.

1976 and 1983 belong to PYT 4 (previous year hot + hot and dry summer). In 1976, the whole growing season is dry/very dry while drought is most pronounced in June (temperature: +2.38z; precipitation: -1.9z). In 1983, the entire previous year's growing season is hot/very hot in combination with a dry previous year's July; April and May are extremely wet.

1946/1947, 1958/1959, and 1963/1964 are defined as PYT 5 (dryness in combination with drought in summer of the current year). In 1947 and 1959, the whole growing season is hot and dry. All of these years are additionally characterised by dry/extremely dry, in 1946/1947 and 1963/1964 also extremely cold winters. However, a further differentiation of the years belonging to PYT 5 is possible. Whereas in 1963/1964 dryness is particularly pronounced already in December, it begins in 1947 in August and 1959 in February. While in 1946/1947 and 1958/1959 nearly the whole growing season is hot/extremely hot, in 1963/1964 only May and June show comparably lower temperature anomalies. October in 1964 is very cold.

1988, 1989, and 1990 belong to PYT 6 (dryness in a hot May). 1988 additionally shows an extremely wet March and a dry April and June, 1989 a dry January, and 1990 a very dry and hot previous year's May.

3.4. Ecological and Climatological Interpretation of the Clusters. Each of the clusters is determined by its characteristic pointer years as well as specific ecological criteria (Table 3). 1976 and 1996 are characteristic for each cluster, with the exception of 1976 in cluster 2 and cluster 9 and 1996 in cluster 10. Final clusters show a more homogeneous increment pattern than all sites including cluster 1, resulting in smaller VaC values and a predominantly higher number of characteristic pointer years, respectively (Figure 2, Table 3).

Several controlling factors for climate/growth relationships can be detected, most importantly shifted reactions of the clusters, followed by tree species and site ecological or topographical aspects. Stands located east of 8°57'E form individual groups showing in general stronger reactions in response to dryness than those of the western part of the

