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ORIGINAL ARTICLE

Extreme growth reaction of larch (*Larix decidua* Mill.) from the Polish Sudetes and Carpathians: spatial distribution and climate impact

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Abstract

Key message **Extreme growth reaction analysis shows that larches in the Sudetes are more vulnerable to climate changes, but negative extreme responses will also be observed in the Carpathians in the near future.**

Abstract Pointer year analysis provides information on extreme tree-ring growth reactions, which can significantly improve the interpretation of tree growth response to climate. Similarities and differences in extreme growth responses of larch (*Larix decidua* Mill.) from the Carpathians and the Sudetes (Polish parts) were studied. To this purpose, a pointer year analysis was performed. Regions with similar extreme growth response patterns to climatic conditions were distinguished. The spatial variability of extreme growth anomalies and the distribution of the determined widespread pointer years and their possible climatic forcing were analyzed. A coincidence of the positive pointer years observed in the Sudetes and lower Carpathians with wet and cold summers (especially during the previous year) was observed. Most of the subregional negative pointer years in the Sudetes are related to droughts whereas in the Carpathians this relation was not observed. Comparison of the extreme growth reaction of larch in both mountain regions suggest that larches in the Sudetes are more vulnerable to climate changes as the negative pointer years observed in the Sudetes are usually associated with droughts that are likely to intensify in the future. Similarities in the drivers of extreme responses of larch in both regions and predicted changes in climatic conditions suggest that negative extreme responses will also be observed in the Carpathians in the near future. The highest parts of the Carpathians (the Tatra Mountains) should be treated separately as both positive and negative pointer years observed there are temperature related. The obtained results suggest that the growth of larch stands in both regions will be negatively affected by predicted climate changes.

Keywords Tree rings · Pointer years · *Larix decidua* Mill. · Climate response · Sudetes · Carpathians

Introduction

Climate change and observed global warming affect forests in many ways in terms of growth, productivity and mortality; these factors can also affect the distribution of forests and tree species (Thompson et al. 2009; Lindner et al. 2010; Dyderski et al. 2018). Mountain areas are very vulnerable to climate change (Kienast et al. 1998; Beniston 2003; Thuiller et al. 2005; Engler et al. 2011), and as climate is one of the main factors affecting tree growth, changes are reflected in tree rings (Fritts 1976). Therefore, the analysis of tree growth can be a valuable tool in understanding the response of trees and their growth to climate. This response can be positive or negative (e.g., Driscoll et al. 2005, Cai et al. 2020) and it changes over time (e.g., Gomes Marquesa et al. 2018); it is species specific (e.g., Eilmann and Rigling 2012; Lyu et al. 2017; Friedrichs et al. 2009) and is dependent on the site-related or microsite-related factors (e.g., Driscoll et al. 2005; Latte et al. 2015). This information can help in understanding the changes in forest ecosystems and support decision-making processes in sustainable forest management, especially those related to long-term strategies

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(Spiecker 2002; Beniston 2003; Hanewinkel et al. 2013; Lindner et al. 2014).

The analysis of the climate–growth relationship enables the general identification and assessment of the influence of the most important growth-limiting climatic factors. However, it cannot provide information about the extremely positive or negative impact of climatic conditions observed in individual years (compare Neuwirth et al. 2004). Therefore, analysis of pointer years that focuses on conspicuously narrow or wide rings (or unusual features of tree rings) observed in a substantial part of the population is an important part of studies on the influence of climate on tree growth (Schweingruber et al. 1990; Esper et al. 2001). When considered in the context of spatial distribution, pointer years can be used to distinguish regions with similar extreme growth response patterns to climatic conditions (Neuwirth et al. 2007, Fischer and Neuwirth 2013). Therefore, pan-regional climatic conditions which substantially influence tree growth can be recognized and interpreted.

Previous studies of larches (*Larix decidua* Mill.) growing in the Polish parts of the Sudetes and the Carpathians have provided detailed information on the spatial variability of growth responses to climatic factors in larch (Danek et al. 2017, 2018). These studies revealed many similarities between both areas, e.g., thermal conditions in the initial stage of cambial activity and tree-ring formation are one of the most important factors affecting tree-ring growth. The main difference between the two regions was in the strength of the observed associations with climatic factors (especially the thermal and moisture conditions of the previous summer). It is probable that the larches in the Sudetes are more affected by drought and; therefore, more likely to be affected by the recent climate changes, which in Poland are generally expressed by the significant increase in temperatures and decreasing contribution of summer precipitation total to the annual total (Szwed 2019; Wypych et al. 2017; Wójcik and Miętus 2014; Michalska 2011; Degirmendžić et al. 2004). For this study, we focused on the extreme growth reaction of larches growing in the two aforementioned mountainous areas of central Europe to find out whether spatially homogenous extreme growth patterns can be observed, as wide-scale growth anomalies can be explained only by common climatic stimuli (Fritts 1976; Neuwirth et al. 2007). Tree-ring growth data of larch from 56 sites in the Sudetes and the Carpathians were used to analyze the spatial variability of extreme growth, the distribution of the determined widespread pointer years, and their possible climatic forcing.

Materials and methods

Study area and site locations

The study sites were located in the Polish parts of two mountain ranges located in Central Europe: the Carpathians (i.e., Western and Eastern Outer Carpathians and Central Western Carpathians, including the Tatra Mountains) and the Western and Central Sudetes (Fig. 1). The Outer Carpathians are medium-elevated mountains, with foothills reaching 400–500 m a.s.l., with the highest parts rarely rising above 1000 m a.s.l. (Kondracki 1978). The Tatra Mountains are the highest part of the Carpathians (highest peaks reaching more than 2000 m a.s.l.), and differ significantly from the lower Carpathians as they have the features of high mountain environments (Warszyńska 1996) and are classified as a true alpine massif with distinct alpine climate zones (Kotarba 1992; Niedźwiedź 1992). The Sudetes are much smaller than the Carpathians, but they are also medium-elevated mountains. Karkonosze, the most prominent massif, is located in the western part and its highest peaks reach more than 1400 m a.s.l. The climates of the Sudetes and the Carpathians differ as a consequence of their geographic locations and the strength of the ocean influence, with the climate of the Carpathians being much more continental (Fig. 1). The altitudinal climate zone boundaries of the Sudetes are situated several dozen to 250–300 m lower than those of the Western Carpathians, which is explained by their more westerly location, smaller size, and their exposure to more frequent advection of fresh air masses. The difference in altitudinal climate zone boundaries between the mentioned regions increases with altitude, which is also a result of the climate of the Sudetes being more oceanic in its uppermost parts (Hess et al. 1980). The climatic diagrams of both study areas are presented in Fig. 1.

In both the Sudetes and the Carpathians, the larch (*Larix decidua* Mill.) grows mainly in the lower montane forest zone. Only in the Tatra Mountains can this species be found higher up. Nowadays, the occurrence of larch is largely the effect of planting, but tree stands of natural origin that contain this species can be found in both mountain areas. Larch grows in mixed stands of the mountain fresh forest type (according to the typology of Polish forests (Matuszkiewicz 1978)) on cambisols and arenosols, mainly with European silver fir, Norway spruce, European beech, and Scots pine. In this study, data from 56 sites located in the Polish parts of the Sudetes (21 sites) and the Carpathians (35 sites) were used. The sites were located at altitudes of 278 to 1387 m a.s.l. Samples were collected between the years 2009–2017. At each site, 11–24 dominant or co-dominant trees were sampled. Usually, two

