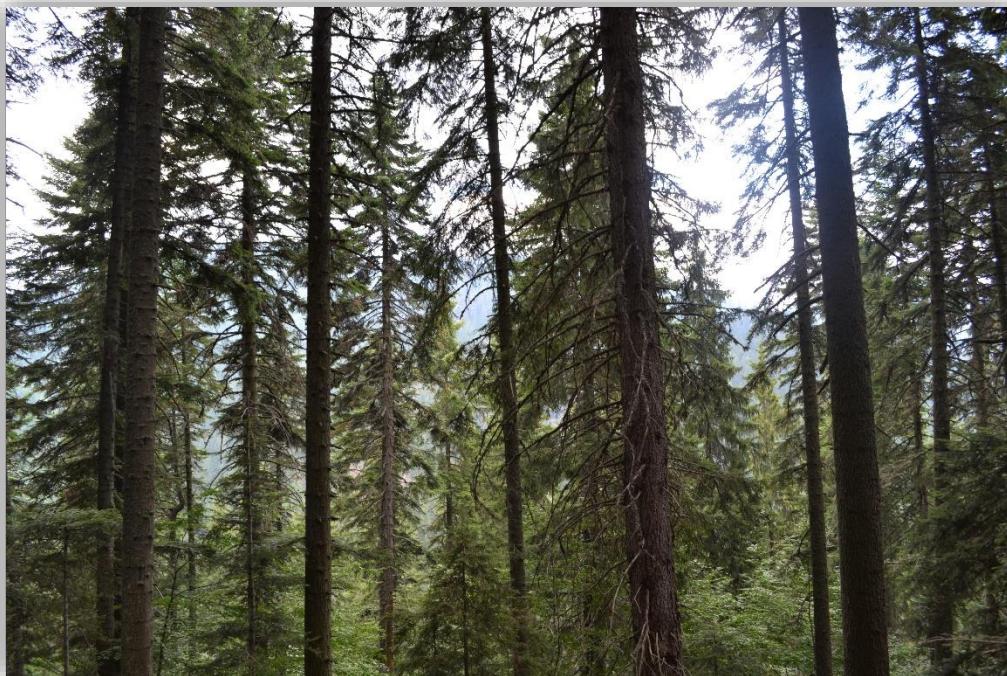


Master's thesis

CLIMATE-GROWTH RELATIONSHIPS IN MIXED FIR-SPRUCE STANDS IN
THE WESTERN RHODOPES, BULGARIA



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Cover image

Mixed fir-spruce (-beech) stand near Smolyan in the Western Rhodopes © Gerhard Schmied

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Abstract

In dendrochronological research the analysis of climate-growth relationships is of crucial importance. Within the last decade new methods for distinguishing temporal changing interactions between climatic factors and tree growth responses as well as for recognizing reactions to extreme climate conditions were introduced. However, in mixed mountain forests in the Western Rhodopes, dominated by Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.), the usage of those methods and the knowledge of growth dynamics and the influences of climate are still limited.

The study aims to describe the climate-growth relationships of fir and spruce trees at their southeasternmost geographical distribution range in the Bulgarian Rhodopes. In detail, this study concentrated on characterizing the forest stands, examining the influence of climatic parameters over time and showing the trees' response to years with extreme weather conditions. Core beams for dendrochronological analysis were obtained in four stands located in the regional forest district of Smoljan. The stands were consistent in climate, site condition and management regime. Competition, diameter breast height, stability, species and height of the cored trees were recorded. Stand characteristics were also assessed. In each stand, 15 to 20 vital dominant and co-dominant trees of spruce and fir for coring in stems were chosen. The radial growth dynamics of spruce and fir was analyzed retrospectively for the period 1958-2019. The climate-growth relationships were examined using CLIMTREG program based upon daily values of temperature, precipitation and relative humidity. Tree growth reaction to extreme episodes was described using the indices: resistance (inverse of growth reduction during the episode), recovery (growth increase relative to the minimum growth during the episode) and resilience (capacity to reach pre-episode growth levels).

The year 1987 was detected as the year in which both species showed a negative growth response on every site. Norway spruce reacted more sensitive towards the disturbance, whereas silver fir had a significantly higher resistance. The climatic data as well as observations from nearby regions revealed unfavourable conditions, in terms of strong late frosts and a very dry late summer, for growth in 1987. Further, it was found out that temperature in wintertime and in previous year July affected growth of silver fir, whereas temperature in spring determined the growth of Norway spruce. In consideration of water supply, early summer precipitation affected growth positively, whereas spring precipitation had a negative impact.

1. Introduction

1.1. Climate change, its impact on forest ecosystems and the possibility for assessment

In the 21st century the change of the world's climate system and the related anthropogenic influence is unequivocal. The cumulative emissions of greenhouse gases by the constantly increasing human population are the dominant cause for the global climate warming. Since the mid-20th century many changes in climate and extreme weather conditions have been observed (IPCC, 2014). The global mean temperature for oceans and land has increased 0.83-0.89 °C in comparison to the pre-industrial level. The land surface in Europe alone shows a rise of 1.5 °C since the pre-industrial age and over the past twenty years, Europe has suffered under several extreme summer heat waves and droughts, e.g. 2003, 2006, 2007, 2010, 2014, 2015 and 2018 (EEA, 2017; BURAS ET AL., 2020). Simulation studies prognosticate that those heat waves and meteorological drought events will most likely become more frequent, last longer and will be more intense (IPCC, 2014; BENISTON ET AL., 2007). Besides, shifts and changes regarding precipitation are observed and will continue to alter. The changes include an increase in winter rainfall and intensity in northern and central Europe (EEA, 2010) as well as a decrease in summer precipitation in the south (BENISTON ET AL., 2007). Further effects of climate change are alterations in hydrological systems (due to shifts in snowmelt and precipitation), wind speed, wildfires and within the ecosystem. Latter is particularly affected. Changes in climate reveal the vulnerability of certain ecosystems. Many species alter their geographical distribution range, abundances, seasonal activities or migration patterns (IPCC, 2014). Especially the mountainous regions of Europe are vulnerable, because they are considered as hotspots of biodiversity, are important for water supply and are expected to shift their species composition due to a changing climate (EEA, 2010; GONZALEZ ET AL., 2010). Furthermore, mountain areas are of high recreational value and are important for timber production. Hereby, the forests play a major role due to their protective functions. But these functions are affected by the global change (HOFER, 2005). In addition, the temperature rise in mountain regions is greater and the changes in precipitation exceed those in the lowlands (EEA, 2010).

Natural systems like the forest ecosystem are prone to climatic changes. The increasing frequency and intensity of heat waves, droughts and changes in water supply, for instance, are causing growth decline in trees (FRITTS, 1976) up to a dieback of thousands of hectares (ALLEN ET AL., 2010). More

frequent extreme weather conditions such as storms, forest fires or bark beetle infestations (MEYBECK ET AL., 2019) are the reason for the increase in disturbances throughout the 20th century (SCHELHAAS ET AL., 2003) as well as the 21st century (SEIDL ET AL., 2014). A further build-up is to expect (SEIDL ET AL., 2014; SEIDL ET AL., 2020). Besides, changes in habitat quality, diversity and carbon storage are linked to the climatic alterations (HANSEN ET AL., 2001; SEIDL ET AL., 2014). On a tree level perspective, alterations in physiology, reproduction and interaction between trees and the environment (e.g. pathogens) are likely (BUGMANN ET AL., 2014). The sensitivity to such changes depends on site conditions, species and stand structure amongst others (BABST ET AL., 2013; PRETZSCH ET AL., 2013; PRETZSCH ET AL.). Due to the fact, that the negative impacts on forests are threatening its ecosystem services on which approximately 1.6 billion people worldwide depend on (MEYBECK ET AL., 2019), it is crucial to have a deep knowledge about climatic changes and the response of forests to this alterations to be able to give recommendations for future forest management.

An established approach to assess the future suitability of tree species are retrospective studies (BOLTE ET AL., 2009). The field of dendrochronology is based on the concept of the annual tree ring, which can be described as a growth band in the xylem, formed once a year within a period of cambial activity (LAMARCHE, 1982). The rings are a result of varying physiological conditions throughout the year, whereas large, thin-walled cells are produced at the beginning of the growing season and small, thick-walled tracheid cells are formed at the end (FRITTS, 1976; LAMARCHE, 1982). Therefore, tree rings can be associated with certain calendar years and each ring can be interpreted as kind of an archive for a trees' response to environmental conditions. It is so to speak an integrating proxy for ecophysiological processes (FRITTS, 1976; SPIECKER, 2002; ZANG ET AL., 2011). The assumption is that trees of a same species and population share a common growth signal, respectively similar growth patterns (FRITTS, 1976). Hence, relationships between environmental conditions and tree growth, can be examined, for example, by comparing tree species with regard to different growth responses to climatic alterations. Especially the reaction to disturbances and extreme conditions, such as drought or frost events, in form of very narrow tree rings can be hereby of interest.

1.2.Silver fir and Norway spruce under climate change

Silver fir (*Abies alba* MILL.) and Norway spruce (*Picea abies* H. KARST) are considered as one of the most productive and demanded forest tree species in Europe. Economically, *Picea abies* is the most relevant conifer tree species in Europe (OECD, 2006; SPIECKER, 2003). Its natural distribution is mainly in the boreal and subalpine regions of central and northern Europe as well as Siberia, ranging from sea level up to above 2400 m in the central Alps (figure 1). But due to its eminent growth under very different site conditions, Norway spruce has been cultivated and spread outside its natural range in the past (CAUDULLO ET AL., 2016).

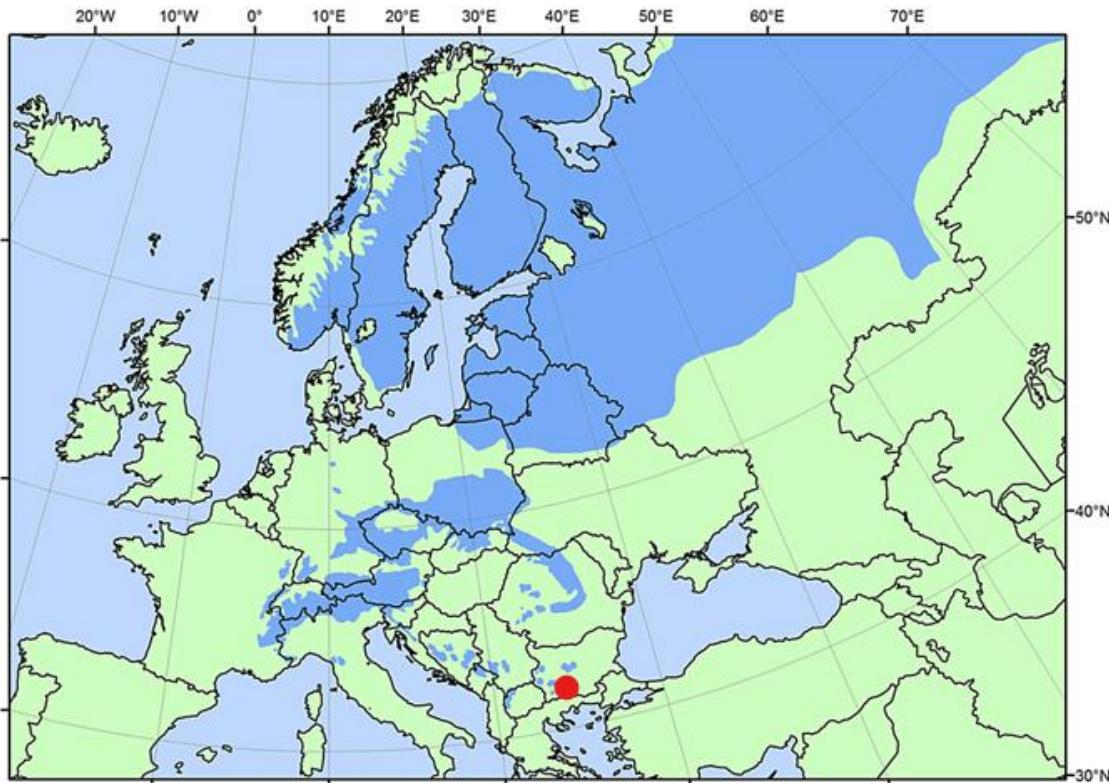


figure 1: Distribution map, showing the natural distribution of *Picea abies*. The red dot indicates the southeasternmost appearance of mixed fir-spruce stands, located in the Western Rhodopes, Bulgaria. Adapted from EUFORGEN (2009b).