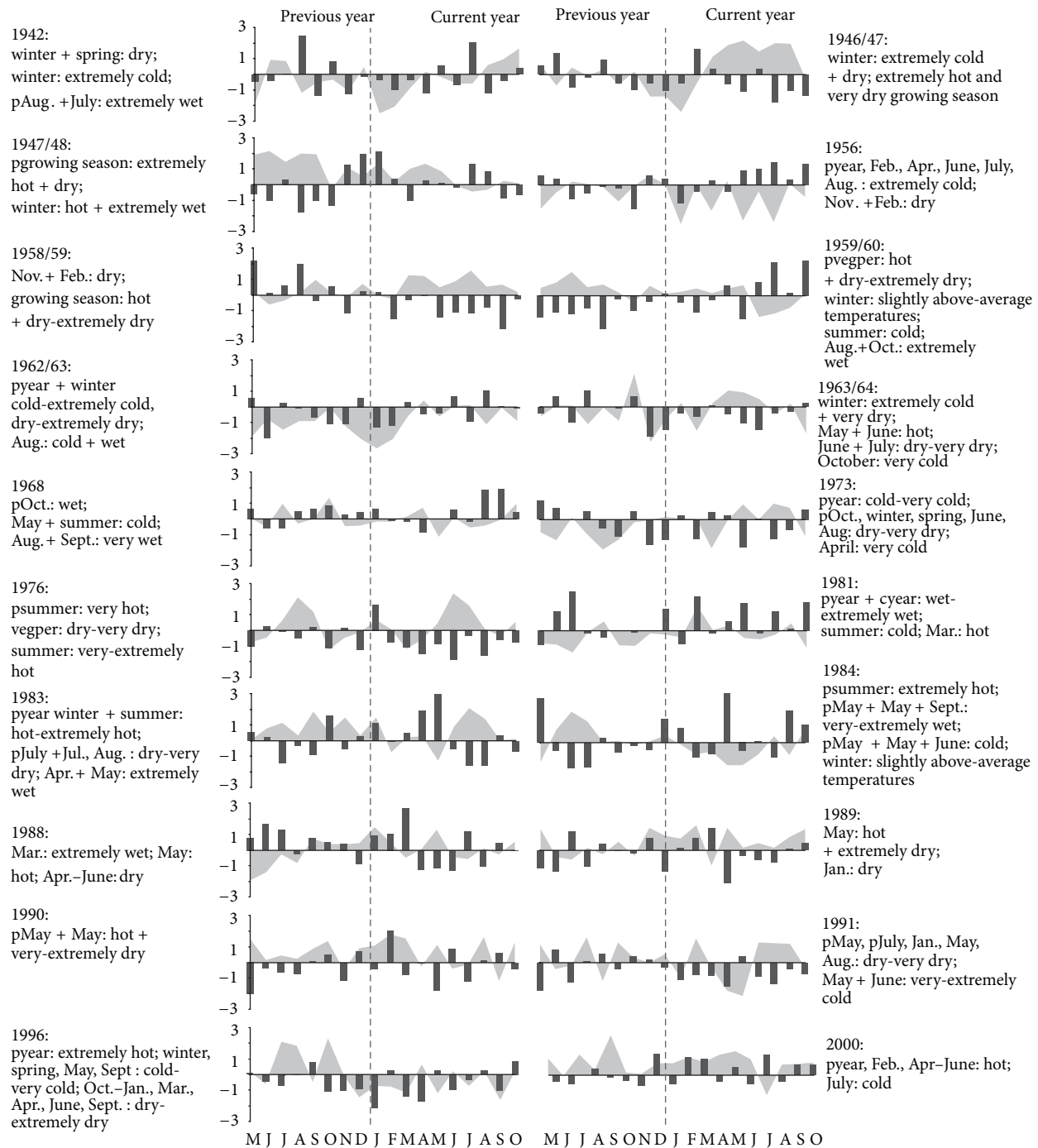


FIGURE 3: Climate anomalies of detected characteristic pointer years from previous year's May to October of the current year. Black bars mark precipitation, grey areas temperature values. Dashed lines denote the transition of previous year to the year of growth, p = previous year, c = current year.

research area. In the following, the interpretation of the clusters begins with the largest (cluster 1) and ends with the defined clusters. For cluster 1–7, a description of typical ecological attributes is not meaningful because of the high number of corresponding sites showing diverse topographical and ecological features (Table 3). Cluster 1 contains all investigated sites representing five tree species. There are only

two negative pointer years, 1976 and 1996, in which more than 80% of the sites show Cropper's values smaller than -1σ . Both of these are strong negative pointer years and appear in each cluster with a different intensity. In general, the investigated temperate forests show strong negative growth anomalies in response to the climatic conditions of PYT 1 (1996) and PYT 4 (1976).

TABLE 3: Cluster-specific attributes in terms of tree species, site ecological aspects, and pointer years.

Clu	Species	Site ecological description ¹	Char. pointer years
Clu 1	FASY, QUPE, QURO, PISY, PCAB		<i>1976, 1996</i>
Clu 2	QUPE, QURO		<i>1942, 1959, 1996</i> <i>1947, 1981</i>
Clu 3	FASY, QUPE, QURO, PISY, PCAB		1976 <i>1948, 1996</i> <i>1960</i>
Clu 4	FASY		1948, 2000 <i>1976, 1996</i>
Clu 5	QUPE, QURO, PISY, PCAB		1976 <i>1996</i>
Clu 6	PISY, PCAB		1976 <i>1996</i>
Clu 7	PISY, PCAB		1996 <i>1976</i> <i>1973</i>
Clu 8	QUPE, QURO	Plain lowlands, wet	1947 <i>1959, 1963, 1968,</i> <i>1976, 1981,</i> <i>1996</i>
Clu 9	QUPE, QURO	Low mountain ranges, 155–560 m a.s.l., 2 lowland sites with bigger gradient, 1 plain wet lowland site	1996 <i>1942</i>
Clu 10	FASY	East of 8°57', 280–420 m a.s.l., dry	1948, 1983 <i>1964, 1976, 2000</i>
Clu 11	FASY	Low mountain ranges, 155–530 m a.s.l.	1948, 2000 <i>1960, 1976, 1990,</i> <i>1996</i>
Clu 12	QUPE	East of 8°57', slope sites	1976 <i>1948, 1960, 1973,</i> <i>1996</i> <i>1964, 1988</i>
Clu 13	PCAB	Low mountain ranges, 170–710 m a.s.l.	1976 <i>1948, 1984, 1996</i>
Clu 14	PISY, PCAB	Coniferous trees, east of 8°57', 340–360 m a.s.l., slope sites	1964, 1976 <i>1989, 1996</i> <i>1973</i>
Clu 15	PISY	Low mountain ranges, 110–490 m a.s.l., western expositions	1996 <i>1956, 1976, 1991</i> <i>1960, 1973</i>