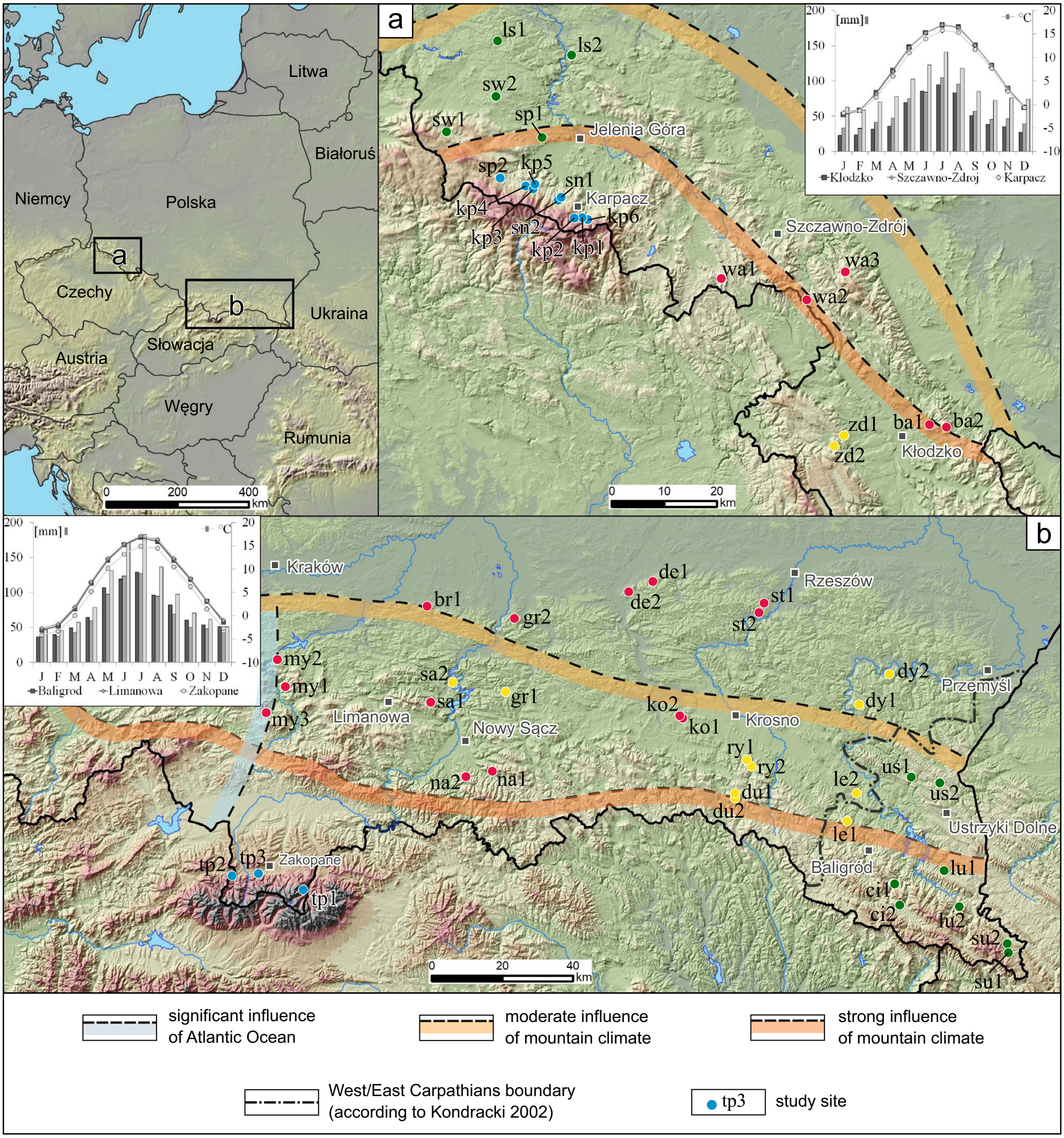

Fig. 1 The study area (map based on SRTM DEM; Jarvis et al. 2008), site locations and climate information (compare Okołowicz and Martyn 1984, and Kondracki 2002; climatic diagrams based on data from meteorological stations, provided by IMGW-PIB for the period 1956–2015). Colors of the points represent obtained clustering results

cores per tree were taken using a Pressler borer. Detailed locations of the sites and their characteristics are provided in Table 1. For more details see Danek et al. (2017, 2018), as this study is based on the tree-ring series, which build site chronologies presented there.

Assessment and analysis of pointer years

For each site, the pointer years were assessed according to Cropper (1979), using the pointRes R package (van der Maaten-Theunissen et al. 2015). The Cropper approach is the most frequently used method (see Jetschke et al.

2019). First, ratios between the raw tree-ring series and their 5-year moving average were calculated. We decided to use raw data and a short time window after testing many different solutions considered in these kinds of studies (Jetschke et al. 2019). The applied combination of data type and window length gave the most spatially consistent result (but still similar to other tested options). Obtained Cropper-values (C) were normalized by setting the mean to zero and standard deviation to one (so-called 'z-transformation'). In the normalized series, high frequency variability is highlighted by removing long-term trends related to tree aging or other processes that change the environment in which trees grow (compare Fritts 1976). In accordance with Neuwirth et al. (2007), we applied three classes of positive or negative growth deviations: "weak" ($|C| > 1$), "strong" ($|C| > 1.28$) and "extreme" ($|C| > 1.645$). Subsequently, the event years (i.e., anomalously narrow or wide tree ring) in each tree-ring series of the particular site (both positive and negative) were determined. A year was considered a pointer year when at least 50% of trees in the site showed the event year (see Weigel et al. 2018). Counting pointer years started when the sample replication for the site chronology reached at least 10 trees.

Subsequently, to distinguish regions with a similar signal pattern, hierarchical agglomerative clustering (Ward's method with Euclidean distance) was used. As the Cropper value highlights inter-annual growth anomalies (Neuwirth et al. 2007), clustering over Cropper values averaged for each site was performed as these series indicate abrupt signal amplitude changes and extreme intrasite signal behavior. Previous studies on climate–growth relationship showed clear differences in larch response to climatic factors between Sudetes and Carpathians (Danek et al. 2017, 2018). In the first stage of this study the existence of regional division between two analyzed mountain areas, but in terms of extreme responses, was checked by the clustering done for all 56 sites together. As expected, the results showed a clear separation between the Sudetes and the Carpathians, with Tatra sites being the third distinguished group. Only one Carpathian site, namely br2, was attached to the Sudetes. This finding gave rise to perform the study as Sudetes vs. Carpathians with final clustering done separately for these two mountain regions. Tatras were considered together with the Carpathians sites as they are in the same geographical region. A pointer year was qualified as subregional when it was present in at least 2/3 of the sites of a particular cluster, regardless of the strength of the pointer year (this is similar to Vitas 2015, who established 1/3 of the sites as a regional threshold).

The analysis was mainly focused on pointer years detected within the common period covered by all 56 chronologies, which is 1931–2006. However, the pointer year 2012, observed in the Sudetes, was also considered, as it was observed in the majority of site series covering this year. The climatic interpretation of pointer years was based on the previously determined climatic factors of particular importance to the growth of larch in the study area (Danek et al. 2017, 2018).

Climatic data

To discover the weather conditions during the occurrence of pointer years, climatic data (average monthly temperatures and monthly precipitation totals) from the Climate Research Unit were used (CRU TS 4.03 dataset, Harris et al. 2014). The data cover the period 1901–2018 and are available in a 0.5° × 0.5° grid. Gridded data were used because of their much wider time range in comparison to available weather station data (which start in the 1950s and 1960s). The high similarity between CRU data and meteorological station data in the research area was confirmed in previous studies (Chuchro and Danek 2017, 2018). For CRU TS 4.03 dataset, mean temperature correlation values for both the Carpathians and the Sudetes equal to 0.96. Precipitation data had lower mean correlation values, respectively 0.85 for the Carpathians and 0.8 for the Sudetes. Gridded climatic data were also used to calculate the SPEI (Standardized Precipitation–Evapotranspiration Index). SPEI is a simple multiscale drought index which combines precipitation and temperature (Vicente-Serrano et al. 2010). The 1-month SPEI values were retrieved for the complete time period.

To highlight the deviation from average values of the mentioned parameters (average monthly temperatures, monthly precipitation totals and SPEI), residuals (differences between climatic data for each month and their monthly means) expressed in standard deviation units (σ; similarly to Neuwirth et al. 2004, 2007) were calculated. Thresholds of 1σ and 0.6σ above and below the mean were used to classify monthly values into categories. For temperature: very warm ($\geq 1\sigma$), warm ($< 1\sigma$ and $\geq 0.6\sigma$), normal ($< 0.6\sigma$ and $> -0.6\sigma$), cold ($\leq -0.6\sigma$ and $> -1\sigma$) and very cold ($\leq 1\sigma$). For precipitation, the corresponding categories are called: very wet, wet, normal, dry, and very dry; for SPEI: very high, high, normal, low, and very low.

Results

Spatial distribution of growth anomalies

The results of clustering obtained for the Sudetes and the Carpathians are shown in Fig. 2a, b respectively. Also, the affiliation of the sites to particular clusters can be seen in Fig. 1. For the Sudetes, four different groups could be identified (Fig. 2a). The first cluster (C1) contains all sites located in the central part of the study area in the Karkonosze, which

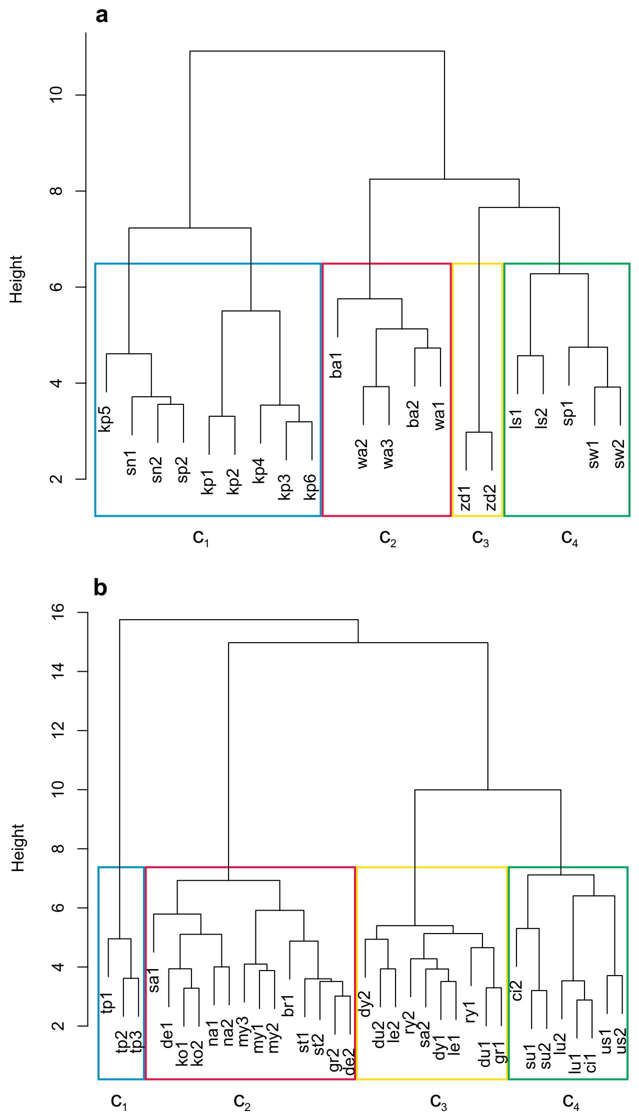

Fig. 2 Results of clustering analysis: **a** Sudetes, **b** Carpathians. Distinguished clusters (C1–C4) are marked

is the highest massif of the Sudetes. Clusters C2 and C4 consist of sites from the lower ranges that are located in the most eastern and western parts of the study area, respectively. Cluster C3 consists of only two sites that are located in the south eastern part of the area on the edge of the Kłodzko Basin (Figs. 1a, 2a).