The ecologically important silver fir on the other hand, is an indigenous tree species in the mountain forests of Europe. Its distribution ranges from the Pyrenees to the East Carpathians and from the Rhodopes to the Beskides in Poland (figure 2). *Abies alba* grows at a high altitude between 500-2000 m. The preferred site conditions are a deep and nutrient-rich soil as well as a relatively high moisture throughout the year, with a mean annual precipitation of approximately 700-1800 mm year⁻¹ (MAURI ET AL., 2016; EUFORGEN, 2009a; KONNERT & BERGMANN, 1995).

Temperature and precipitation are often limiting to tree growth. There are clear relationships to geographical locations, elevation and topography, amongst others (SCHWEINGRUBER, 1996). The relationship between climate and growth varies from species to species. Therefore, the response to climatic alterations also differs between the tree species, even if they occur in the same stand. For Norway spruce it has been observed that May and June precipitation is positively correlated with radial growth within the inner Alpine dry valleys (SCHUSTER & OBERHUBER, 2013). Further, temperatures of March, April, June and July have been noticed of being significant towards annual growth in the Tatra Mountains, Poland, whereas June and July temperatures got more important with an increase in elevation (SAVVA ET AL., 2006). A high sensitivity towards summer precipitation and temperature was also determined for Norway spruce throughout Bavaria (ZANG ET AL., 2011; DIETRICH ET AL., unpublished). The annual growth of silver fir corresponds positively to an increased winter, spring and early summer temperature at mid and high elevations. Very low temperatures in late winter and spring can lead to growth reduction. At lower elevations a higher influence of precipitation has been noticed in central Europe (LEBOURGEOIS, 2007; VITASSE ET AL., 2019).



figure 2: Distribution map, showing the natural distribution of *Abies alba*. The red dot indicates the southeasternmost appearance of mixed fir-spruce stands, located in the Western Rhodopes, Bulgaria. Adapted from EUFORGEN (2009).

In addition, the growth of the current year is often influenced by environmental conditions of the previous year, the so-called *physiological preconditioning* (FRITTS, 1976). These effects can have a huge impact on the potential of the current year growth (COOK, 1987). Development of drought resistance and frost hardiness, accumulation and storage of nutrients and capacity of photosynthesis are just a few examples to which the physiological preconditioning can have an impact on (FRITTS, 1976). Lingering climatic effects on current year growth of *Picea abies* has been observed throughout Europe. Especially late hot summer temperatures affected subsequent tree growth negatively (DESPLANQUE ET AL., 1998; BOURIAUD & POPA, 2009; ZANG ET AL., 2011; DIETRICH ET AL., unpublished). For fir, a previous summer with high precipitation was considered as favorable in central Europe (DESPLANQUE ET AL., 1998).

In general, the isohydric Norway spruce is considered as vulnerable to drought events and is therefore expected to be inferior to climate change, especially outside its natural distribution range (DESPLANQUE ET AL., 1999; SAVVA ET AL., 2006; KÖLLING, 2007; ZANG ET AL., 2011; HARTL-MEIER ET AL., 2014; ZANG ET AL., 2014; VITALI ET AL., 2017). In contrast, it is assumed that silver fir can benefit from a warmer climate if rainfall is sufficient. Especially in warmer winters and springs fir could thrive under these changing conditions and therefore be better suited for the future (KÖLLING, 2007; BOURIAUD & POPA, 2009; VITALI ET AL., 2017; VITASSE ET AL., 2019). Besides, it has been noticed that spruce responds in general stronger than fir to temperature within the growing season of both, the current and the previous year (BOURIAUD & POPA, 2009).

For silver fir, however, it is described that the species is susceptible to frost events. Especially intensive frosts in late spring are bad for growth (LEBOURGEOIS, 2007; LEBOURGEOIS ET AL., 2010; MAURI ET AL., 2016). But also severe frost events in January and February, can negatively influence the annual increment (SCHWEINGRUBER, 1996). In comparison, spruce is less affected (LEBOURGEOIS, 2007).

Mixing different tree species in a stand has proven to be a reasonable method for reducing the risk of damages and impact of disturbances, because of the improved resource supply, uptake, and use efficiency. This effect exists due to niche complementarity (PRETZSCH ET AL., 2012; PRETZSCH ET AL., 2013). In forests where fir and spruce are mixed or occur in mixture with other species, such as common beech, it has been observed that silver fir benefits from this situation in terms of growth. For Norway spruce, however, no positive mixing effect has been noticed (VALLET & PÉROT, 2011; PRETZSCH ET AL., 2013; VITALI ET AL., 2018).

Mountainous regions are particularly vulnerable to climate change (EEA, 2010). In such extreme environments, climate is often limiting tree growth (FRITTS, 1976), particularly at the upper tree limit, where the temperature of the growing season is considered for restricting growth (KÖRNER, 1998). Further, research showed, that tree ring growth at lower elevated mountain areas is correlated with precipitation, whereas at higher elevations temperature is the limiting factor (DITTMAR & ELLING, 1999; MÄKINEN ET AL., 2002). On the other hand, studies from the French Alps have shown, that cold-wet summers at high altitude, and summer aridity and winter frost in low altitude is limiting to tree growth (DEPLANQUE ET AL., 1999). This shows that the limiting climatic conditions cannot always be generalized and that other conditions may prevail from site to site. In comparison, spruce and fir are both susceptible to climate change at lower elevations (CARRER ET AL., 2010). Nevertheless, *Picea abies* is at all altitudes consistently less resistant and resilient to drought (HARTL-MEIER ET AL., 2014; VITALI ET AL., 2017). For this reason, among other things, there will be shifts in forest distribution and species composition. In some areas, it is expected that silver fir will replace Norway spruce as the dominant tree species (SCHUSTER & OBERHUBER, 2013; ZLATANOV ET AL., 2017). To prepare the European forests for forthcoming climatic alterations, the common aim of forest management is to reduce climate susceptible forest stands and replace them with stable mixed forests. Because of those silvicultural measures and increasing disturbances, a decline of spruce stands and an increase of fir stands can already be observed throughout central Europe (BMEL, 2012; FISCHER ET AL., 2014; BFW, 2019).

1.3.Aim of the study

As described before, for some parts of Europe several publications about the climate-growth relationships and reaction to disturbances of major tree species already exist. But there is a gap of knowledge in many other regions, for instance, the western Rhodope Mountains in Bulgaria. In this region, forests at lower elevations (1000-1450 m a.s.l.) are dominated by mixed stands, whereas at higher elevation level (1550-2100 m a.s.l.) spruce forests are common. There, mixed stands consisting of *Abies alba* and *Picea abies* reach their southeasternmost geographical distribution range (figure 1 & figure 2) (PANAYOTOV & YURUKOV, 2016; ZLATANOV ET AL., 2017). In the mountainside of south-eastern Europe, including the Rhodopes, an increase in extreme weather events and changes in climate has been observed over the past 20 to 30 years – the winters are less cold, the frequency and intensity of warm temperature extremes rise, summer dry periods last longer, and heavy rainfall events increase (ALEXANDROV ET AL., 2009; IPCC, 2014; ZLATANOV

ET AL., 2017; MARINOVA ET AL., 2017; PANAYOTOV ET AL., 2010; ZHELEV & ANEVA, 2019; PANAYOTOV ET AL., 2019). These changes are projected to induce a shift in the present forest tree species composition (ZLATANOV ET AL., 2017; PANAYOTOV ET AL., 2019). Possible would be a general decline of moisture-depending species (PANAYOTOV ET AL., 2019) or shifts from drought-sensitive species, like Norway spruce, towards more drought-tolerant ones, like scots pine or silver fir (ZLATANOV ET AL., 2017).

In conjunction with the forthcoming changes, the forests in the Western Rhodopes are confronted with an increasing social demand for forest ecosystem services which extend beyond the request for timber. The constantly increasing harvest intensity clashes with concerns regarding vulnerability and risks of these forests. The lack of knowledge of potential impacts of climate change on growth and species shift in the area intensifies this conflict (ZLATANOV ET AL., 2017). A field study was conducted in these stands to help to overcome the gaps of knowledge regarding climate-growth response, reaction to disturbances and regeneration dynamics. Latter was part of a second master thesis, conducted by AMBS (2020), which will not be further discussed here. The knowledge gained should contribute in the long term to a better understanding of the climate-growth relationships of spruce and fir trees in Europe and especially in the western Rhodope Mountains.

Hence, the present thesis addresses the following main questions:

- i) What are the characteristics of the mixed fir-spruce stands at their southeasternmost distribution limit?
- ii) How was the growth course of silver fir and Norway spruce over the past?
- iii) Were there any disturbing events in the past and if so, were they drought induced?
- iv) Are there any differences between spruce and fir regarding the growth response to disturbances?
- v) What is the relationship between the climate and the growth of fir and spruce in the Western Rhodopes?
- vi) Which climate parameters in what time periods determine tree growth in the Western Rhodopes?
- vii) How will climate change most likely influence these forests?

2. Methodology and materials

From 15th August until 14th September 2019 the field study for this thesis was conducted in mixed mature fir-spruce stands at two areas in the south of Bulgaria in the Western Rhodopes. Within the two areas four sites were chosen for research. Every site consisted of 25 (30) subplots, where several information was acquired. The working procedure in the field comprised gaining general information about the stands, recording regeneration dynamics and coring trees for the dendrochronological analysis. For the latter, the sampled tree cores were prepared and measured in the tree ring laboratory of the *Bayerische Landesanstalt für Wald und Forstwirtschaft* (LWF) in the period from November to the end of December 2019. Afterwards, the acquired tree ring data was statistically analysed, and climate-growth relationships were examined. In the following section, the precise method behind this master thesis will be explained extensively.

2.1. Study area

2.1.1. Selection of the study region

Mixed stands of silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) H. Karst.) are reaching their southeasternmost geographical distribution range in the Western Rhodopes, Bulgaria. Due to the fact, that only little is known about the climate-growth relationship as well as the natural regeneration dynamics, this region was chosen for this study. Besides, for obtaining satisfactory results regarding dendroclimatic research it was advantageous to be near the margin of the distribution range of those species. That's because there, species often occur only on a small variety of sites where climate is much more likely to be limiting to growth and other physiological processes (FRITTS, 1976). In more detail the study area is located 100 km south of Plovdiv near the village Pamporovo and the city Smolyan. The precise location is mapped in figure 3.