¹ Descriptions of the characteristic site ecological aspects are only reasonable for final clusters. Extreme pointer years are designated by bold font, strong pointer years by italic font, and weak pointer years by regular font numbers.

The differentiation of clusters 2 and 3, the parts of cluster 1, can only be explained by their shifted reactions concerning 1947/1948 and 1959/1960, neither by tree species, nor by site ecological or topographical aspects. Beside 1996 in cluster 2

and 3 and 1976 in cluster 3, there are no negative pointer years that appear in more than 80% of sites.

Because of obvious differences in interannual increment pattern in terms of shifted growth reactions, further pointer

years are interpreted as characteristic. Cluster 2 consists of 26 oak stands from the lowlands and the low mountain ranges and one oak site from the eastern part of the research area. There are sessile oak as well as pedunculate oak sites. Five years are classified as characteristic for this cluster: 1942 (70% of the sites react), 1947 (65% of the sites react), 1959 (78% of the sites react), 1981 (65% of the sites react), and 1996. Negative growth reactions occur in cluster 2 when climate conditions in the winter are extremely cold and dry followed by a dry spring, such as that in 1942 and 1996. Lower temperatures and high precipitation values, along with a lack of solar radiation, in August 1941, July 1942, July 1980, and June and October 1981 also reduce the tree growth. Extremely cold and very dry winter months provoke immediate growth reductions in response to a hot/extremely hot and dry/extremely dry growing season (PYT 5; 1947, 1959).

As well as five sessile oak sites, cluster 3 contains all the investigated stands of beech, Scots pine, and spruce. This group is characterised by 1948 (78% of the sites react), 1960 (68% of the sites react), 1976, and 1996. Compared to cluster 2 there is a shifted reaction in 1948 and 1960 to the hot and dry summer/growing season in 1947 and 1959. Thus, climatic conditions of PYT 1 (1947/1948, 1959/1960, 1996) and PYT 4 (1976) are growth reducing.

Whereas cluster 2 is affected by cold and dryness during the winter months followed by a hot and dry summer, as well as lower temperatures and a lack of solar radiation in previous year autumn and current year summer, growth of cluster 3 is less influenced by the climate conditions in winter. However, it is more susceptible to summer heat and dryness in the year prior to ring formation.

The mixed oak clusters 8 and 9, parts of cluster 2, are differentiated by site ecological and topographical aspects. Cluster 8 contains plain oak stands in the lowlands characterised by soil wetness. Cluster 9 includes oak stands of the low mountain ranges as well as two pedunculate oak stands from the lowlands on more inclined sites, one plain wet lowland oak stand (site 23), and one eastern oak stand (site 9). 1996 is characteristic for both of the clusters but for cluster 9 more important (extreme negative pointer year). Cluster 9 is characterised only by two negative pointer years, 1942 and 1996, along with a comparatively high VaC value (cluster 9: 0.45; cluster 8: 0.35). This comparably lower homogeneity reflects the varied ecological spectrum of lowland and low mountain range sites belonging to cluster 9. Beside winter dryness and cold during 1996 and 1942, lower temperatures and high precipitation values, along with a lack of solar radiation, in August 1941 and July 1942, as well as the dry April are crucial for cluster 9.