In the Carpathian sites, four groups can also be distinguished (Fig. 2b). The first cluster sites are in the Tatra Mountains. Cluster C2, the biggest cluster, consists of sites from the western part of the study area located in the Outer Western Carpathians and the foothills (Figs. 1, 2b). Cluster C3 consists mostly of sites located in the Western Carpathians but closer to its eastern boundary (with the exception of sites sa2 and gr1, which are located further to the west, Fig. 1b). The last cluster, C4, has sites located in the Outer Eastern Carpathians (Fig. 1).

Pointer years of the subregional class

Figure 3 presents the series of mean Cropper values for all sites grouped in clusters with pointer years marked. In the common period (1931–2006), the number of detected pointer years for particular sites ranged from 6 to 18. Correlation analysis and visual analysis of correlograms showed no distinct relationship between the number of pointer years in the common period and the altitude of the sites or the age of the tree stand. The prevailing number of recorded pointer years in the common period represented a “strong” class of growth deviations: 57% in the Sudetes (58% of positive and 56% of negative) and 57% in the Carpathians (61% of positive and 53% of negative). The number of “extreme” pointer years was very low (Fig. 3).

The most prominent pointer years (subregional pointer years) are presented in Table 2 together with their climatic interpretation. In the Sudetes, 20 subregional pointer years were detected in the common period 1931–2006 (Table 2a). The highest replication was observed for two negative pointer years: 1992 and 1995. The negative pointer year 1992 was recorded at 14 of 21 sites and the year 1995 was recorded at 16 of the 21 sites (Fig. 3a). A “strong” class of growth deviations dominated (57% for 1992 and 69% for 1995 respectively). The year 1995 was qualified as a subregional pointer year for all four clusters, whereas 1992 was a subregional pointer year for three of them, as were two other pointer years: 1980 (negative) and 1946 (positive; Table 2).

In the Carpathians, 13 subregional pointer years were observed in the common period (Table 2b, Fig. 3b). The most prominent is the positive pointer year 1966 as well as negative pointer year 1980, both of which were recorded for all three Outer Carpathians clusters (Table 2b, Fig. 3b). However, the pointer year 1961 is also worth mentioning as it was observed in the same number of sites as 1966 (i.e., 25 of 35). This year was observed in 100% of the sites of cluster C2, 60% of cluster C3 sites, and in half of the sites of cluster C4. The obtained pointer year pattern for the Tatra Mountains cluster is different, which was expected, taking into consideration the results of clustering and previous climate–growth relationship studies (Danek et al. 2017). Five negative (1952, 1962, 1965, 1996, and 2001) and four positive (1931, 1950, 1957, and 1986) years were detected.

Discussion

The patterns of clusters obtained in two regions (Figs. 1, 2) are generally very similar to those from previous studies, which used larch tree-ring width chronologies from the same

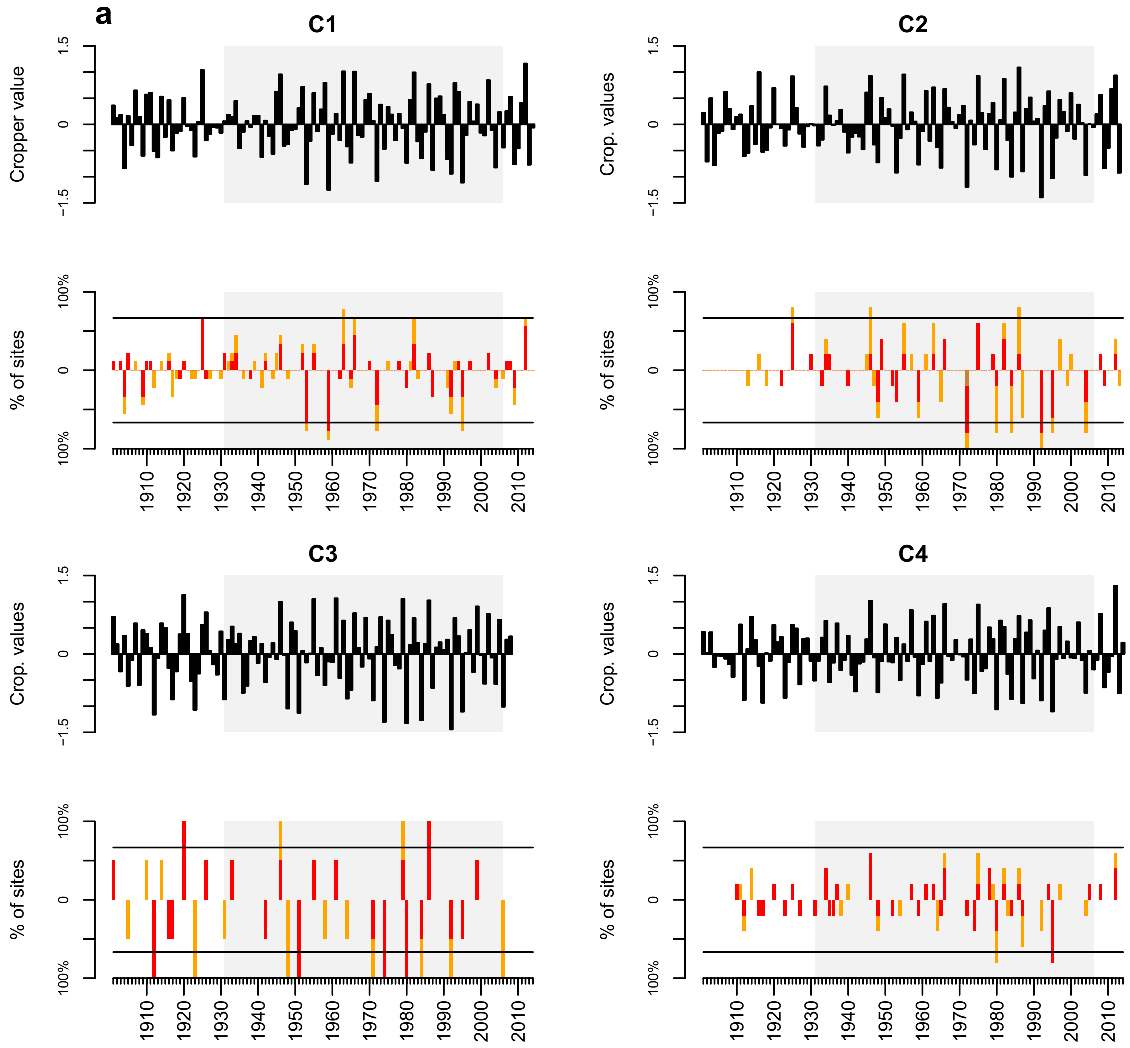

Fig. 3 Average cluster (C1–C4) Cropper values (black bars), and percentage of sites with pointer years (color bars) over time for the Sudetes (**a**) and the Carpathians (**b**). Yellow, red, and brown colors represent "weak", "strong" and "extreme" pointer years, respectively. Bars above zero correspond to positive pointer years, and below zero to negative pointer years. The gray area represents the common period. Black horizontal lines show pointer year criterion (2/3 of sites)

sites (Danek et al. 2017, 2018). In the Carpathians, only two sites (us1 and us2) were moved between neighboring clusters to make them more aligned with the geographical division of the Carpathians (compare Danek et al. 2017, Figs. 1 and 2, see also Sect. 4.2 below). For the Sudetes, the change in the received pattern is more substantial, with clearer separation between central, eastern, and western parts of the study area that probably reflect the differences in the climatic characteristics of these regions (compare Danek et al. 2018, Fig. 1 and 2, see also Sect. 4.1 below). As the obtained clusters of the mean Cropper value series seem to be strongly related to the climatic diversity of the regions, it suggests that the extreme growth reaction patterns and subsequently subregional pointer years have climatic origins.