2.1.2. Site selection

As illustrated in figure 3 four sites were established in the course of the field work. Those sites were not randomly chosen in the area and had to fulfill several requirements to be selected. The selection of similar sites seems to be contrary to the concept of random sampling in statistics but is necessary to reduce variation of the limiting factors and to get useful replications for enhancing the desired signal (SCHWEINGRUBER ET AL., 1992; LAMARCHE, 1982). Homogeneity between the

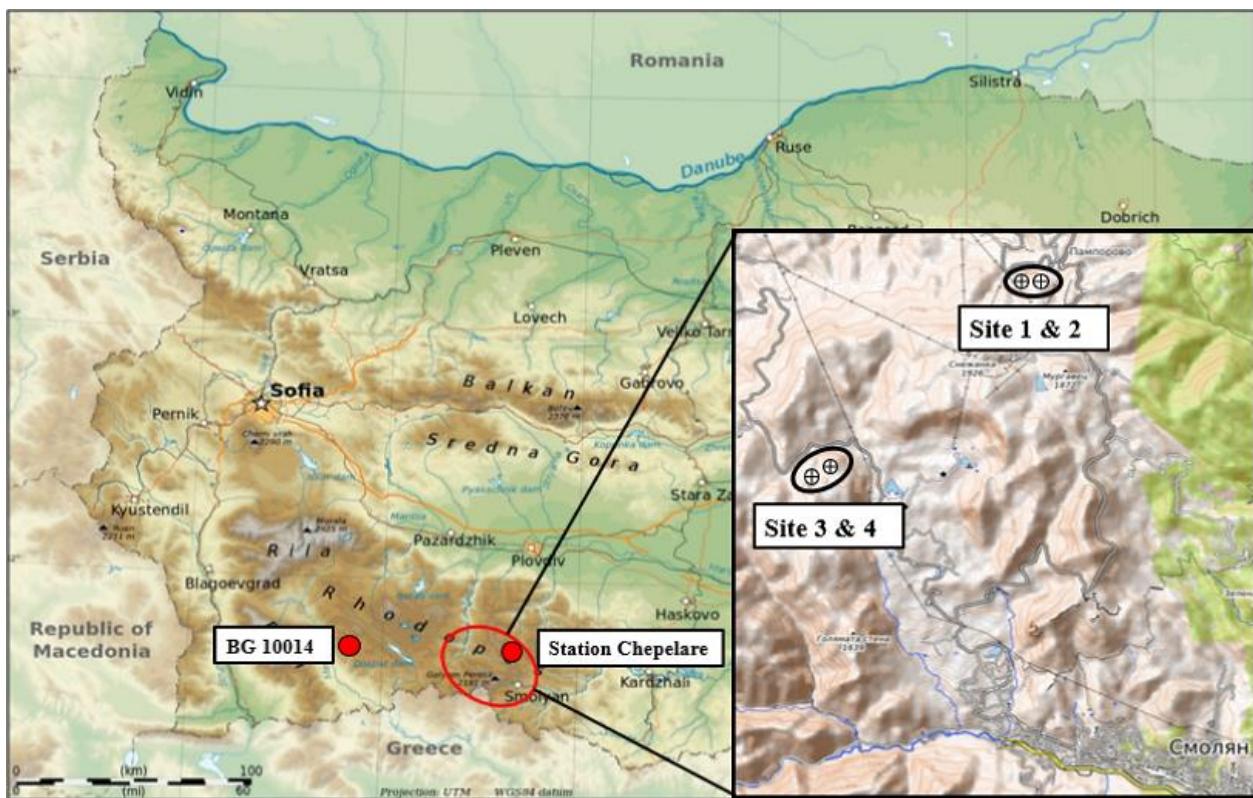


figure 3: Map of Bulgaria with marked locations of the research sites as well as the location of the climate station in Chepelare and gridpoint BG 10014, from which the daily climate data was acquired (MOUNTAIN FORECAST, 2020; ONTHEWORLDMAP, 2020).

sites is considered as major for the study quality (SCHWEINGRUBER ET AL., 1992; SCHWEINGRUBER, 1996). First, high priority had the tree species composition. The stands had to be dominated by silver fir and Norway spruce trees, whereas the less occurring species had at least 10-20 % coverage. Those stands were found around an elevation of 1500-1600 m above sea level, which is the typical range for spruce-fir stands in that area. In the Rhodopes, 1600 m a.s.l. is considered as a threshold for the occurrence of spruce forests. Above that level, pine trees get more and more dominant. It was determined, that the selected stands were aligned in northern exposition (north, north-west, north-east) and that the soil consisted out of the same parent rock material. In case of this study, all stands were on rhyolite and never on limestone, which is the other common parent rock material there. Furthermore, to enable climate-growth analysis for a long period, no young stands with an age under 50 years were allowed. Forest management activities are very present in the region, because of high demand of the local population. This plays a major role for regeneration dynamics and tree growth, so it had to be considered that the same kind of silvicultural treatment was applied on the sites. The stands at the study sites were treated with single tree selection and forms of group shelterwood. To prevent falsification of regeneration results, recent forest

management activities (< 10 years) were forbidden. The region around Pamporovo is in Bulgaria famous for wintersport, especially skiing. Thereby associated ski-lines influence the water regime of forests and stands, which were close to them, were excluded. As a final requirement, to guarantee an observable workload, it was necessary, that the stands were quite easily accessible.

2.1.3. Tree selection

For analysing climate-growth relationship in the course of dendroclimatology, the selection of the trees to be sampled is crucial. SCHWEINGRUBER (1996) states that the sampling depths (=replication) is one of the main factors influencing the quality of a study. The number of trees to be cored per site depends on tree species, region and site conditions (FRITTS, 1976; MÉRIAN & LEBOURGEOIS, 2011). In general, the higher the number of the cored trees, the lower is the standard error of the resulting mean chronology and increases the climatic signal within (FRITTS & SWETNAM, 1989). SCHWEINGRUBER (1996) recommends coring a minimum of 15-20 trees per site and species, twice. MÉRIAN & LEBOURGEOIS (2011) mention that 20-30 trees are usually cored under temperate climate but can be reduced to under 10, depending on sites where one factor is limiting. This is concordant with findings by SCHWEINGRUBER ET AL. (1992). The *expressed population signal* (EPS), a statistic which will be described later, can also give information about the appropriate sample depth (SPEER, 2010). In dendrochronology only trees of the same social position should be merged together into one site chronology. For climatic studies, especially in closed-canopy forests, the social position should be dominant or at least co-dominant. By doing so, influences of competition are reduced, even though not excluded (SCHWEINGRUBER ET AL., 1992). SCHWEINGRUBER ET AL. (1992) mention to core every tree twice to respect the variability within a tree. Further, they recommend to core only vital trees and to avoid reaction wood by drilling rectangular to the slope direction.

In consideration of the quoted findings above, for this thesis, 17-20 (co-) dominant, vital trees per site and species were cored twice, rectangular to the slope and in opposite direction to each other. To achieve a more random, evenly distributed sampling procedure within a site, on every established plot, the surrounding fir and spruce trees were checked regarding their suitability for coring. Only if both, one suitable fir and spruce, were present within a radius of 15 m, sampling was carried out. An additional condition was that the sample trees on a plot had to be at least 10 m apart to avoid competing influences between them. The suitability for sampling was checked for

every tree by evaluating the vitality, stability, competition and social status. Later, this will be described in detail.

2.1.4. Climatic conditions

The Western Rhodopes are characterized by a subcontinental to continental climate. Distinctive for this type of climate are the strong and cold winters with a precipitation maximum during the early summer. The late summer, however, is often comparatively dry (HORVAT ET AL., 1974). Like in many mountainous areas in South-Eastern Europe, shifts in climate and an increase of the frequency of extreme weather events have been noticed over the past two decades (ALEXANDROV ET AL., 2009).

To describe the climatic conditions on the research sites in more detail, monthly temperature and precipitation data were gained for the period of 1930 to 2019 from local climate stations. The data was obtained from the *Bulgarian Academy of Sciences* (BAS) by the *Swiss Federal Institute for Forest, Snow and Landscape Research* (WSL). From 1930 to 2013 a station in Pamporovo delivered the data, while from 2014 to 2019 the climate data from a station in Chepelare were used. The sampling plots were 1-15 km away from the stations. A Walter-Lieth graph shows the

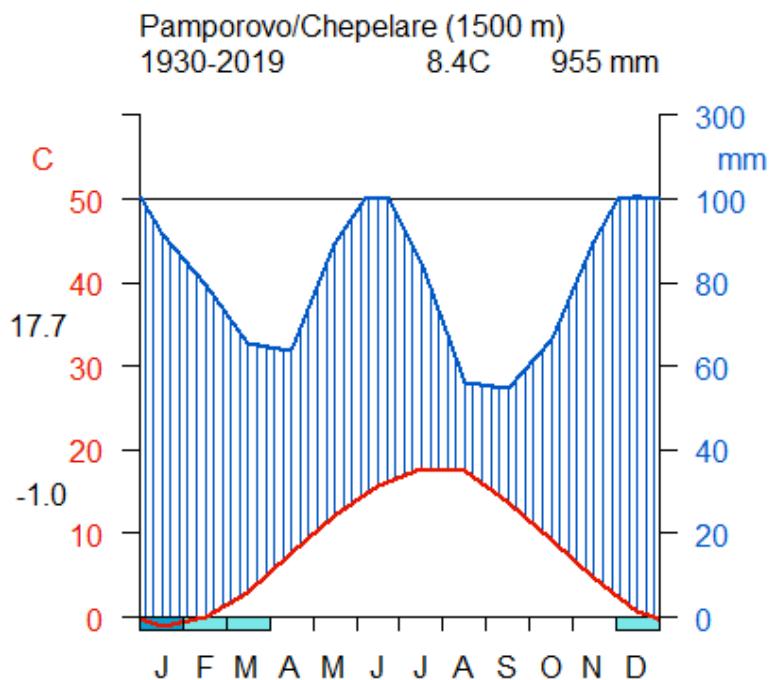


figure 4: Walter-Lieth graph of the climate station Pamporovo/Chepelare near the sampling plots.

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meteorological data in figure 4. The annual average temperature for the region is 8.4 °C and the average precipitation sum is 955 mm/year which leads to a mild climate.

The winter month December, January and February are quite cold, frost events can occur, and high precipitations are measured. The heavy snowfall in this period is the reason why the region is famous for skiing and other winter sports. January is the coldest month with an average of -1 °C. Contrary to that are the month June, July and August which are the warmest. Its peak getting reached in July with a mean temperature of 17.7 °C.