For cluster 8 seven pointer years are classified as characteristic (Table 3). Climatic conditions of PYT 1 (1996), PYT 4 (1976), and PYT 5 (1947, 1959) lead to strong, even extreme (1947) growth reductions. While cold, particularly in the previous year (1963, 1981) and during winter (1963), that influences tree growth in a negative manner, high precipitation values, along with a lack of solar radiation, in previous year's summer and March (1981), and summer and autumn months (1968, 1981) cause stress.

Both of the groups are strongly negatively influenced by coldness as well as by a lack of solar radiation in previous and current year's summer. Whereas climatic conditions in March are important for cluster 8, April moisture controls the growth of cluster 9. Hot and dry conditions during the growing season after a hot previous year's summer restrict the growth of cluster 9 less.

The differentiation of clusters 4 and 5, as parts of cluster 3, is apparently conditioned by tree species. While cluster 4 includes all beech sites, cluster 5 contains five sessile oak sites situated in the east of the research area as well as all conifer sites.

Cluster 4 and 5 are both characterised by 1976 and 1996; additionally, cluster 4 is extremely negatively affected by 1948 and 2000. More than 80% of the beech sites react with a negative growth anomaly smaller than -1σ when previous climate conditions correspond to PYT 1 (1947/1948, 1996, 2000) and 4 (1976). In 1960 only 76% of the beech sites react with a negative pointer year. While summer in 1960 is comparably cold, similar to 2000, the previous year's summer is less hot than those during the years 1947/1948, 1976, 1996, and 2000. Hence, the most important factor for growth reduction in beech is a hot previous year's summer. The influence of previous year's heat and dryness seems to be crucial for beech growth.

Cluster 5 clearly shows less homogenous growth behaviour than beech cluster 4, which is reflected by a comparatively high VaC value (0.55 versus 0.31 for cluster 4). Additionally, there are no further characteristic pointer years other than 1976 and 1996 that are characteristic for nearly all clusters.

Beech clusters 10 and 11, as parts of cluster 4, are differentiated by the degree of continentality. Cluster 10 contains all beech stands located east of $8^{\circ}57'E$. These beeches show growth reductions in years of PYT 4 (1976, 1983). In 1983, the entire previous year's growing season is hot/very hot in combination with a dry previous July followed by a hot/extremely hot and dry/very dry summer. In spite of high precipitation values in April and May, cluster 10 reacts with an extreme growth reduction (-1.66σ). Water supply at the beginning of the growing season is not high enough to compensate for the following summer dryness.

Furthermore, climatic conditions of PYT 1 (1947/1948, 2000) lead to growth reductions of cluster 10. In 1947/1948, the very dry previous year's summer strengthens growth reductions. No significant negative reactions can be detected in 1959/1960, 1984, and 1996 belonging also to PYT 1. Whereas in 1947/1948 and 2000 the entire previous year's growing season is hot/extremely hot, in 1984 and 1996 only single months are extremely hot. Furthermore, high precipitation values in the previous May and May 1984 appear to lessen the influence of dryness. In 1959/1960, temperature anomalies during the previous year's growing season are clearly of lower magnitude than those in 1947/1948. Additionally, high precipitation values in August and October may have positively influenced the growth of cluster 10, which is predominantly limited by dryness. Negative growth anomalies in 1963/1964 also reveal the sensitivity of cluster

10 to dryness. Additionally, the very cold October in 1964 could shorten the growing season. Cluster 11 contains all other beech stands. These respond strongly to PYT 4. High precipitation values in March and April 1983 lead to the absence of negative growth reactions of cluster 11, revealing the lower sensitivity of cluster 11 to dryness compared to cluster 10. The strong growth reduction in 1990 refers to a vulnerability particularly to climatic conditions of PYT 6. The absence of negative reactions in 1988 and 1989, belonging also to PYT 6, reflects the importance of climate conditions in the previous May for cluster 11.