Sudetes

The obtained cluster pattern seems to be in agreement with the climatic diversity of the region (Figs. 1, 2a). All sites of the C1 cluster are located in the Karkonosze. This is the highest and most prominent massif within the Sudetes, which affects the local climate: it is much harsher than the neighboring regions. The precipitation reaches the highest values observed in the study area, with a relatively high fog share (Blas and Sobik 2000). The Karkonosze are one of the windiest mountains in continental Europe (Blas and Sobik 2005). Clusters C2–C4 contain the sites located in the lower mountain massifs and the foothills. Cluster C4 contains the most western sites, whereas clusters C3 and C2 contain the most eastern ones. This division can be

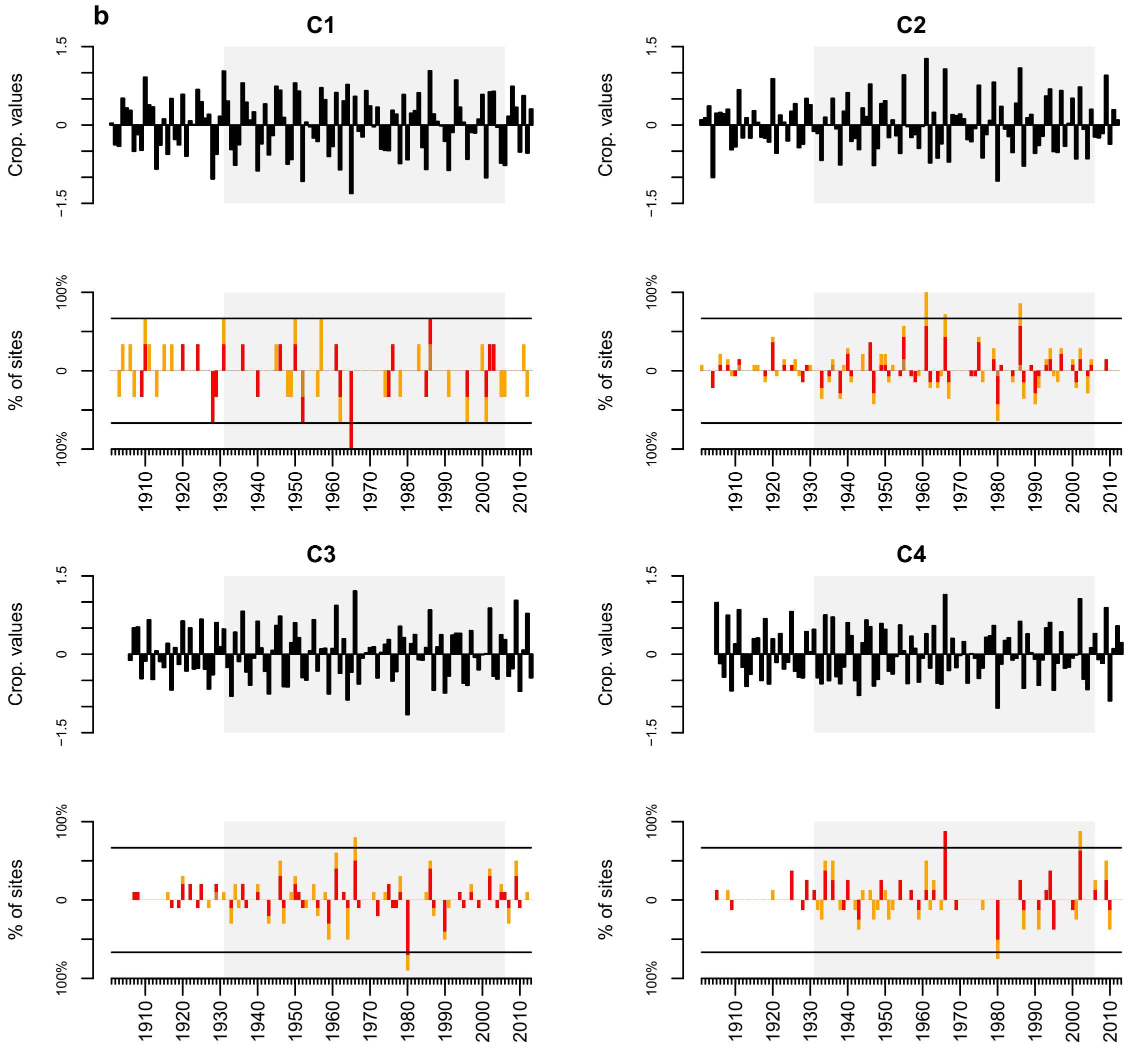

Fig. 3 (continued)

related to the decreasing influence of the Atlantic Ocean and the influx of more humid air masses from the western and north-western directions that are received by the western part of the Sudetes (Walczak 1968). The separation of the C3 cluster can be explained by the influence of the Kłodzko Basin, on the south-western edge of which sites of this cluster are located. The relatively dry climate of Kłodzko Basin is related to the influence of warm air masses, which flow into it from the north, and the rain shadow effect (Walczak 1968; Hess et al. 1980; Pawlak 1997). However, the sites ba1 and ba2, located on the opposite side of the mentioned basin (NE), were classified to the C2 cluster along with sites located in the same mountain range separating Kłodzko Basin from the lowlands (Fig. 1).

Climatic interpretation of major observed negative pointer years

The results of the previous climate–growth relationship analysis (Danek et al. 2018) show that the most important influences on larch growing in the Sudetes are the temperature in May of the year of the tree-ring formation and the climatic conditions in the summer months (especially July) and November of the year preceding the tree-ring growth. Climatic conditions in July and August of the year in which the tree-ring is formed are also of some importance. This knowledge was used to interpret climatic drivers of both positive and negative pointer years in this region.

In total, the five negative pointer years: 1972, 1980, 1984, 1992, and 1995 were widely observed (i.e., recorded as subregional pointer years in at least two clusters). The negative influence of a warm and dry summer (during the year of tree-ring formation and the previous year to that) on

Table 1 Characteristics of the sampled sites

No.	Site	Longitude	Latitude	Altitude (m a.s.l.)	Slope aspect	Forest type	Soil type	No. of trees in analysis	MSL	AGR [mm]
1	ls1	15° 28′ 40.80″ E	51° 03′ 25.88″ N	402	Flat	UMFF	Cambisols	16	125	1.604
2	ls2	15° 41′ 02.00″ E	51° 02′ 32.00″ N	325	N	UMFF	Cambisols	12	110	1.811
3	sn1	15° 41′ 05.99″ E	50° 47′ 36.53″ N	646	W	MCMFF	Podzols	15	125	1.284
4	sn2	15° 40′ 43,81″ E	50° 47′ 24,64″ N	709	NE, near summit	MMFF	Cambisols	13	127	1.090
5	zd1	16° 29′ 23.10″ E	50° 25′ 02.00″ N	486	NE, slope flattering	MFF	Cambisols	14	148	1.783
6	zd2	16° 27′ 53.50″ E	50° 23′ 55.00″ N	499	NW	MFF	Podzols	12	146	1.811
7	ba1	16° 43′ 07.70″ E	50° 26′ 39.60″ N	486	N	MFF	Cambisols	14	92	2.194
8	ba2	16° 45′ 59.90″ E	50° 26′ 31.60″ N	546	S	MFF	Cambisols	14	89	2.567
9	kp1	15° 44′ 48.90″ E	50° 45′ 41.30″ N	823	E–EN	MMFF	Arenosols	18	109	1.602
10	kp2	15° 43′ 34.10″ E	50° 45′ 37.20″ N	930	N–NE	MMFF	Arenosols	19	129	1.363
11	kp3	15° 36′ 29.90″ E	50° 48′ 25.60″ N	726	SW	MMFF	Arenosols	19	111	1.506
12	kp4	15° 35′ 12.70″ E	50° 48′ 32.80″ N	744	N–NW	MMFF	Arenosols	15	117	1.658
13	kp5	15° 36′ 38.80″ E	50° 48′ 45.90″ N	620	N	MMFF	Arenosols	18	133	1.264
14	kp6	15° 45′ 40.20″ E	50° 45′ 33.70″ N	752	NE	MMFF	Cambisols	20	106	1.798
15	wa1	16° 07′ 57.60″ E	50° 40′ 22.70″ N	604	SE–SEE	MMFF	Cambisols	19	88	2.009
16	wa2	16° 22′ 00.60″ E	50° 38′ 44.40″ N	706	S–SSE	MCMFF	Podzols	20	109	1.854
17	wa3	16° 27′ 56.50″ E	50° 41′ 49.80″ N	658	SW	MMFF	Cambisols	20	105	1.742
18	sp1	15° 37′ 13.80″ E	50° 53′ 43.30″ N	543	W	MFF	Cambisols	20	88	2.283
19	sp2	15° 30′ 54.20″ E	50° 49′ 08.50″ N	717	N–NW	MMFF	Planosols	19	134	1.372
20	sw1	15° 21′ 31.90″ E	50° 53′ 30.20″ N	606	N–NW	MMFF	Cambisols	17	138	1.309
21	sw2	15° 29′ 09.20″ E	50° 57′ 36.90″ N	469	Flat	MMFF	Planosols	19	83	2.547
22	tp1	20° 5′ 1.90″ E	49° 14′ 17.00″ N	1387	SE	MFF	Cambisols	14	225	0.620
23	tp2	19° 48′ 6.20″ E	49° 16′ 2.90″ N	1211	NE	MFF	Cambisols	18	133	1.295
24	tp3	19° 54′ 31.00″ E	49° 16′ 36.80″ N	971	N	MFF	Cambisols	20	142	1.567
25	my1	19° 59′ 34.32″ E	49° 44′ 59.59″ N	471	WWS	MFF	Cambisols	12	131	1.834
26	my2	19° 57′ 30.38″ E	49° 49′ 12.45″ N	376	NNW	MFF	Cambisols	11	127	1.646
27	my3	19° 55′ 26.74″ E	49° 41′ 0.50″ N	489	S	MFF	Cambisols	11	139	1.717
28	br1	20° 33′ 13.54″ E	49° 57′ 50.60″ N	278	N	USFF	Cambisols	12	129	1.829
29	sa1	20° 34′ 11.17″ E	49° 43′ 2.14″ N	528	N	MFF	Cambisols	10	101	1.964
30	sa2	20° 39′ 31.23″ E	49° 45′ 59.33″ N	349	SSE	UFF	Cambisols	10	89	2.568
31	na1	20° 48′ 53.20″ E	49° 32′ 35.90″ N	562	SW	MFF	Cambisols	14	99	2.795
32	na2	20° 42′ 43.50″ E	49° 31′ 40.70″ N	600	NE	MFF	Cambisols	13	112	2.015
33	gr1	20° 51′ 45.10″ E	49° 44′ 40.10″ N	447	NE	UFF	Cambisols	12	110	1.904
34	gr2	20° 53′ 46.30″ E	49° 55′ 48.70″ N	361	E	UFF	Cambisols	13	119	1.625
35	de1	21° 26′ 36.20″ E	50° 1′ 29.83″ N	325	N	UFF	Luvisols	11	93	2.534
36	de2	21° 20′ 51.46″ E	49° 59′ 56.94″ N	306	W	UFF	Luvisols	11	105	1.964
37	ko1	21° 33′ 22.68″ E	49° 40′ 47.77″ N	340	SW	UFF	Cambisols	16	118	1.760
38	ko2	21° 33′ 16.10″ E	49° 41′ 12.02″ N	325	NE	UFF	Cambisols	19	112	1.960
39	st1	21° 51′ 37.57″ E	49° 56′ 39.57″ N	306	WSW	UFF	Cambisols	15	130	1.549
40	st2	21° 52′ 55.23″ E	49° 57′ 52.84″ N	282	NNE	UFF	Cambisols	15	110	2.012
41	ry1	21° 48′ 33.12″ E	49° 34′ 18.90″ N	474	S–SE	MFF	Cambisols	16	107	1.601
42	ry2	21° 49′ 36.64″ E	49° 33′ 19.12″ N	534	N	MFF	Cambisols	13	110	1.679
43	du1	21° 45′ 34.52″ E	49° 29′ 9.77″ N	536	NW	MFF	Cambisols	17	102	1.981
44	du2	21° 45′ 21.46″ E	49° 28′ 44.65″ N	590	SSE	MFF	Cambisols	19	111	1.651
45	dy1	22° 15′ 3.50″ E	49° 42′ 37.00″ N	487	WNW	UFF	Cambisols	18	99	1.858
46	dy2	22° 22′ 21.80″ E	49° 47′ 7.40″ N	414	SW–SSW	UFF	Cambisols	13	104	1.465