In consideration of precipitation distribution over the year it is distinctive that there are two peaks with high precipitation. One is, as already mentioned, during the winter month December and January, while the second one is in June. The lowest values of average monthly precipitation were observed in March/ April and August/ September. Those observations were also confirmed by locals, like the former forest director, who also mentioned that, from time to time, there are years where basically close to no rain is falling in August and/ or September. Furthermore, the climate data revealed that there were years like 2013 (0.2 mm precipitation in August) or 1992 (9.0 mm in

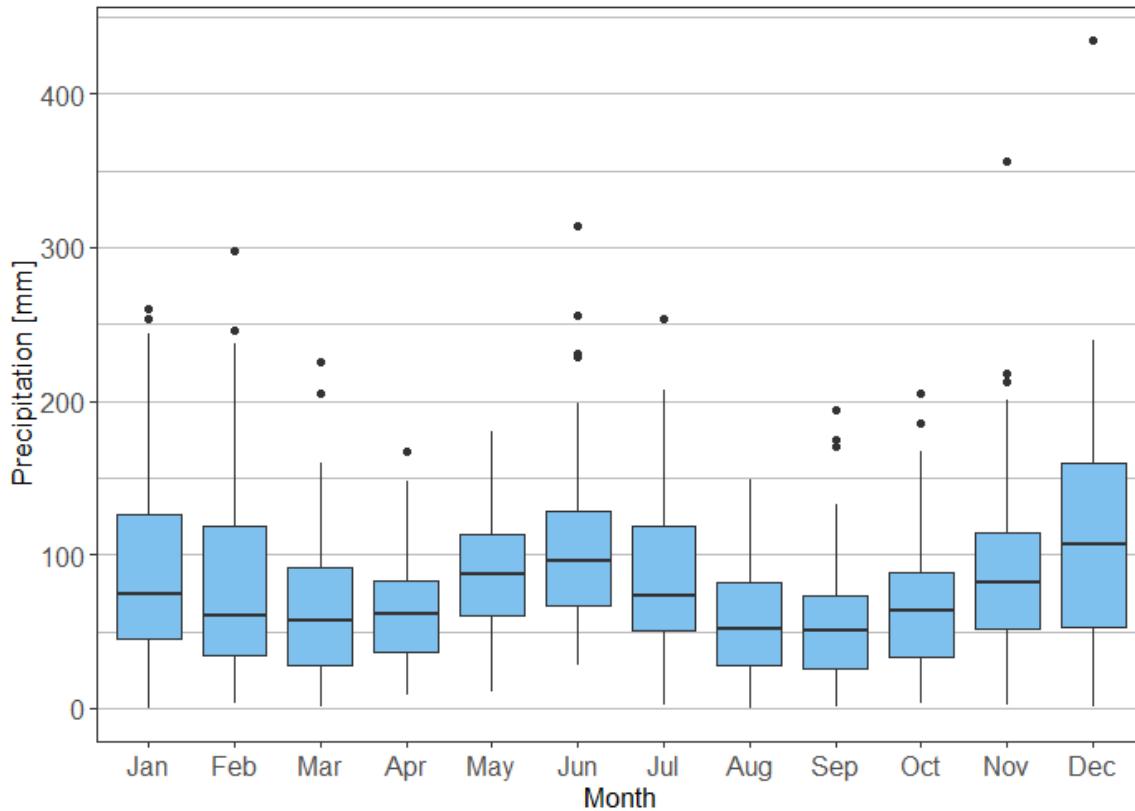


figure 5: Monthly average precipitation fluctuations in the period 1930 to 2019 represented by box-whisker plots.

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August and 3.2 mm in September) with extreme low values. A closer look to the precipitation data reveals that the monthly average precipitation fluctuation differs from month to month (figure 5). The strongest fluctuations and highest average precipitation (\varnothing 109 mm) are in the month December, whereas September has the lowest fluctuation and average precipitation (\varnothing 54.9 mm). In most of the months very low precipitation can occur. Except for June, where it was never recorded that the precipitation dropped under 30 mm/ month.

Of further interest is the temperature development in the study area. Therefore, the course of the temperature is illustrated in figure 6. It is recognizable that the annual mean temperature fluctuates strongly from time to time. Mentionable is the relatively cold period in the seventies. From then on, the mean annual temperature seems to increase continuously. Over the entire observation period an increase of the annual mean temperature can be noticed.

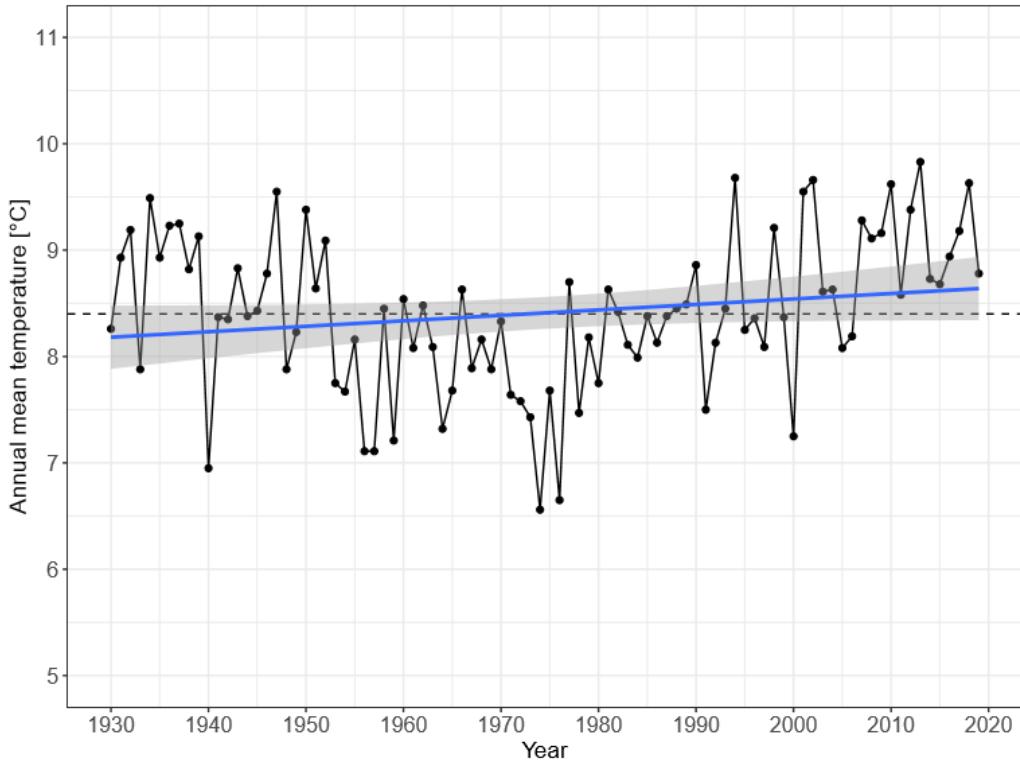


figure 6: Course of the temperature development in the period from 1930-2019. Climate data is obtained from the climate stations from Pamporovo/Chepelare. The black line indicates the course of the mean temperature, while the dotted line shows the long-term average. The blue line shows the long-term trend and is surrounded by a grey zone, which indicates the 95 % confidence level interval.

2.1.5. Soil

For the description of the growing conditions of the trees, next to the climatic conditions, the soil is important. The Western Rhodopes are a truncated upland in the south of Bulgaria and consist of acid as well as alkaline vulcanite. Prevalent parts of the Rhodopes were formed in the Mesozoic era and were part of the alpine orogenesis. Common rocks are rhyolites and gneisses, but also limestones occur in some areas. As already mentioned, the research sites were only chosen on rhyolite to enable homogeneity. On this parent rock material typical soils are brown mountain forest soils (HORVAT ET AL., 1974). Due to the soil unit description of the FAO (2006), SHISHKOV & KOLEV (2014) assign humid and dystric cambisols to the area. This is concordant with findings from this master thesis and the one carried out simultaneously by AMBS (2020), where all soils were identified as cambisols. The organic layer was, depending on the location, characterized as duff or mildew. Further, the soils were skeletal. The soil thickness fluctuated from plot to plot. Some of the plots had a quite shallow soil with a thickness of ≤ 30 cm (22 %), whereas others showed a soil thickness > 60 cm (27 %). According to SHISHKOV & KOLEV (2014) Bulgarian mountainous soils with hard parent rock material, like rhyolite, have commonly a shallow soil. But in general, brown forest soils are associated with favourable physical properties and show high soil aeration and water movement (SHISHKOV & KOLEV, 2014).

In conclusion it should be noted that the mild climate with occasionally high precipitation and the good physical properties of the soil are beneficial for trees like Norway spruce and silver fir, but very shallow sites and a long-term changing climate have the potential to get problematic for tree growth.

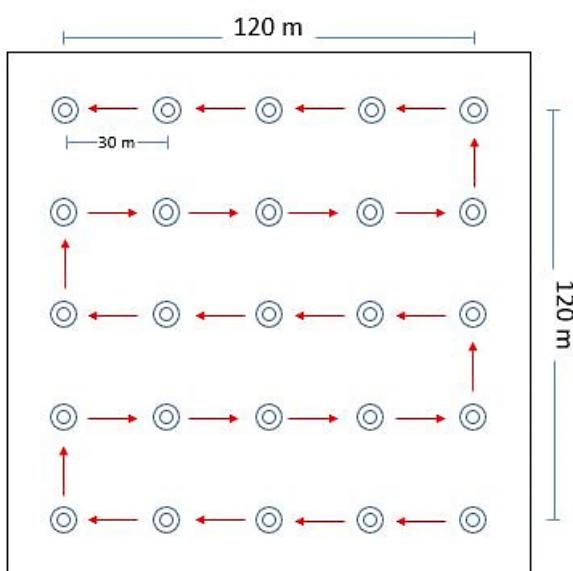
2.2. Plot design description

Each of the four sites consisted of 25 plots. An exception was plot 1, which comprised 30 plots. To guarantee random sampling within the site, the plot positions were set in the same distance of 30 m to each other. The plots were arranged in a 5x5(6x5) grid, but adjustments due to environmental conditions were allowed, if necessary. So, every site ranged over 1.44 (1.8) hectares and in total 105 plots were established. Every plot on the other hand was subdivided into a big circle, a small circle and, if applicable, two trees for coring, including additional circles for measuring competition. The detailed sample site and plot design is mapped in figure 7. Within the big circle ($=100$ m 2) the general stand information was obtained. Therein every tree with a diameter in breast

height (dbh) > 8 cm was gauged with a girth measuring tape and the tree species was identified. Also, the size and the amount of dead wood, as well as gaps in the canopy were determined. Furthermore, the characteristics of the environment, means the exposition, inclination and the stoniness were registered. While the stoniness and the gap size in the canopy were estimated, the exposition was determined with a Suunto KB-14 (SUUNTO, 2020) and the inclination with the Vertex IV ultrasonic hypsometer (HAGLÖF SWEDEN, 2020).

The small circle (25 m^2) contained recordings regarding vegetation, regeneration, shoot growth and solar radiation amongst others. This part of the methodology will not be explained further here, due to the fact, that it is content of the second master thesis, published by AMBS (2020). The third and last part of the plot got formed by the dendrochronological part. As described in the previous chapter, one silver fir and one Norway spruce, if applicable, were examined. To this, the dbh, height and crown length were measured. Further, the trees, which compete for resources with the sample trees within a radius of 10 m (314 m^2), were analysed. For those trees, the species, dbh, distance and the angle to the sample tree was determined.