Climate conditions of PYT 1 are, however, crucial for growth reductions of cluster 11 (1948, 1960, 1996, 2000). Hence, summer coldness is of high importance for growth reductions of cluster 11, whereas growth of cluster 10 is more heavily influenced by permanent dryness, especially in previous and current years' summers and by coldness at the end of the growing season. Previous year's heat is crucial for the growth performance of both beech clusters; the growth of cluster 10 is also controlled by the duration and intensity of the hot period.

The differentiation of the parts of cluster 5, cluster 6 (coniferous trees), and cluster 12 (five sessile oak sites) is also determined by tree species. Cluster 12 contains all oak stands situated east of $8^{\circ}57'E$, with the exception of site 9. Climate conditions are more continental than those in other parts of the research area. Whereas cluster 6, according to cluster 5, only shows the characteristic pointer years 1976 and 1996 in combination with an even high VaC value (0.55), oak cluster 12 is characterised further by 1948, 1960, 1964, 1973, and 1988 (VaC 0.1). Negative growth reactions of cluster 12 are caused by climatic conditions of PYT 1 (1947/1948, 1959/1960, 1996) in combination with a very dry beginning of the growing season of the current year (1996) and PYT 4 (1976). Probably, high precipitation values in August and October 1960, along with a lack of solar radiation, also lower the growth performance of eastern oak. Dryness during the growing season leads to negative growth anomalies of cluster 12 (1964, 1973, 1988). In 1973, dryness already begins in previous year's October with a maximum in July ($-1.81z$) affecting a stronger growth reduction than detected for 1964 and 1988. The extremely wet March in 1988 ($+2.65z$) primarily lowers the dryness in the following growing season, but a simultaneous negative impact due to too little solar radiation cannot be excluded here. In 1976 the growth reduction is the strongest (-1.72σ). Thus, dryness especially in the summer months of the current year and in the late summer/autumn of the year prior to ring formation is the most important growth limiting factor for oak sites in the region eastwards of $8^{\circ}57'E$. Coldness, a lack of solar radiation, or dryness at the beginning of the vegetation period can enhance growth reductions.

Clusters 13 and 7, composed of clusters 14 and 15, are parts of cluster 6. They can be differentiated by tree species in combination with the degree of continentality. Cluster 13 consists of all spruce stands located west of $8^{\circ}57'E$ and shows 1976 (PYT 4), 1948, 1984, and 1996 (PYT 1) as characteristic pointer years. In 1983 (PYT 4), high precipitation values in

April and May lead to an absence of negative growth reactions of cluster 13. Similar to cluster 11, climatic conditions of PYT 1 reduce growth of cluster 13 (1947/1948, 1984, 1996). The extremely high precipitation values in previous year's May and the current May as well as in September 1984, along with a lack of solar radiation and below-average temperatures, have growth-reducing effects. In 1960 and 2000, also characterised by summer coldness, cluster 13 does not react with negative growth anomalies. Whereas coldness begins in 1984 and 1996 in May, and in 1948 in June, below-average temperatures first occur in 1960 and 2000 during July.

Cluster 7 mainly includes stands of Scots pine. VaC is comparably high (0.48), reflecting low homogeneous growth reactions of the corresponding sites also shown in the low number of characteristic pointer years, 1973 (PYT 2), 1976 (PYT 4), and 1996 (PYT 1). All of these years show below-average precipitation values over large parts of the growing season, leading to the assumption that dryness is the most important growth-limiting factor for cluster 7.

Cluster 14 and 15 are differentiated by topography in terms of the degree of continentality. Cluster 14 consists of all spruce and Scots pine stands located east of $8^{\circ}57'E$. Cluster 15 contains all other Scots pine stands. For both clusters, VaC is smaller than that for cluster 7 (cluster 14: 0.28; cluster 15: 0.42; cluster 7: 0.48).