Table 1 (continued)

No.	Site	Longitude	Latitude	Altitude (m a.s.l.)	Slope aspect	Forest type	Soil type	No. of trees in analysis	MSL	AGR [mm]
47	us1	22° 27′ 3.09″ E	49° 31′ 27.80″ N	522	S	MFF	Cambisols	15	116	1.898
48	us2	22° 33′ 47.08″ E	49° 30′ 27.61″ N	580	N	MFF	Cambisols	14	111	2.573
49	le1	22° 11′ 48.80″ E	49° 24′ 45.60″ N	582	NE	MFF	Cambisols	19	102	1.932
50	le2	22° 14′ 4.70″ E	49° 29′ 4.20″ N	481	NW-SW	UFF	Cambisols	18	110	1.466
51	lu1	22° 34′ 33.10″ E	49° 17′ 5.80″ N	569	NW	MFF	Cambisols	17	97	2.784
52	lu2	22° 37′ 50.00″ E	49° 11′ 32.00″ N	749	N	MFF	Cambisols	18	111	2.233
53	ci1	22° 22′ 51.70″ E	49° 15′ 5.10″ N	604	NNE	MFF	Cambisols	17	105	2.600
54	ci2	22° 23′ 56.60″ E	49° 11′ 58.60″ N	723	SE	MFF	Cambisols	18	94	2.287
55	su1	22° 49′ 6.30″ E	49° 4′ 15.80″ N	875	SW	MFF	Cambisols	17	92	1.919
56	su2	22° 48′ 57.50″ E	49° 5′ 39.90″ N	760	WNW	MFF	Cambisols	19	92	2.292

Forest types abbreviations: *UMFF* upland mixed fresh forest, *UFF* upland fresh forest, *USFF* upland strongly fresh forest, *MCMFF* —mountain coniferous mixed fresh forest, *MFF* mountain fresh forest, *MMFF* mountain mixed fresh forest (forest types classification after Matuszkiewicz 1978). *MSL* mean series length, *AGR* average growth rate

tree-ring growth seems to be reflected in four of them; as these conditions occurred in 1972, 1984, 1992, and 1995 (Table 2a, Fig. 4a). It seems that previous July climatic conditions are of main importance as in all these years July was dry/very dry with low/very low values of SPEI (Fig. 4a). In 1971, the dry conditions with low and very low SPEI were prolonged into August. In addition, August of 1972 was rather dry for most of the area, which could cause this pointer year to be more widely observed than the pointer year 1984 (Fig. 3a).

These years, such as 1992 and 1995 were the most commonly observed pointer years in the Sudetes which could be related to the extremity of the unfavorable conditions, as both summers (the year of the tree-ring formation and the previous year) were characterized by dry and warm conditions, with low/very low values of SPEI for July (Fig. 4a and Table 2a). Please note that these two pointer years coincide with the well-documented droughts of 1992 and 1994, which were catastrophic summer droughts that spanned almost the entire country (Niedźwiedź 2000; Łabędzki 2004; Wypych et al. 2017). However, the aforementioned spatial prevalence of the pointer years 1992 and 1995 could also be caused by the fact that hot and dry conditions concerned both the preceding summer and the summer of the tree-ring formation.

The nature of the remaining negative pointer year (1980) is definitely different. During this year, the entire vegetation season was cold, with May being one of the coldest during the period of analysis. It seems that the temperatures for this season fell below the range in which larch can develop a ring of a regular width, even though other weather conditions were favorable (i.e., a wet July). It is worth noting that the 1980 pointer year was not prominent in the Karkonosze cluster (C1) and was not classified as such (two out of nine sites fulfilled the pointer year classification criterion). This may be related to the high mountainous characteristic of this region that clearly affect the larch growth pattern (compare with the Tatra Mountains discussed below, where a similar phenomenon was observed). Notably, although it was very cold, May 1980 was also very dry which is very unusual (first percentile of May data). This could suggest limited cloudiness and therefore higher insolation, which rises in intensity with altitude (Raja 1994). This effect could mitigate the negative influence of the low May temperature, which according to the climate–growth relationship analysis is the most important factor affecting the ring width of larch in the study area (Danek et al. 2018).

Additionally, the two negative pointer years, 1953 and 1959 are worth mentioning. They were only recorded in trees from higher locations (Fig. 3a and Table 2a), which suggest the possible dependence of altitude on their occurrence. Some explanation can be found in the climatic conditions of late winter to early spring (especially February and March) as well as late summer of the year of tree-ring formation; both of these periods were similar in both mentioned years, i.e., dry or very dry with low or very low SPEI values. To some extent, drought (especially in August) can be considered a reason. This argument is supported by the fact that significant positive correlations between tree-ring growth and precipitation (and SPEI) for this month were observed for the highest study sites (Danek et al. 2018); a shortage of water can also speed up growth cessation at the end of the growing season (Saderi et al. 2019). For February's precipitation, similar climate–growth relationship analysis results were observed (Figs. 5b and 7 in Danek et al. 2018). The negative influence of a late dry winter could be related to shallow snow cover and winter desiccation (compare Tranquillini 1979).

Climatic interpretation of major observed positive pointer years

In the common period, three positive pointer years were commonly recorded: 1946, 1966, and 1986. However, the pointer year 2012, which is outside of the underlying research period, is also worth mentioning because it was observed in 11 out of 13 site chronologies which were long enough to cover this year (for the particular chronology periods covered, please see Table 2 in Danek et al. 2018). The common feature of 1946, 1986 and 2012 was a very warm May (Fig. 4b). It seems to reflect a strong, positive relationship between growth and May temperatures (Danek et al. 2018). Another positive factor could be rather good moisture conditions during the summer months and normal to very high SPEI values (Fig. 4b). Moisture conditions seem to be responsible for the remaining positive pointer year (1966) as the summer months (July and August) were wet or very wet, with very high SPEI values.

Carpathians

Among the four clusters distinguished within the Carpathians, the group of Tatra Mountain sites (C1) stands out, which was expected as this part of the Carpathians differs significantly from the rest of the study area. This is the only region with a typical alpine character and reflects the climatic features of high mountain environments (Niedźwiedź 1992). The division of the remaining sites may indicate a connection with the growing influence of the continental climate towards the east observed in the Carpathians (Cheval et al. 2014). The C2 cluster contains the western locations (together with foothills), whereas the C3 cluster consists mainly of sites situated further to the east. The sites of the last cluster (C4) are already located within the Eastern Carpathians (Fig. 1) and have the most continental climate within the study area. Please note that the number of observed subregional pointer years for the Outer Carpathians clusters (C2–C4) is lower than for the Sudetes. This can be partially the result of the bigger study area, meaning greater diversity between the sites constituting the distinguished clusters.