Sample site design



One plot consisting of:

- Big circle ($100 \text{ m}^2 / r = 5.64 \text{ m}$):
 - Dbh all trees (> 8 cm)
 - Dead wood (> 8 cm)
 - Gap (Size, age, overlap)
 - Stoniness, exposition, inclination
- Small circle ($25 \text{ m}^2 / r = 2.84 \text{ m}$):
 - Solar radiation
 - Gap (Size, age, overlap)
 - Ground vegetation
 - Regeneration (species, number, height class)
 - Shoot length (2x per species)
 - Soil (organic layer, depth, stoniness)
- Trees for coring (17-20 trees per species and site):
 - Sample trees (dbh, height)
 - Competing trees (species, dbh, distance, angle) and tree stumps (age, diameter, height, distance, angle) within radius of 10 m (314 m^2)

figure 7: Detailed sample site and plot design. The arrows indicate the workflow direction during the field recordings

2.3. Assessment of the general stand information

To enable classification of the research stands, to verify the homogeneity and to show possible differences for the discussion of the results, general information about the stands, which are common in applied forestry, were gained. By measuring the dbh (1.3 m) of all trees within the 100 m² circle, a computation of the basal area (m²/ha) was possible. In addition, the tree species composition and their corresponding basal area were identified. Based on dbh, tree height and age estimations the site classes were determined using yield tables. For classifying *Picea abies* the yield table according to ASSMANN & FRANZ (1990) was used, while the yield table by HAUSSER (1990) delivered the grading for *Abies alba*. Those yield tables are based on pure stands in Germany (STMELF, 1990) and therefore their application on mixed fir-spruce stands in the Western Rhodopes are limited, but due to missing similar counterparts in Bulgaria, they are applied for classification and comparison.

As already mentioned, also the inclination and the exposition were measured. Hereby it was the focus to ensure homogeneity between the stands and plots. It was specified that only plots with northern exposition were allowed for sampling.

2.4. Assessing information for dendrochronological research

2.4.1. Description of the cored trees

2.4.1.1. Vitality and stability of the trees

For the selection, which fir and spruce should be cored and the verification how stable and vital each of them were, several factors were measured. First the vitality was inspected by controlling if the trees were healthy and hadn't any scars, top cracks or other signs of damage that indicate that the tree could be rotten inside or strongly influenced by other factors than climate. Besides, the live crown ratio [%] was checked. The live crown ratio results from the proportion of crown length to total height of the



figure 8: Vertex IV ultrasonic hypsometer (HAGLÖF SWEDEN, 2020) in use. The display shows the angle as well as different height measurements.

sampled tree. For the measurements, the Vertex IV ultrasonic hypsometer (HAGLÖF SWEDEN, 2020) was used (figure 8).

Next to the crown ratio an applied value in forestry, to make a statement about stability, is the h/d-ratio, describing the relation of the height to the diameter in breast height. The height data was already given by the crown ratio measurements, whereas the diameter was examined with a girth measuring tape at 1,3 m. Referring to MAYER (1984) and ABETZ (1976) a h/d-ratio < 60 is graded as very stable. Whereas values from 60-80 are classified as stable and > 80 are comparatively unstable. In general, the relative crown length (crown ratio) is linked with the h/d-value. A higher crown ratio results in a lower h/d-ratio (FREISE, 2005).

2.4.1.2. Social status and competition

The social status of each sample tree was ranked by the concept of *Kraft'sche Klassen* (KRAFT, 1884), which is illustrated in figure

9. Only dominant (class 1) and co-dominant (class 2) trees were considered for sampling. Further, the competition of the trees, which is highly linked to the social status, was evaluated. The competition a tree is exposed to, results from the distance and dimension from the competing trees. Based on this insight, the *Iterative Hegyi's competition Index* (CI) can be calculated for estimating competition (GADOW, 2003). The biological significance is assumed to be high (MAILLY ET AL., 2003). The equation for the calculation of the Hegyi-Index is as follows (VITALI ET AL., 2016; GADOW, 2003):

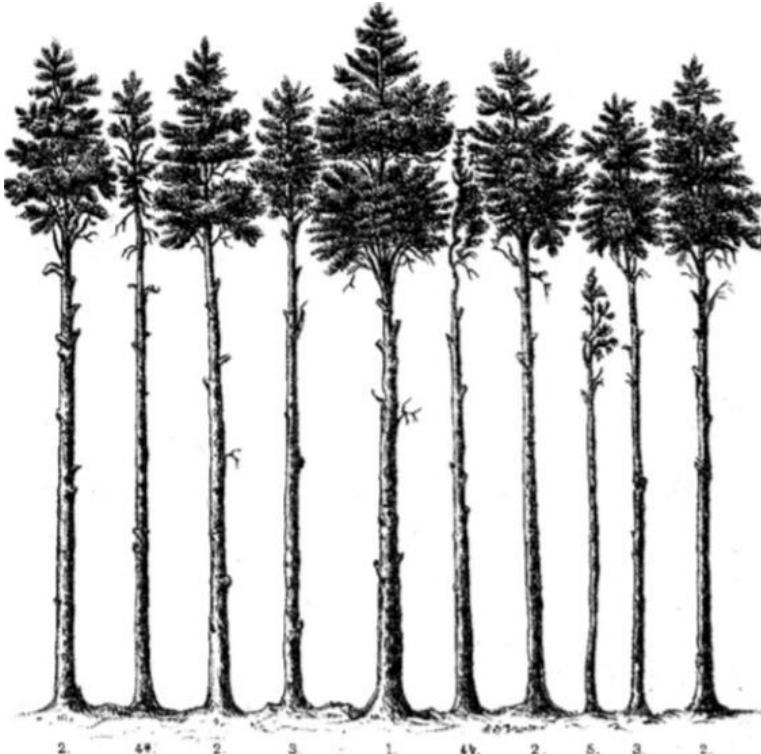


figure 9: The tree classification according to KRAFT (1884) resulting from the competition for resources. The classification ranges from dominant trees (1) down to dying individuals (5), which depends on tree height and crown size (PRETZSCH, 2019).

Equation 1

$$CI_i = \sum_{j=1}^n \frac{d_j}{d_i} \times \frac{1}{Distance_{ij}}$$

whereas CI_i is the competition index for tree i , n is the number of competing trees, d_i is the dbh of the target tree and d_j is the dbh of the particular competing tree. Hence, larger and closer trees contribute more to competition stress. The higher the value for CI_i is, the higher is the competitive stress for the tree. Every tree within the radius of 10 m and a dbh over 8 cm was considered as a possible competing tree and was therefore measured.

2.4.2. Tree sampling

The procedure of gaining increment cores from trees, including the technique of coring and the maintenance of the increment borer, is exemplified by GRISSINO-MAYER (2003) and was respected during field work. All trees, which were selected for dendroclimatic analysis, were sampled twice. To reduce influences of reaction wood, the increment cores were taken perpendicular to the slope direction. Due to the northern exposition of the sites, the cores were therefore taken from western and southern position at 130 cm height (dbh). Conditioned by the steep and diverse terrain, the height of the coring varied to a certain, negligible extent. The core beams were taken with two Haglöf increment borers with a core diameter of 5 mm (HAGLÖF SWEDEN, 2015). Depending on the diameter of the tree, the used borer was 30 cm or 40 cm long. Increment cores were stored in paper straws, which were sealed and labelled. Every core beam was distributed with a unique number for identification. The ID consisted of six components and are listed below (see also figure 10):

- 1. region (R for Rhodopes)
- 2. site number (1-4)
- 3. plot number (1-30)
- 4. tree species (Fi = *Picea abies*; Ta = *Abies alba*)
- 5. core beam number (1-20)
- 6. a/b for drilling position (a = west; b = east)

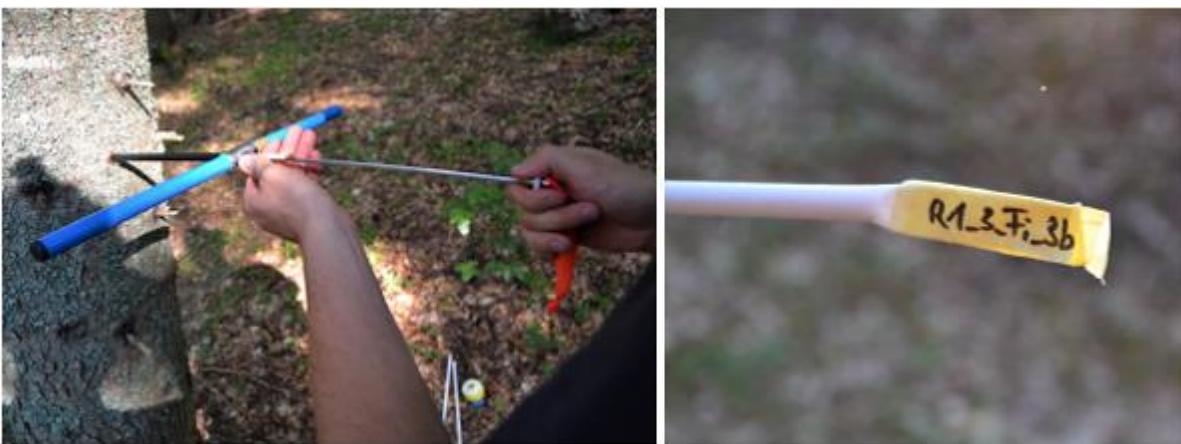


figure 10: On the left- extracting a core beam from a cored Norway spruce using the Haglöf increment borer. Right side- example of a sealed and labelled increment core.

2.4.3. Core beam preparations and measurements

After the sampling in the field it is necessary to prepare the surface of the increment cores before measuring to increase the visibility of the tree rings. The increment cores were air-dried and cut with the core-microtome developed by GÄRTNER & NIEVERGELT (2010). This method was favoured over the common sanding procedure due to better results regarding visibility. The increment cores were cut with the sharp blade of the microtome in a 90° angle to fiber direction (see figure 11). To facilitate the cutting process water was spread over the surface of the core (SCHWEINGRUBER, 2012). Afterwards, the processed cores were stored in a wooden frame.

Next, the ring widths were measured to the nearest of 1/100 mm with LINTAB 5 (RINNTECH, 2013) measuring table and the software TSAPWIN 4 (RINNTECH, 2012). For missing rings, the value 0.01 mm was entered for easy identification. Further, visual crossdating was performed with the help of respective site samples of easily measurable increment cores. The two measured ring width series from every tree were merged into one series, which represents the particular tree. The files, containing the ring width measurements, were stored in Heidelberg format (.fh). For analysis programs R STUDIO (R CORE TEAM, 2018), POINTER (BECK, unpublished) and CLIMTREG (BECK ET AL., 2013) were used. Further visualization, computation and statistical analysis was done with the packages dplR (BUNN, 2008), dplyr (WICKHAM ET AL., 2020), multcomp (HOTHORN ET AL., 2020), car (FOX & WEISBERG, 2020), ggplot2 (WICKHAM, 2016), RColorBrewer (NEUWIRTH, 2015), gridExtra (AUGUIE, 2017), climatol (GUIJARRO, 2019) and SPEI (BEGUERÍA & VICENTE-SERRANO, 2017) for R STUDIO (R CORE TEAM, 2018).

The preparation of the increment cores, as well as the microscopic measurement of the ring width was executed in the tree ring laboratory of the *Bayerische Landesanstalt für Wald und Forstwirtschaft* (LWF).