Cluster 14 shows negative growth anomalies in response to the climatic conditions of PYT 1 (1996) and PYT 4 (1976). Additionally, in 1996, winter and April are very/extremely dry. Because of wet conditions in April and May 1983, no negative growth anomaly occurs in this year. Beside 1996, no negative growth anomalies occur in any other year of PYT 1. All of these years show above-average winter temperatures, especially 1947/1948. Dry conditions in winter and summer reduce growth in the years 1964 and 1973; in 1989 this is further influenced by an extremely dry May. In 1964, the growing season is probably shortened by very low temperatures in October. Additionally, extremely cold conditions in winter 1963 lead to an extreme growth reduction in eastern coniferous growth (-1.77σ). Only clusters in the eastern part of the research area (cluster 10, 12, 14) are affected by the climatic conditions of 1964. Among these clusters, coniferous tree cluster 14 shows the strongest reaction, followed by clusters 10 (-1.55σ) and 12 (-1.18σ). Growth of eastern coniferous tree cluster 14 is mainly limited by dryness in summer and May. Winter dryness causes a lack of moistness at the beginning of the vegetation period, whereas above-average winter temperatures enhance growth performance.

The climatic conditions of PYT 1 (1959/1960, 1996) and PYT 4 (1976) limit the growth of Scots pine cluster 15. Reasons for the absence of negative growth anomalies in 1983 (PYT 4) and the other years belonging to PYT 1 are similar to those described previously for cluster 14. The growth anomaly in 1959/1960 detected in cluster 15 is possibly caused by a lack of solar radiation in combination with below-average temperatures in August and October. These high precipitation values in turn have a positive influence on the growth of cluster 14, limited mainly by dryness. Similarly, eastern beech cluster 10 does not show

a negative growth anomaly in 1960. Climate conditions of PYT 4 lower growth of cluster 15. An extremely cold February and a cold/extremely cold growing season (1956) also reduce growth, as do dryness in winter (1973) and the growing season (1973, 1991) in combination with a very/extremely cold spring or summer.

Tree growth of cluster 15 is less strongly limited by dryness compared to cluster 14 and more reduced by coldness during winter and growing season. Winter temperatures are crucial for the growth performance of clusters 14 and 15.

4. Discussion

Grouping of the Cropper series leads to the detection of eight subsets of trees with specific growth anomaly patterns within an already fairly homogeneous growth behaviour on a regional scale. Nearly all of these subsets can be explained by the detected driving factors, which control the climate/growth relationships of the different groups. This is possible for a tree-ring network consisting of five tree species in the transition zone from the lowlands to the low mountain ranges in temperate forest regions of Germany. The group assignment of only one site cannot be explained by ecological and climatological features.

Results show predominantly more homogeneous growth patterns for the clusters than for the species-specific groups, confirming the progress of this particular growth-specific clustering process in contrast to widely used species-specific approaches. While in numerous studies the species-specific vulnerability to changing climatic conditions has been analysed [16, 42], results of this investigation lead to the assumption that it is not primarily the tree species but a shifted tree reaction that is the most important forcing factor for the climate/growth relationship. These findings can only be detected using this particular growth-specific clustering approach.

Whereas Neuwirth et al. [43] can detect immediate reactions of oak stands and lagged reactions of beech stands from the northwest German low mountain ranges, this study shows that shifted growth reactions are mainly not controlled by tree species as evidenced by the immediate as well as lagged reactions of oak groups. Z'Graggen [21] suggests an enhancing effect of previous year's autumn and winter dryness on spring dryness. We hypothesise that clusters which are strongly influenced by winter/spring dryness are already weakened when dryness and heat begin in summer, thereby leading to an immediate growth reduction in the same year. However, these groups, which are predominantly susceptible to summer heat and dryness, react in the year after the climatological event. Lebourgeois and Ulrich [44] detect an earlier onset of the growing season for oak stands between 10 and 15 days in the warmer, more oceanic and southerly regions of France, when compared to the beginning of the vegetation period of the more continentally located oak stands. This corroborates our assumption that the more continentally situated oak stands are less influenced by winter/spring dryness. Furthermore, the annual timing of the growing season is primarily controlled by temperature [45], and an increase of altitude delays budburst [44]. A later