Climatic interpretation of major observed negative pointer years

Previous climate–growth relationship analysis showed that the most important factors for larch tree-ring growth in the Carpathian region are the temperatures of the previous May and July (negative correlation), the previous October (positive), and the current May (positive). In the case of precipitation, the most important months are the current April (negative), June and July (positive), and September (negative) (Danek et al. 2017). Additionally, increased positive correlations were observed for precipitation in the previous May, June and July for some sites. As for the Sudetes, this knowledge was used to interpret negative and positive pointer years.

The very cold May conditions characterized three of the five negative pointer years detected for the Tatra cluster (C1), i.e., 1952, 1962, and 1965 (Table 2b, Fig. 5a). In addition, in the two latter years, most of the growing season months were cold. The nature of the remaining negative pointer years (1996 and 2001) seems to be different as both had a warm May. In the case of 2001, the month of June was very cold. This could be the reason for the negative pointer year as the temperature during June is also important for larch growth in the Tatras (Danek et al. 2017). May 1996 was exceptionally wet which is unusual as normally, if May is warm it is also rather dry. High precipitation is associated with high cloudiness and hence lower insolation. As insolation can be an important factor that positively affects tree-ring growth at high altitudes (Takahashi et al. 2005), limited insolation could mitigate the positive effect of a high temperature. This claim can be supported by the fact that a negative correlation between tree-ring growth and precipitation during this month was observed for the lowest of the three Tatra sites (i.e., tp3, Danek et al. 2017). Furthermore, July 1996 was very cold which could also have had a negative influence. Even so, the climatic explanation for this negative pointer year is not clear.

In the remaining area of the Carpathians (i.e., clusters C2–C4), only one negative pointer year (1980) of the subregional type was detected. This pointer year was observed in 69% of the sites (Fig. 3b). In most of them (71%) it was classified as “strong”. As with the Sudetes, the climatic conditions in the Carpathians during 1980 were outstanding. The vegetation season was very cold with an extremely cold May (Fig. 5a). Moreover, the climatic conditions of the previous growing season were also unfavorable: May was warm and dry, and June was dry. It is worth noting that in 1979 the extremely warm June was followed by an extremely cold July. Please note that the year 1980 was not classified as a negative pointer year for any of the Tatra sites, despite having the most temperature-related growth of larches in high locations (Danek et al. 2017). As mentioned previously, in the context of the Karkonosze cluster, this effect could suggest that larches in high mountain areas have a different climatic response (see Čejkowá and Kolář 2009). However, after the analysis of the Tatra sites series, it was found that the tree rings formed in the year 1980 were indeed narrow, but were preceded by a period of relatively narrow rings in the 1970s, which could affect the results. This period of reduction coincides with a cold decade recorded in the Tatra Mountains during the 1970s that was characterized by cold summers (Niedźwiedź 2004). Therefore, this could be a reason for the observed reduction in tree-ring width during this period.

Climatic interpretation of major positive pointer years

Among the four positive pointer years recorded for the Tatra cluster (i.e., 1931, 1950, 1957, and 1986), three were characterized by a very warm or warm May (i.e., 1931, 1950, and 1986, Fig. 5b). As mentioned, the Tatra Mountains are the highest part of the Carpathians and differ strongly from the lower parts due to their more alpine climate where tree-ring growth is more affected by temperature (Frank and Esper 2005). May temperatures are the most important climatic factor, but the positive relationship with June temperatures is also relevant (Danek et al. 2017; Büntgen et al. 2007; Ermich 1955). The remaining May (1957) was very cold but it was very warm during June; this may have compensated for the unfavorable conditions at the beginning of the growing season. For the years 1931 and 1950, an additional positive factor could have been the rather warm summers (Fig. 5b). In the year 1986, such an additional positive factor could have been the exceptionally warm April which facilitated an earlier start of the growing season as high temperatures can accelerate the onset of cambial activity (Rossi et al. 2007).

For the lower Carpathians, the similarities between the two widely observed positive pointer years (1961 and 1966) relate to the climatic conditions of the previous May (it was cold, or even very cold in 1966) and to the previous July, which in both cases was very cold. The previous summer months were also abundant in precipitation. The conditions during the year of tree-ring formation were also rather favorable in both cases. April was warm/very warm and July was very cold/normal, with normal or abundant precipitation (Fig. 5b). A dry September in 1961 may have acted as a climatic positive factor for cluster C2; a negative correlation with precipitation for this month was observed for sites in this cluster (Danek et al. 2017). The percent of sites in the C2 cluster which record this pointer year was 100%; whereas for the other two clusters is much lower (Fig. 3b). This supports the conjecture on the importance of September precipitation for the C2 cluster, as does the fact that similar climatic conditions occurred in September 1986, the other subregional positive pointer year of this cluster.

Comparison of extreme reactions between the Sudetes and the Carpathians

The pointer years observed for both the Sudetes and Carpathians (i.e., the trans-regional pointer years) are very infrequent. There are only two positive years (1966 and 1986) and one negative year (1980). The years 1966 and 1980 are the most prominent and both were observed in 36 of the 56 study sites (|Table 2, Fig. 3). The low number of trans-regional pointer years is most likely caused by regional climate differences. This effect is probably further enhanced by the local character of the larch climatic response caused mainly by the importance of precipitation (compare the results of Rolland 2002 obtained for southeastern French Alps). However, the larch responses to climatic forcing in these two regions are similar. The positive trans-regional pointer years (i.e., 1966 and 1986) coincide with wet and cold summers, especially during the previous year. This finding supports the previous results received for both regions of the climate–growth relationship studies (Danek et al. 2017, 2018). The observed response could be related to the negative effect of high temperatures on respiration, and the initiation of buds and fruit set; all of which could indirectly influence tree-ring growth in the following year, probably by affecting carbohydrate reserves (Oleksyn and Fritts 1991). It is also important to factor in the relatively high water requirements of larch (Oleksyn and Lorenc-Plucińska 1986; Olaczek 1986). Also, the remaining negative pointer year (1980) seems to be caused by the same climatic factor, i.e., an exceptionally cold growing season.

Only a few of the most prominent pointer years recorded in this study were observed in larches from other, more distant areas (e.g., Neuwirth et al. 2007; Vitas and Žeimavičius 2010;; Vitas 2015). Interestingly, the two most prominent negative pointer years observed in the Sudetes (i.e., 1992 and 1995) were observed in larches from Lithuania (Vitas and Žeimavičius 2010; Vitas 2015). It should be added that the climatic forcing of positive and negative pointer years recorded in Lithuania are mainly similar, e.g., the coincidence of negative pointer years with dry and hot summers, or a cold spring and summer, and the positive effect of a warm spring (Vitas and Žeimavičius 2010).

The relevance of observed extreme reactions to thermal and pluvial conditions in summer seems to be stronger in the Sudetes. Here the most commonly observed negative pointer years coincide with hot and dry summers of the previous year and/or the year of tree-ring formation. Hot and dry summers characterized the majority of negative