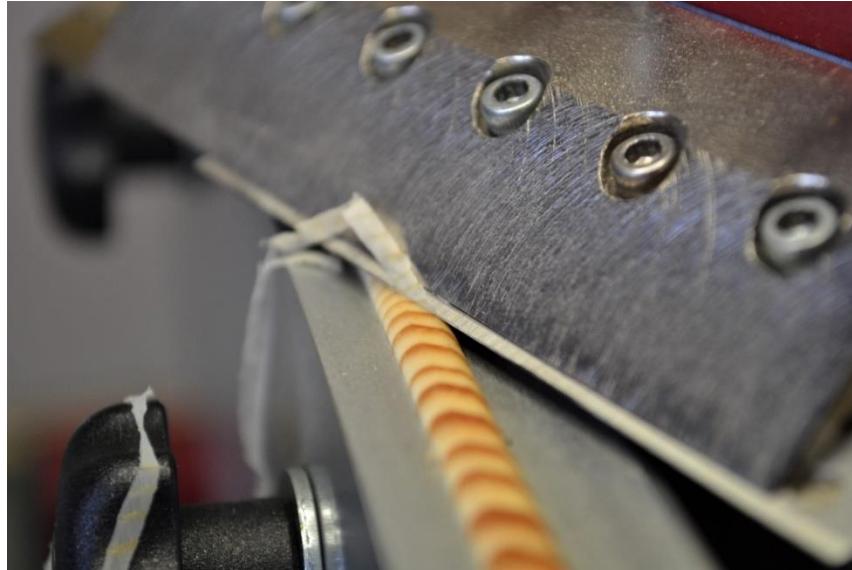


figure 11: Cutting of a spruce increment core with the core microtome

2.5. Tree-ring analysis

2.5.1. Standardization

The growth of a tree and therefore also the ring widths are strongly influenced by the given environmental conditions in the forest. There are many different external and internal conditions, which alter from time to time and may limit tree growth. But not only environmental conditions are responsible for ring width fluctuations. The systematic changes in tree age or in height within the tree stem also influence the ring widths (FRITTS, 1976). In the field of dendroclimatology and in this thesis, the focus is on the relationship of climatic conditions and growth dynamics. To gain reliable information about the climate-growth relationship of the cored trees, non-climatic trends must be removed (FRITTS, 1976; FRITTS & SPEER, 2005). So, changes in ring width which are not associated with climate, e.g. biological growth trends are not requested within the tree ring data. The common procedure in dendrochronology to get rid of non-climatic signals is known as *standardization* (FRITTS, 1976; COOK & PETERS, 1981; GRAYBILL, 1982). The removal of those very low-frequency trends and growth changes is achieved by fitting an appropriate curve to each measured ring-width series. The ring-width series is than divided by the expected growth ascertained from the curve-fitting. This division has the impact of the variance getting scaled so

that it is almost constant over the length of the time series. Further, the mean has a defined value of 1.0 afterwards, the first order autocorrelation gets reduced and younger trees are made comparable to older ones. The result of the transformation are dimensionless values referred to as *ring width indices* (RWI) (FRITTS, 1976; GRAYBILL, 1982; COOK, 1987; COOK ET AL., 1992a; HELAMA ET AL., 2004; FRITTS & SPEER, 2005).

For the curve-fitting, different approaches exist. HELAMA ET AL. (2004) differs three general types of methods for estimating growth: deterministic, stochastic and empirical. Latter will be not discussed here since it is commonly not used for this kind of analysis. Deterministic methods involve predetermined smoothing functions for the curve-fitting and are often represented by negative exponential functions, straight lines or functions with a curve, like the *Hugershoff function*. Deterministic models are usually used for tree series obtained from undisturbed trees in open-canopy stands or semiarid sites and produce unimodal and consistent curves, which presume a simple underlying age trend to be removed. Within a stand with a closed canopy, detecting and removing the age trend is far more difficult, because more noise occurs, e.g. by competition for light or forest management activities. Therefore, stochastic methods are utilized. They function as some kind of low-pass filters, mostly applied by the use of spline functions as well as weighted running means (FRITTS, 1976; COOK & PETERS, 1981; COOK, 1987; SCHWEINGRUBER, 1996; HELAMA ET AL., 2004). By detrending the raw ring-width series, there is the possibility that long-term climatic growth trends are also removed (SCHWEINGRUBER, 1996; FRITTS & SPEER, 2005). According to COOK & BRIFFA (1992) there is no indexing method, which fits for every series. Because of that and the fact that “the method of standardization can have profound effects on the resultant chronology” (COOK & BRIFFA, 1992) it is major to choose a method which highlights the wanted signals the best. Therefore, prior to the standardization process, it is necessary, that signal and noise is defined. In terms of dendroclimatology climatic growth effects are considered as signals and non-climatic trends as noise. The decision what kind of curve is used for indexing also depends on site conditions, stand history and characteristics of specimen (GRAYBILL, 1982; COOK, 1987; COOK & BRIFFA, 1992).

For this thesis two different standardization methods are used. Due to the fact, that the tree coring was conducted in a managed forest stand with a closed canopy, deterministic methods were out of question. So, two different stochastic methods for estimating the age trend, called *exponential smoothing* and *cardinal splines*, were applied. Exponential smoothing was first introduced to dendrochronology by BAREFOOT ET AL. (1974) and is calculated as follows:

Equation 2

$$\begin{aligned} A_t &= \alpha \bar{R}_t + (1 - \alpha) \tilde{R}_t \\ \bar{R}_t &= \alpha(R_{t-1}) + (1 - \alpha)(\bar{R}_{t-1}) \\ \tilde{R}_t &= \alpha(R_t - R_{t-1}) + (1 - \alpha)/\alpha(\tilde{R}_{t-1}) \end{aligned}$$

where A_t is the smoothed estimate for year t , \bar{R}_t is the average ring width series and \tilde{R}_t a lag correction for the trend. Further, α is a weighting factor, which indicates the degree of smoothing, respectively, how much ring width information is included for the estimate. BAREFOOT ET AL. (1974) chose the value 0.2 for α for smoothing the ring width series. Thus, the last 10-15 years are included to the estimation of A_t . This kind of stochastic method is described as a one-sided filter, because it only uses current and prior values. It is a biologically reasonable method, because it respects changes in tree growth due to age (COOK, 1987; COOK ET AL., 1992a). COOK (1987) further describes the difficulty of selecting factor α , which is currently not longer a problem because of the possibility to do a complete enumeration. Next to exponential smoothing, cardinal splines with selectable flexibility are used for standardization as recommended by BECK ET AL. (2013). Splines are a stochastic method for growth-trend description and trend removal (COOK ET AL., 1992a; BECK ET AL., 2013). They are considered of fitting more natural to the data set by operating as a central weighted moving average in comparison to e.g. exponential curves. The perfect spline is described as straight as possible by still eliminating most of the variance, which is not shared with all series from the site (COOK & PETERS, 1981). Whereas COOK & PETERS (1981) are recommending cubic smoothing splines, BECK ET AL. (2013) is favouring cardinal splines, because they underline local, shorter term influences of the chronologies instead of distinguishing global features. The general difference is, that in case of the cardinal splines the position of knots is chosen uniformly over the data (FAHRMEIR & TUTZ, 2011).

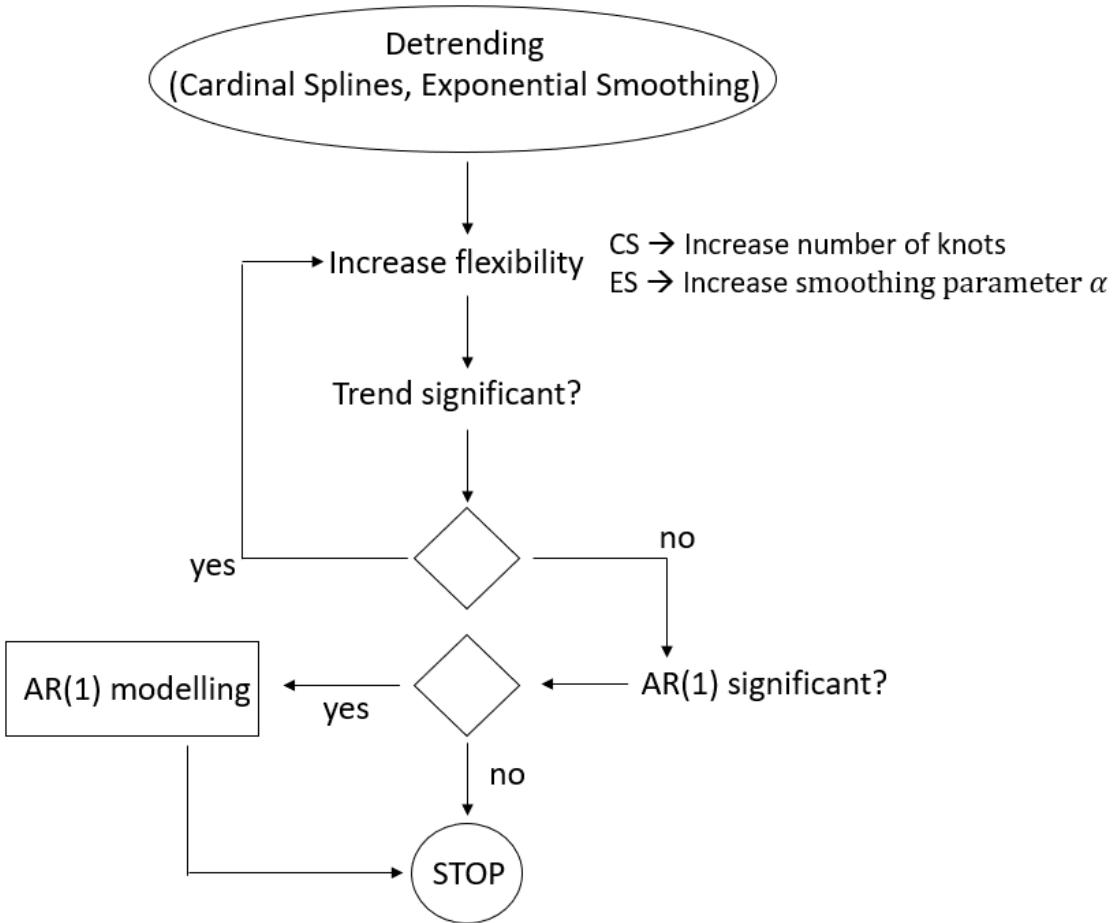


figure 12: Scheme for the process of tree ring data transformation

Both described methods are used for the detrending of the tree ring series. First, the methods are applied on every series of a tree species for every site separately. Secondly, if the trend is still significant afterwards, the detrending is getting repeated with a higher flexibility until no trend is significant anymore. The flexibility for the exponential smoothing is getting enhanced by increasing the smoothing parameter α , while in case of cardinal splines the number of knots is getting raised. In the next step, if the first order autocorrelation AR(1) is significant, an autoregressive modelling has to be applied to the data to minimize the autocorrelation. In doing so only the residuals are considered further (WIGLEY ET AL., 1987; BECK ET AL., 2013). This process “transforms a time series from one with noticeable amounts of low-frequency variance to one with variance distributed more evenly across the frequency range” (WIGLEY ET AL., 1987). It converts the former autocorrelated series into so-called *white noise* series, which consist of independent observations. The correct term for this procedure is referred to as *pre-whitening* (BIONDI & SWETNAM, 1987). As soon as there is no significant AR(1) left, the procedure of pre-whitening and

hence, the process of the transformation of the raw ring width series, is finished. The process is visualized in figure 12.