beginning of the growing season due to altitude would explain the impact of climatic conditions in March 1981 for plain wet lowland cluster 8 and the climatic influence in April 1942 on higher altitude cluster 9. For cluster 8, this impact occurs in March, whereas for cluster 9 it occurs later, during April. This may also explain the fact that 1947 and 1959 are characteristic for lowland cluster 8 only, but not for cluster 9 which is, on average, located at higher elevations. In cluster 9 stands react during 1947 or 1948 and predominantly, but less than 80%, in 1959. Cluster 9 stands that react during 1947 and 1959 are located predominantly at lower altitudes than those that react during 1948 or indeed do not react during 1959. However, there are stands that show growth reduction in 1947 as well as in 1948 but are situated at lower altitudes than those that react in only 1947 or 1948. Furthermore, a species-specific differentiation such as that detected by Friedrichs et al. [4], with pedunculate oak growth controlled by winter and spring climatic conditions and sessile oak growth influenced mainly by June precipitation, can not be confirmed here. This suggests perhaps a more complex system of controlling factors of cluster 9, as indicated by the high VaC values and the low number of characteristic pointer years. For beech, Lebourgeois and Ulrich [44] detail a later beginning of the growing season. However, due to the higher elevation (~400/1000 m a.s.l.) of the French tree-ring network beech stands than their oak stands (200 m a.s.l.), we cannot transfer their findings to our network; in this study beech and oak stands both show a similar altitude distribution. Due to a relatively homogeneous topographical distribution of all our investigated stands, we assume that a complex interaction of forcing factors control the stronger influence of early spring climatic conditions on tree growth of cluster 2, when compared to cluster 3.

Climatic conditions in the eastern sector of the research area can be described as more continental than these in the western sector [26]. Comparably lower VaC values confirm a higher homogeneity of the easterly located clusters and reflect a stronger climate control of the corresponding stands. Noticeably, chronology statistics are most favourable for the eastern oak cluster, which reveal its strong reaction to climate and complement the findings of Bonn [15], who identifies beech as the most sensitive tree species. Beside a delayed growing season, as discussed above, the amount of water supply is smaller for easterly situated clusters. Trees growing on dryer sites are generally more sensitive to drought [2, 46], thus explaining the comparably stronger reactions of the eastern stands to dryness. The occurrence of negative growth anomalies in 1964 is typical for stands exposed to more continental conditions. While dryness is, with the exception of the winter months, not strong or extreme, its extended persistence leads to growth reductions. Neuwirth et al. [43] detect the contribution of low autumn temperatures, such as those seen in 1964, to negative growth reactions of beech in the same year. The duration of the vegetation period is generally limited by daily mean temperatures above 5°C [8]. Below-average autumn temperatures at the end of the growing season can, especially in more continental regions, lead to an earlier end of the physiological productivity and smaller ring widths.

The degree of continentality is an important driving factor for the climate/growth relationship at a regional scale and is empirically defined in this study with a threshold delineated here as east of $8^{\circ}57'$. This result is similar to findings of Babst et al. [47], regarding the existence of a boundary that separates temperature- and moisture-sensitive areas on a continental scale. The eastern oak stand which does not belong to cluster 12 could be influenced by more oceanic climatic conditions because of its lower situation close to the Edersee compared with stands belonging to the eastern oak cluster (Table 1).

Growth of the oak clusters and of the spruce cluster is influenced by extremely high precipitation values, predominantly at the beginning or at the end of the vegetation period. Whereas sufficient precipitation normally affects growth positively, extremely high precipitation values have a negative influence on tree growth and can be interpreted as a resonance effect, going along with lower temperatures [38, 48] and a lack of solar radiation. A strong positive relationship between Norway spruce growth and intercepted radiation is demonstrated by several authors including Bergh et al. [49]. A clear designation of the impact of high precipitation anomalies is, however, not always possible. Clusters that are very sensitive to dryness at the beginning of the growing season may also be influenced positively by extremely high precipitation values, thereby lessening the influence of any subsequent dry months. This may result in missed negative reactions, such as that during 1984 where cluster 10 does not show a growth reduction in spite of an extremely hot and very dry previous year's summer due to extremely high precipitation during previous year's May, this compensating for the effects of the previous year's dryness.