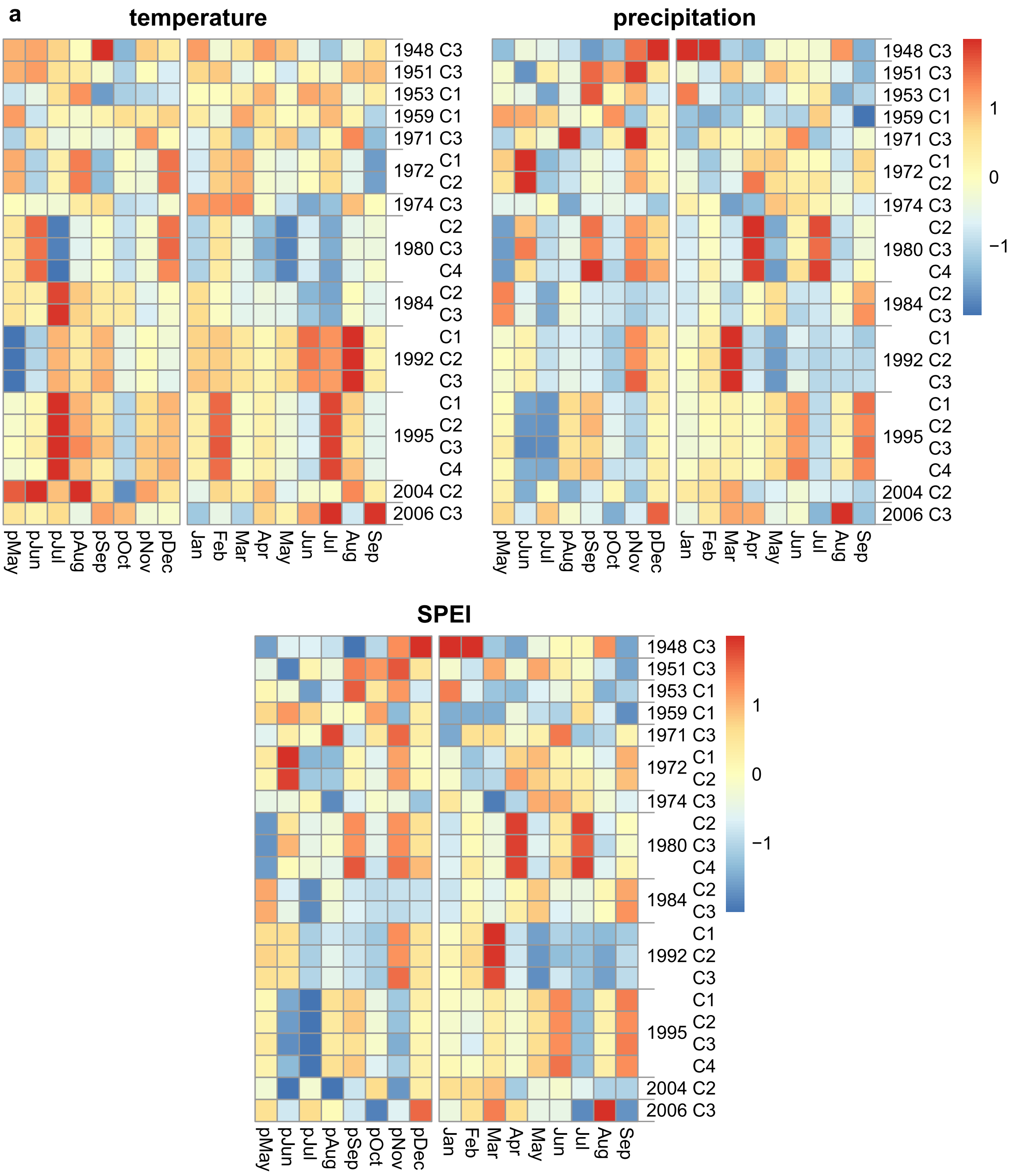

Fig. 4 The climatic monthly anomalies (i.e., temperature, precipitation, and SPEI for the period from the previous May to September of the year in which the tree ring is formed) for the Sudetes clusters pointer years presented in Table 2a: **a** negative pointer years, **b** positive pointer years. Colors represent the deviation from average values expressed in standard deviations

pointer years observed in Lithuania lowlands (Vitas and Žeimavičius 2010; Vitas 2015). The coincidence of extreme negative growth reactions with similar conditions was observed also for other conifer species growing at lower and medium altitudes of European mountain regions (Cejkowá and Kolár 2009; Neuwirth et al. 2004, 2007; Fischer and Neuwirth 2013; Rolland et al. 2000). Unlike in the Sudetes, drought-related pointer years were not observed at all in the Carpathians. This could be surprising, as the relationship between larch tree-ring growth and precipitation in the summer was found in both regions. However, a stronger relationship with previous summer climatic conditions was observed for the Sudetes tree-ring chronologies (Danek et al. 2018). It can be explained by differences in the climatic characteristics of these mountain regions, with less precipitation during summer being observed in the Sudetes (Błażejczyk 2006,

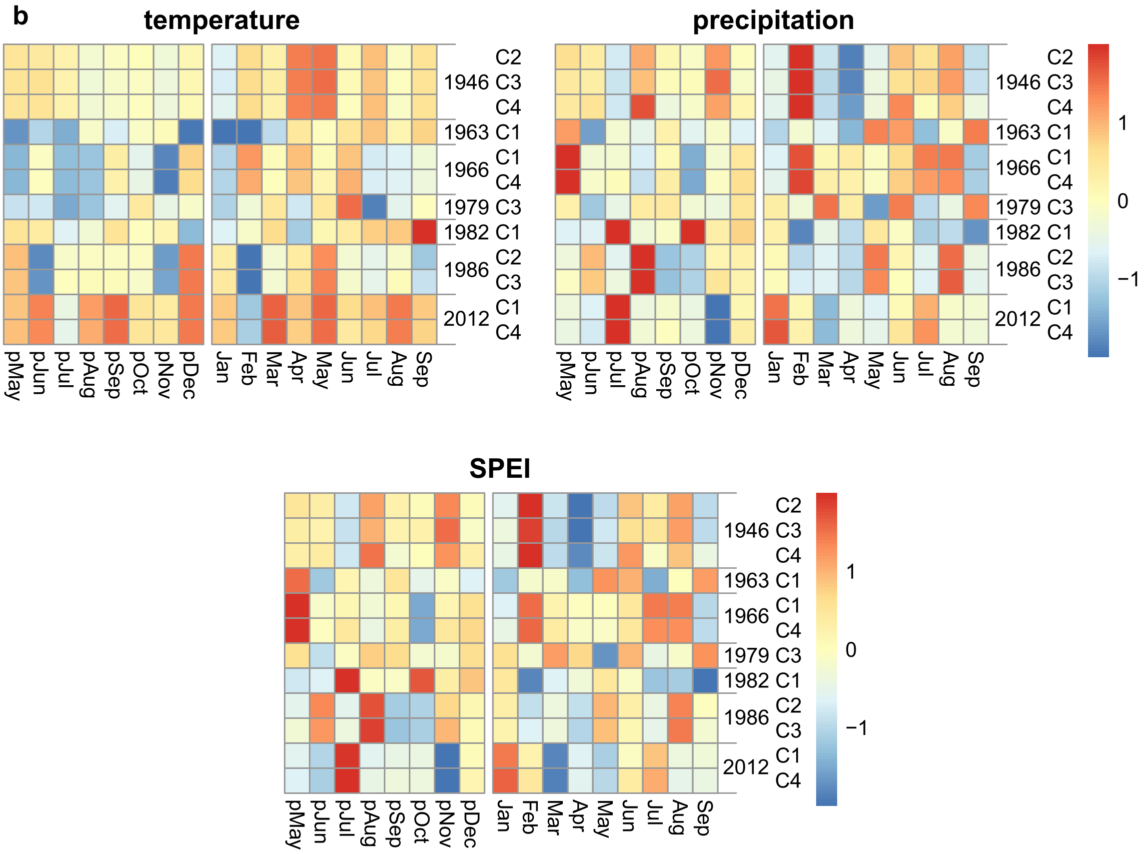

Fig. 4 (continued)

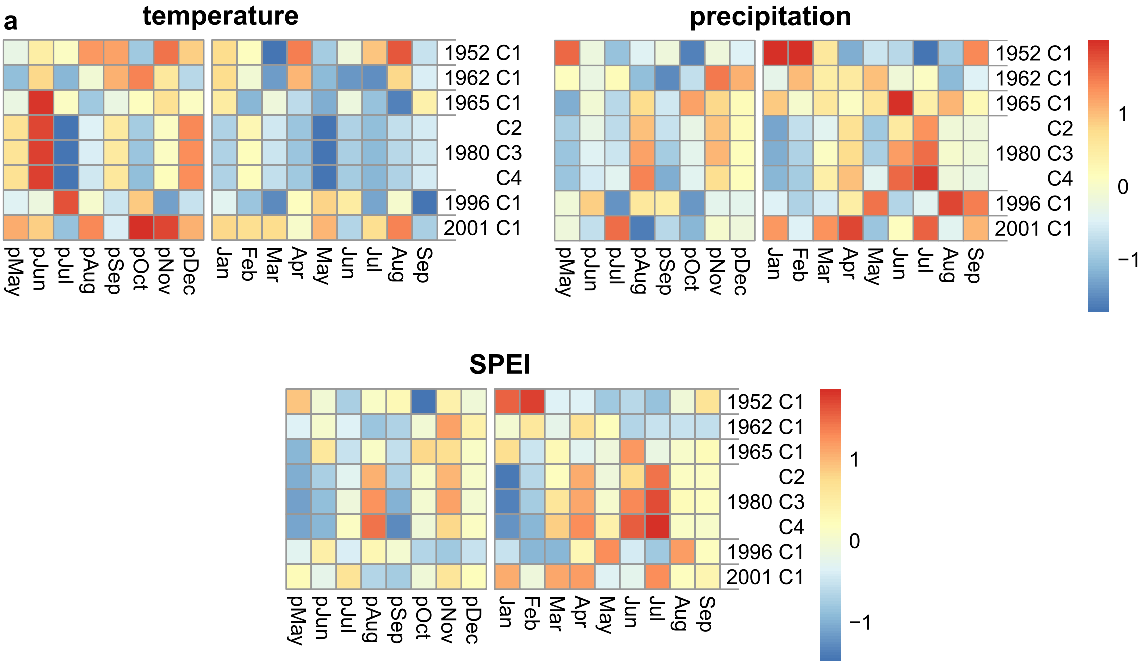

Fig. 5 The climatic monthly anomalies (i.e., temperature, precipitation, and SPEI for the period from the previous May to September of the year in which the tree ring is formed) for the Carpathians clusters pointer years presented in Table 2b: **a** negative pointer years, **b** positive pointer years. Colors represent the deviation from average values expressed in standard deviations