2.5.2. Chronology building and basic assessment and statistics

2.5.2.1. Chronology building

Next to removing non-climatic “noise” and enhancing the climatic signals, the purpose of standardization is to enable that the RWI of individual trees are averaged together into a *mean chronology* (mean standardized indices) for a site (FRITTS, 1976; COOK ET AL., 1992a). The objective of building a mean chronology is to decrease the random error which is within every series and to get a chronology with a ratio of climatic signal to non-climatic noise which is as high as possible (GRAYBILL, 1982). So, it is an advantage of building a mean chronology that the climatic signal, which is existing in most of the trees, does not vanish, while non-climatic noise, to a certain extent, cancels each other out. Hence, the variance in the index values gets reduced (FRITTS & SPEER, 2005). The term signal hereby is referred to the common variability, which is existing in all series of a species at a site and gets distorted by variance that is only present in single trees or cores (noise) (BRIFFA & JONES, 1992).

But before building the chronologies with the detrended indices, the raw ring width data get checked regarding their presence in the data set. This is necessary, because trees within a stand differ in age and thus, the tree ring series in length. So, the sample size decreases, which leads to an increase in variance and will influence the standard error of the mean (SHIYATOV ET AL., 1992). Therefore, SCHULMANN (1956) recommended to delete the part of the chronology, which are inadequately replicated. This is up to now common sense in dendrochronology. BECK (personal communication) recommends a threshold of 70 % of presence of all series from a species in the data set for a site as the minimum requirement. Hence, for this thesis the series are cut off at the point where the presence is falling below the threshold of 70 %.

In the course of this thesis, the ring width indices, separated by tree species and site, get averaged together to mean chronologies. So, because on four different sites fir and spruce trees were sampled, eight mean chronologies are built. A common procedure in dendrochronology is to use Tukey’s biweight robust mean to develop the mean index chronology (COOK ET AL., 1992b), but it has been criticized for the effects of the weight function on the exclusion of tree numbers from the calculation of the mean (BECK, 2008). Therefore, BECK (2008) proposed an alternative method,

which is used for this thesis. It is based on evaluating single series of already detrended and pre-whitened index series. It is iterative and starts in the first step with calculating the chronologies signal strength. In the second step the signal strength of each series, which are part of the chronology, is getting measured. The equation for the *chronology signal strength* \hat{S} reads as follows:

Equation 3

$$\hat{S} = \frac{n(n-1)}{2} \times \sum_{i < j} \text{cor}(I^i, I^j)$$

whereby n is the amount of series in the chronology and $I^{i,j}$ are the index series, which are getting correlated to another.

Secondly, the signal strength of each series is computed and is defined as:

Equation 4

$$S_k = \frac{1}{n-1} \times \sum_{j \neq k} \text{cor}(I^k, I^j)$$

The *signal strength of a single series* S_k may be calculated as the mean correlation to the other series included in the chronology. Thus, S_k is tested for significance. If S_k is non-significant or negative it is excluded from the chronology building. The process starts again with step one until all left series are significant within the chronology.

In a final step the mean chronology is built, where the individual index series may get weight by their signal strength:

Equation 5

$$C_t = \frac{1}{\sum_i S_i} \times \sum_{i=1}^n S_i \times I_t^i$$

$t=1, \dots, s.$

This procedure is extensively described in BECK (2008) and is based on calculations by BRIFFA & JONES (1992) and NEUMANN (2001). By identifying series, which have non-significant or negative mean cross correlations to the other series and excluding them stepwise, improves the signal strength of the chronology (BECK, 2008). With applying the described method, the principles of crossdating are fulfilled. Crossdating is known as one of the basic techniques in dendrochronology

and guarantees the correct assignment of individual tree rings to its year of formation (WENK, 1997; MARTINEZ, 2000).

2.5.2.2. Basic chronology assessment and statistics

The questions that arise after building the chronologies is, how the actual quality of the chronology is and how it is measured. In this regard, in dendrochronology it is state of the art to work with the concept of the already described chronology signal. The quality of the obtained chronology is getting measured by quantifying the signal expression in the chronology to answer, in what degree the chronology is representing the hypothetical population chronology (BRIFFA & JONES, 1992; GRAYBILL, 1982; FRITTS, 1976). Besides, the ratio between wanted signal and the undesired noise is measured.

2.5.2.2.1. Expressed Population Signal (EPS)

It is required, when the chronology signal strength and the related noise is estimated, to determine the degree, to what extent the chronology signal is expressed after the indices are averaged together (BRIFFA & JONES, 1992). WIGLEY ET AL. (1984) introduced the expressed population signal (EPS) to show how well an infinite population is portrayed by the sample chronology (BURAS, 2017; BRIFFA & JONES, 1992). It is used to measure common variability and changing signal strength within a chronology (SPEER, 2010; ESPER ET AL., 2001). The computation is as follows (BRIFFA & JONES, 1992):

Equation 6

$$EPS(t) = \frac{\bar{r}_{eff}}{\bar{r}_{eff} + (1 - \bar{r}_{eff})/t}$$

where t is the amount of averaged tree series and \bar{r}_{eff} is the effective chronology signal (equal to the chronology signal strength). The threshold of 0.85 is commonly used as an appropriate point to which the statistical quality is accepted (BRIFFA & JONES, 1992; SPEER, 2010; WIGLEY ET AL., 1984). Within this thesis, EPS is used for estimating the chronology confidence, but it is controversially discussed recently (BURAS, 2017).

2.5.2.2.2. Signal-to-Noise Ratio (S/N, SNR)

A basic term in dendrochronology is the already mentioned signal-to-noise ratio (S/N, SNR). It is defined as the proportion of mean variance in common among trees ($\%Y$) divided by mean variance attributed to differences in trees ($100 - \%Y$) (FRITTS, 1982; CROPPER, 1982; GRAYBILL, 1982; KAENNEL & SCHWEINGRUBER, 1995). It follows from the above:

Equation 7

$$SNR = N \times \%Y / (100 - \%Y)$$

where N is the number of trees, which are included. Basically it gives information about the amount of desired information included in the constructed chronology versus the unrequested, random variation (SPEER, 2010). It is considered as a quality measure for chronologies (DEWITT & AMES, 1978; BRIFFA & JONES, 1992). BRIFFA & JONES (1992) further mention the difficulty of interpreting SNR due to missing upper bounds. According to BECK (personal communication) values between 20 and 30 are desired, but values ranging between 15 and 20 are also fine.

2.5.2.2.3. Selection of the detrending method

Both detrending methods, exponential smoothing and cardinal splines, which were applied on the raw ring width series are getting matched because a decision must be made, which one is used for further analysis. Therefore, chronologies are built with both detrending methods and are compared by mean signal strength, EPS and SNR. The resulting chronologies with the better detrending method, equals higher values, are used. Besides, the resulting TRI of both methods are getting compared and evaluated regarding Gleichläufigkeit and changing mean sensitivity to examine differences between each other. The process of detrending, chronology building and assessment is operated with program POINTER by BECK (unpublished). Program POINTER includes the process of crossdating and replaces the use of programs like COFECHA, which is a widespread and common tool for crossdating, standardization and quality control (GRISSINO-MAYER, 2001).

2.5.2.2.4. Mean sensitivity (MS)

The examination of tree rings can give a hint in what frequency the climatic conditions are limiting to tree growth. The tree reacts to changes in growth conditions with variability in ring width. The stronger the limitation is the more distinctive is the alteration from ring to ring. *Sensitivity* is the known term in dendrochronology as the variability in ring width, whereas the term *complacency* describes the opposite, the lack of variability (FRITTS, 1976). The *mean sensitivity* (MS) is commonly used to indicate the average relative fluctuations in ring width from contiguous rings (FRITTS, 1976; COOK & KAIRIUKSTIS, 1992; NIKOLOVA ET AL., 2011). It reflects the relationship of high-frequency growth patterns in the chronology for a short period and shows the strength of the relationship between radial growth and limiting factors. (NASH & KINCAID, 1992; FRITTS, 1976). The calculation of the average mean sensitivity for a series is as follows:

Equation 8

$$MS_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right|$$

In the formula above x_t represents each datum and the vertical lines mark the absolute value of the enclosed term. Further, the denominator of the term defines the differences in ring width between the contiguous rings x_t and x_{t+1} . The differences stand in proportion to the average of the two widths. The resulting values range from 0 to 2. A value of 0 indicates that there are no differences, whereas a value of 2 means that there is a maximum difference, like if a value of zero appears next to a nonzero value. Due to SPEER (2010) values close to 0.1 are often too complacent, values above 0.4 are very sensitive and a mean sensitivity around 0.2 is considered as appropriate for climatic analysis. A high mean sensitivity indicates the presence of high-frequency variance whereas a low mean sensitivity indicates less high-frequency variance (FRITTS, 1976).

2.5.2.2.5. Gleichläufigkeit (Glk)

Because he thought it was not sufficient to rely only on narrow rings for dating, HUBER (1943) presented a method called *Gegenläufigkeitskoeffizient* (gglk, coefficient of parallel variation) to evaluate the similarity of tree ring series by the assessment of the total course of the series. Extreme narrow rings were pointed out stronger than the middle and high increments throughout the use of

a logarithmic ordinate. The proportion of the in opposite directions running curve sections were the quantitative measure. The ring width was not considered (HUBER, 1943; COOK & KAIRIUKSTIS, 1992). ECKSTEIN & BAUCH (1969) developed a complementary value to the one introduced by HUBER (1943). It is called *Gleichläufigkeitswert* (glk, Gleichläufigkeitskoeffizient, coefficient/percentage of agreement, sign test) and is today a commonly used measure for synchronicity (ECKSTEIN & BAUCH, 1969; ANIOL & SCHMIDT, 1982; NIKOLOVA ET AL., 2011; BECK ET AL., 2013; SCHWEINGRUBER, 2012). It can be applied with or without a standardization of the tree ring width (FRITTS, 1976; ANIOL & SCHMIDT, 1982). The glk considers the sense of direction on a particular position for the following sequence. The sense of direction is defined as the sign of the gradient from a certain position to the following one (WENK, 1997). According to SCHWEINGRUBER (2012) the glk for a series is calculated as:

Equation 9

$$glk(x, y) = \frac{1}{n-1} \sum_{i=1}^{n-1} |G_{ix} + G_{iy}| \text{ in \%}$$

with $\Delta_{ix} := x_{i+1} - x_i$ and $\Delta_{iy} := y_{i+1} - y_i$ of the two series x and y of the same length are compared. The sign of Δ_{ix} and Δ_{iy} dictate the values of G_{ix} and G_{iy} , which represent the associated sense of direction of the series. G_{ix} and G_{iy} are set to $+\frac{1}{2}(\Delta_i > 0)$, $0(\Delta_i = 0)$, or $-\frac{1}{2}(\Delta_i < 0)$ (SCHWEINGRUBER, 2012; BURAS & WILMKING, 2015; WENK, 1997; SPEER, 2010). BURAS & WILMKING (2015) modify the calculation of the glk due to a minor mistake in the original one presented by SCHWEINGRUBER (2012), which is not considering the case, that when both series synchronously have no growth change from one year to another. Thus, the corrected formula is used for the analysis within this thesis. The computation is performed with the function $glk(x)$ of the ‘dplR’-package (BUNN, 2008) of R Studio and reads as follows (BURAS & WILMKING, 2015):

Equation 10

$$glk(x, y) = 1 - \frac{1}{n-1} \sum_{i=1}^{n-1} |G_{ix} - G_{iy}| \text{ in \%}$$

In conclusion the glk shows the sum of the intervals with the same gradient in % (RINNTECH, 2012), respectively, depicts the percentage of agreement between the growth signs for consecutive years of two comparing ring series (BERNABEI ET AL., 2019). So, it is a simple and nonparametric test to

measure association between two series (FRITTS, 1976). The higher the glk, the higher is the similarity of two series (ECKSTEIN & BAUCH, 1969). BAILLIE & PILCHER (1973) mention that the method of percentage agreement only presents significant crossdating if it is higher than 60 % and the overlap between the two chronologies is long. Further, the glk only measures the sense of direction and not the magnitude of the ring width variation (BAILLIE & PILCHER, 1973; FRITTS, 1976; WENK, 1997). Therefore, it is important to have further matching criteria.