In general, beech growth is negatively affected by previous year's heat and dryness [19]. Above-average temperatures, in combination with a deficit of precipitation in June and July of the year prior to ring formation, stimulate the formation of flower buds and potentially lead to a beech mast [50]. Negative correlations are detected between fruit production and radial growth [51]. Oswald [52] suggests that tree-ring width can be reduced by 50% in good mast years. However, other studies discuss that reserve substances that are needed for a radial tree growth are not necessarily mainly used for fructification but that climate conditions enhancing reproductive growth have a coincident limiting influence on the radial tree growth [53, 54]. In succession to Neuwirth et al. [43] and Fischer and Neuwirth [26], it was possible to differentiate beech sensitivity to climate by detecting two beech groups that both react with growth reductions to previous year's heat, but, conversely, both show cluster-specific climatic sensitivities. Whereas growth of the low mountain range beech stands is more limited by coldness during summer, growth reductions of the easterly located beech stands are more controlled by permanent dryness, particularly dryness in the previous and current year's summer and coldness at the end of the growing season.

Winter temperatures can have a positive influence on the growth performance of coniferous trees, which may be explained by supplementary rates of photosynthesis, because

needles are photosynthetically active when temperatures are above freezing even in the winter months [55]. The impact of growth-reducing climatic factors can be weakened or compensated due to above-average temperatures during winter.

For spruce cluster 13, the growth-enhancing impacts of the above-average winter temperatures, such as those seen in other coniferous tree clusters, cannot be identified here. According to Neuwirth [38], below-average precipitation in March 1948 likely results in a lack of any positive impact from warm and wet winter conditions during 1947/1948. His results suggest that, after mild winters, the precipitation volumes around the onset of the growing season are important for the growth performance of spruces below 750 m a.s.l. While solar radiation has a strong positive influence on spruce growth, coldness in May and summer can reduce growth, as can drought, particularly in June [56].

Western Scots pine cluster 15 is limited by dryness, albeit less strongly than the more easterly situated coniferous tree cluster 14; however, it is also limited by cold during the growing season. Winter coldness precludes additional photosynthetic activity in both clusters 14 and 15. Clusters characterised by a more continental location could be found for all of the broadleaved tree species. Only coniferous tree species form one easterly situated cluster. This is likely caused by the comparably low number of coniferous stands. Further investigation, including more Scots pine and spruce stands, is now necessary to gather more results supported by statistical evidence.

5. Conclusion

We investigate an extended tree-ring width network of five tree species in temperate forest regions of West Germany. We adopt a particular approach whereby we group sites with similar growth anomaly patterns. Here we show for the first time that growth clusters with homogeneous interannual increment patterns regarding growth anomalies in single years can be detected on a regional scale. Climate/growth relationships of these groups are controlled by several ecological factors, such as tree species, soil moisture, or continentality. Overall, the tree species is not the most important controlling factor. Our analyses show that, first of all, shifted reactions due to differing influences of coldness and dryness in winter and spring distinguish growth behaviour of the clusters. The tree reaction to climatic conditions in early spring is determined by a complex system of controlling factors and cannot clearly be described by just one forcing factor, such as altitude, continentality, or tree species. The length of the growing season clearly plays a major role. Increasing the duration of the vegetation period due to climate warming is likely to change the climate/growth behaviour of the trees, considerably complicating the climate reconstructions. General statements concerning tree species' reactions to climate are not necessarily valid for stands in temperate forest regions with various topographical and ecological features. Growth controlling factors that are more important than the tree species can only be detected using a particular growth-specific clustering approach. Analyses

of climate sensitivity in temperate forest regions should therefore be based on growth-specific approaches rather than species-specific grouping approaches.

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