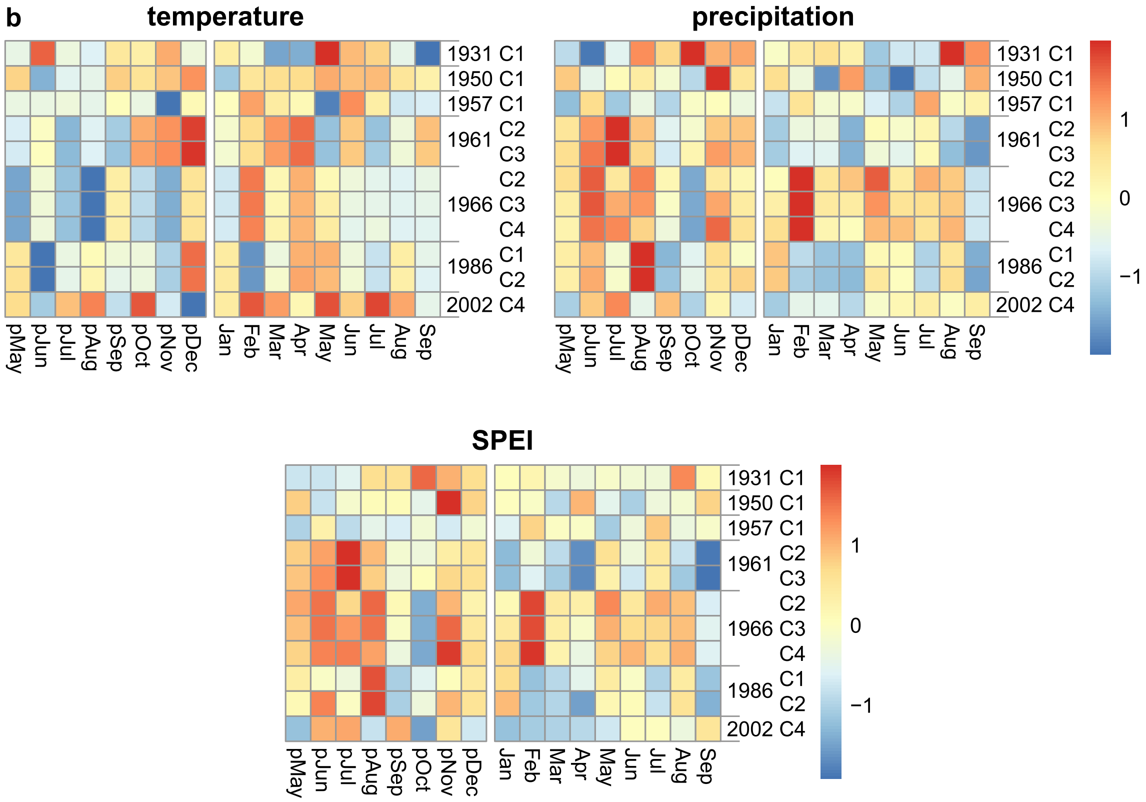

Fig. 5 (continued)

2019; Szwed 2019). In the light of the observed and predicted changes in climatic conditions in Poland, i.e., a further decrease in warmer season precipitation and an increase of "hot" extremes (Wypych et al. 2017; Graczyk et al. 2017; Szwed 2019), the currently obtained results suggest that the extremely negative responses in tree-ring growth will be more frequent in the Sudetes. However, the temperature is rising in the Carpathians much faster than in the Sudetes (Wójcik and Miętus 2014). The rising of maximum and minimum temperatures in the May–August period (Cheval et al. 2014) together with a strong decrease in the share of summer precipitation to annual precipitation (Szwed 2019, Fig. 5.) observed for the Carpathians suggest that extreme negative responses of a similar nature could be observed there in the near future.

The comparison of the extreme growth reaction pattern and possible climatic forcing of pointer years shows that the Tatra Mountains differ significantly from the lower Carpathians and the Sudetes. The relevance of pointer years to thermal conditions in the first part of the growing season is reflected in both positive and negative pointer years. This aligns with the more temperature-related growth of trees in high mountain environments (Tessier et al. 1997; Frank and Esper 2005) as precipitation is not a growth-limiting factor for larches in the higher locations of Central Europe (Carrer and Urbinati 2006; Büntgen et al. 2007).

In general, the results suggest that rather cold (or normal) and wet (or normal) early summer months (previous and/or tree-ring formation year) are optimal for the growth of larch at lower and medium elevations in the mountains of this part of Europe. According to Neuwirth et al. (2007), moderate, cool, and wet climate conditions during the growing season are optimal for the growth of Central European trees. The obtained results support this claim.

Table 2 Climatic interpretation of pointer years distinguished for particular clusters in the common period, 1931–2006: a) Sudetes; b) Carpathians

(a) Pointer year	Type	Sudetes—clusters				Climatic interpretation of pointer years
		C1 (9→6)	C2 (5→4)	C3 (2→2)	C4 (5→4)	
1946	Pos		✓	✓	✓ *	Very warm current April and May, summer rather wet (SPEI normal or very high)
1948	Neg			✓		Previous vegetation period warm and dry (low SPEI)
1951	Neg			✓		Very warm and dry previous June (very low SPEI), warm July; cold current May
1953	Neg	✓				Previous summer (July–August) very warm with low/very low SPEI; dry late winter-early spring, very dry end of the growing season
1959	Neg	✓				Dry winter-early spring, dry/very dry end of the growing season
1963	Pos	✓				Previous vegetation period rather cold, previous July abundant in precipitation
1966	Pos	✓			✓ *	Previous July and August very cold, November very cold; wet current summer (July and August SPEI very high)
1971	Neg			✓		Unclear, very warm November, dry current July
1972	Neg	✓	✓			Previous summer dry (July–August; very low or low SPEI); very dry/dry February, warm current July and dry current August
1974	Neg			✓		cold current May and very cold June-July
1979	Pos			✓		Previous vegetation season cold, warm current May, current June SPEI high, normal SPEI for subsequent summer months
1980	Neg		✓	✓	✓	Cold whole growing season with very cold April, May and July
1982	Pos	✓				Previous July cold and very wet (high SPEI)
1984	Neg		✓	✓		Very warm and dry previous July, very cold current June and July
1986	Pos		✓	✓		Very cold and wet previous June, July normal, wet August; very warm current May, current summer normal with wet August
1992	Neg	✓ *	✓	✓		Previous July warm/very warm and dry; current summer very warm and dry/very dry (drought of 1992)
1995	Neg	✓	✓	✓ *	✓	Previous July very warm and dry (drought of 1994), warm and dry current July
2004	Neg		✓			Previous June and August very warm and dry, warm previous July; current August very warm and dry
2006	Neg			✓		Very warm and very dry current July
2012	Pos	✓	no data	no data	✓ *	Very warm current May, very wet current July (for zd and ba sites—normal)

Table 2 (continued)

(b) Pointer year	Type	Carpathians—clusters				Climatic interpretation of pointer years
		C1 (3→2)	C2 (14→10)	C3 (10→7)	C4 (8→6)	
1931	Pos	✓				Very warm current May, warm current Jun and July, dry previous June
1950	Pos	✓				Very warm current May, warm current June and July
1952	Neg	✓				Very cold current May, very cold previous October
1957	Pos	✓				Very warm current June (however current May very cold)
1961	Pos		✓	✓ *		Cold previous May, very wet previous summer with very cold July, very dry and warm current April, normal (on prevailing area) precipitation in current July
1962	Neg	✓				Very cold current May, also current June and July very cold
1965	Neg	✓				Very cold current May, also current July and August very cold
1966	Pos		✓	✓	✓	Very cold previous May, very wet previous summer (on prevailing area) with very cold July, warm/very warm current April, current summer normal (but rather wet and cold)
1980	Neg		✓ *	✓	✓	Very cold whole growing season with exceptionally cold May
1986	Pos	✓	✓			Warm or very warm current April and May (positive for both clusters), very cold and wet previous June and very dry current September (positive for C2)
1996	Neg	✓				Very cold current July, current May very wet (however warm)
2001	Neg	✓				Very cold current June
2002	Pos				✓	Wet previous June and very wet previous July, very warm previous October, very warm current May, current July precipitation normal (but very warm July)

Cx(y→z): Cx cluster number, y number of sites in the cluster, z subregional pointer year criterion (see Sect. 2.2), * $z-1$ sites fulfill the pointer year criterion. Colors of the background of the rows: light red—positive pointer years, light blue—negative pointer years

Conclusions

It seems that the extreme growth reactions commonly observed in larch in the study area were caused by the complex influence of many climatic stimuli, but they were usually clearly related to those defined during the analysis of the climate–growth relationships. There were only three pointer years present both in the Sudetes and Carpathians; this is most likely caused by regional climate differences as the larch responses to climatic forcing in both these regions are similar. In general, positive pointer years are usually related to cold or normal and wet or normal conditions during previous and/or recent summers. In the lower Carpathians, a cold previous May, a warm April and a dry September could be additional positive factors, whereas in the Sudetes the factor could be a warm May. In the Tatra Mountains, climatic forcing of both positive and negative pointer years was different and was usually related to May temperature conditions. In the lower Carpathians, 1980 was the only negative pointer year that was widely observed. This year was also widely observed in the Sudetes with the same climatic forcing, i.e., a very cold vegetation season with an extremely cold May. Other negative pointer years in the Sudetes could be related to summer droughts of the current and previous year. The fact that more subregional negative pointer years are observed in the Sudetes and that they are associated with droughts supports the previous results that larches in the Sudetes are now more vulnerable to recently observed climate changes, and that extreme negative responses will be more frequent there in the future. Even if negative extreme responses of this nature are not widely observed in the Carpathians, similarities in the responses of larch in both regions and predicted changes in climatic conditions (i.e., a faster temperature increase in the Carpathians, and a decrease in summer precipitation), suggest that negative extreme responses will also be observed in the near future in the Carpathians.

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Data availability The data are available on GitHub: https://github.com/danek9/pointers-.git.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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