2.5.3. Tree-Ring/ Environment interactions

2.5.3.1. Pointer year analysis

As already mentioned, trees react to changes in environmental conditions, such as climatic conditions, abiotic or biotic influences, with growth responses (FRITTS, 1976; SCHWEINGRUBER, 1996). From time to time the external influences on tree growth are extraordinary strong and many trees respond with distinctive variation in tree ring properties (ANIOL & SCHMIDT, 1982; JETSCHKE ET AL., 2019). Usually this will be apparent by extreme wide or narrow rings, but amongst others variations in proportions of latewood or intra-annual density fluctuations are also possible (SCHWEINGRUBER, 1992). SCHWEINGRUBER ET AL. (1990) described, that a year with prominent characteristics in growth for a single tree is referred to as an *event year*, whereas a *pointer year* is a year where the majority of the trees at a site react to extraordinary growth conditions (SCHWEINGRUBER ET AL., 1990; ANIOL & SCHMIDT, 1982; KAENNEL & SCHWEINGRUBER, 1995). A distinction is made between positive and negative pointer years (significant increase, respectively, reduction in growth). Pointer years are an important tool in dendrochronology as they allow, for example, predictions about growth reactions to drought and comparisons between tree species. The first statistical definition is given by ECKSTEIN & BAUCH (1969), but since then many, more or less slightly divergent, methods for pointer year analysis were used. Depending on the statistical filters applied, the quality and frequency of the pointer values fluctuate (CROPPER, 1979; SCHWEINGRUBER, 1996). The variety of definitions and calculations can lead to hindrance in comparison (JETSCHKE ET AL., 2019). For pointer year analysis raw ring width series are used as well as indexed series. Latter is recommended by JETSCHKE ET AL. (2019), which refer to CROPPER (1979) and SCHWEINGRUBER ET AL. (1990). Therefore, indexed values are utilized for pointer year deduction within this thesis. Besides, the hereby applied definition of pointer years is conform with

DIETRICH ET AL. (unpublished). Thus, a pointer year is present, if the mean of the tree ring indices in a certain year is significantly deviant from the mean of the whole series.

Within this analysis for every site and tree species pointer values are obtained. The site conditions vary from site to site and there are differences in the reaction of tree species to disturbances. Hence, the pointer years differ as well. For growth reactions caused by climate, most of the sites need to indicate pointer values for the same year. These years, where the majority of trees, across all sites and species, show significant growth reactions are distinguished and used for further analysis and comparisons.

2.5.3.2. Determination of extreme climatic events

Of high importance, regarding the examination of climate-growth relationships, is the determination and quantification of extreme climate events, such as drought. In this regard, many different approaches exist to identify extreme years. Starting from the results of the pointer year analysis, possible pointer years are compared with drought events resulting from the calculation of drought indices. A commonly used value for characterizing climatic conditions over time is the aridity-humidity index by DEMARTONNE (1926). Therefor the annual sum of precipitation (P) is getting divided by the mean annual temperature (T) plus the value 10. So, the calculation for the *DeMartonne aridity-humidity index* (DMI) is as follows: $DMI = P/(T+10)$ (MALIVA & MISSIMER, 2012). Due to the fact, that especially the weather during the summer months of June, July and August (jja) have important influence on tree growth, they must be considered separately. For calculating the DMI during summer, respectively, the given values of the summer months are used (DMI_{jja}) (DEMARTONNE, 1926; VITALI ET AL., 2017; ZANG ET AL., 2014).

For this thesis, next to the DMI, a further index is applied to get a comprehensive insight into the climatic conditions. The other used index is the *Standardized Precipitation Evapotranspiration Index* (SPEI). The SPEI is based on the *Standardized Precipitation Index* (SPI), which was first mentioned by MCKEE ET AL. (1993) and estimates the dry, respectively, wet conditions based on a precipitation probabilistic approach (VICENTE-SERRANO ET AL., 2010). This index considers usable water resources, including factors like ground water and soil moisture. Due to the circumstance that the SPI is only based on precipitation data, other drought influencing factors are missing (VICENTE-SERRANO ET AL., 2010; MCKEE ET AL., 1993). Thus, VICENTE-SERRANO ET AL. (2010) developed the more explicit index SPEI, which is additionally based on the *potential*

evapotranspiration (PET). The climatic water balance calculated by using monthly differences between precipitation and potential evapotranspiration results in the SPEI values. For the estimation of the PET several different methods exist. Here, the simplest calculation by THORNTHWAITE (1948) was applied. This equation only requires monthly-mean temperature data and was therefore adequate (VICENTE-SERRANO ET AL., 2010). ZANG ET AL. (2019) recommended not solely to use the SPEI, so here a combination of DMI and SPEI has been used to describe possible drought events.

2.5.3.3. Growth responses to disturbances

The pointer year analysis delivers points in time in which tree growth is disturbed. Pointer years that occur in most trees overall site and tree species are related to changes in non-site-specific conditions, such as climate. In many cases drought events are highly related to growth decline, respectively, negative pointer years. Of interest within this thesis is, how well trees recover from stress events, like drought, and how fir and spruce differ in growth reactions from each other. For the comparison of how well trees perform under drought stress, LLORET ET AL. (2011) introduced indices for resistance, recovery and resilience. The calculation of these indices can be computed based on raw ring-width, detrended growth series or *basal area increments* (BAI) (SCHWARZ ET AL., 2019). For this thesis annual basal area increments ($\text{cm}^2 \text{ year}^{-1}$) are used. Optional detrending of the BAI is relinquished, because the identified stress events are within the middle-aged phase of the cored trees. PRETZSCH ET AL. (2013) mentions, that during this period the growth course is quite parallel to the abscissa and consequently, any detrending is unnecessary. The calculation of the BAI is described by BIONDI & QEADAN (2008) and is performed with the package dplR ('Outside-in' method) (BUNN, 2008). The three indices are described by the following components (PRETZSCH ET AL., 2013; LLORET ET AL., 2011):

- *PreDist*: the mean basal area increment for the chosen period of three years before the disturbance (drought)
- *Dist*: the mean basal area increment for the disturbance period
- *PostDist*: the mean basal area increment for the chosen period of three years after the disturbance (stress event)

Resistance (R_t), $R_t = Dist/PreDist$, is defined as the decrease of growth from the period before the stress event to the stress period. The lower the obtained value gets, the lower is the resistance to

stress events, whereas a value of 1 indicates complete resistance. *Recovery* (R_c), $R_c = PostDist/Dist$, indicates the reaction of the trees after the stress period. A resulting value of 1 implies no recovery after the event, whereat a $R_c < 1$ shows a further decline and a value of > 1 stands for recovery to a certain degree. Last, *Resilience* (R_s), $R_s = PostDist/PreDist$, displays the ratio between post-disturbance and pre-disturbance. $R_s < 1$ shows a growth decline conditioned by the stress event and $R_s \geq 1$ implies a full recovery, respectively, an increase in growth to the pre-disturbance level (PRETZSCH ET AL., 2013). The original publication by LLORET ET AL. (2011) refers to drought events instead of the hereby used terminology of disturbing events (Dist). That's because for this thesis no drought events were already known before the analysis.

For quantifying differences between the tree species and the sites, in terms of resistance, recovery and resilience, an independent two-way factorial mixed ANOVA (Analysis of variance) was conducted. The required normal distribution was validated by the Shapiro-Wilk-test, whereas the homogeneity of variances was confirmed by the Levene-test. To get rid of slight skewness and kurtosis and achieve normal distribution a logarithmic transformation was applied on the obtained resistance (R_t) values. The model evaluation for the ANOVA was done by type III sum of squares due to advantages with unequal sample sizes. To get a more detailed insight into differences between sites and species the ANOVA was followed up by a Tukey test for *post-hoc* analysis of differences between means.

So, the respective dataset comprised the indices R_t , R_c and R_s of *Abies alba* and *Picea abies* as well as the affiliated sites. R_t , R_c and R_s were the alternating response variables, whereas tree species and sites were the independent variables.

For this statistical analysis, packages ‘car’ (FOX & WEISBERG, 2020) for Levene-test and ‘multcomp’ (HOTHORN ET AL., 2020) for Tukey *post-hoc* test of R Studio were applied.

2.5.3.4. Examination of climate-growth relationships using program CLIMTREG

Further dendroclimatological analysis was carried out with the statistical analysis tool CLIMTREG (*climatic impact on tree growth*). In the following section the methodology behind this tool is explained briefly. All the here mentioned information are based on personal communication with Wolfgang Beck and publications by BECK ET AL. (2013) and BECK & HEINZIG (2018), where the fundamental statistics, ideas and procedures behind CLIMTREG are described extensively.

In dendrochronological research the analysis of climate-growth relationships is mostly based on monthly climate variables within a year. This leads to a discrepancy between the continuous growth of a tree over the vegetation period and mean climate variables, which extend over much longer periods. Further, tree growth is not tied to artificial monthly boundaries and so, by using monthly values, actual processes in the climate-growth system of trees can't be represented fully. Therefore, in contrast to other climatic analysis tools, CLIMTREG is using daily climate data with variable temporal width as well as moving correlations to describe the climate-growth relationship on a short-term and long-term basis. Besides, impacts of short extreme events and annual changes in the length of the vegetation period are getting considered.

Due to the circumstance that CLIMTREG is based on daily climate data and only monthly data was available for the climate station from Pamporovo and Chepelare, the daily data from an adjacent measuring point (grid point BG 10014) at the same latitude was used. The precise location is marked in figure 3. The climate data was generated using a mixture of observation data and modelling. For this, the data from four climate stations located in Kurdjali, Sofia, Varna and Vidin were merged (LANGE, 2019). The obtained climate data ranged from 1901-2016 and was provided by the *Potsdam Institute for Climate Impact Research* (PIK). For the calculations with CLIMTREG the period 1958-2016 was examined since the shortest chronology was dated back to 1958. This period was divided into two subsections with the same time spans of 30 years each. The first time span ranged from 1958-1987 and the second one from 1987-2016. In the year 1987 both subsections overlapped. The decision to divide the entire period was made due to recommendations by BECK (personal communication), who suggested using time intervals of 19-35 years to achieve good results. A further advantage is to be able to gain information about possible changes in the climate-growth relationships over time, which is especially relevant considering climate change impacts. Mean temperature as well as precipitation and relative humidity were the daily climatic variables which were used for the analysis.

The approach of CLIMTREG is to apply intra-annual moving time intervals of varying width. In this regard, CLIMTREG uses daily climate data beginning on the 1st July of the previous year running to 31st October of the current year (488 days) in ever-changing periods and segments. This procedure has the aim to reflect the climatic window of tree growth, including the effects of physiological preconditioning. For every period/segment, calculated deviations of mean temperature and precipitation sums from the long-term average are correlated with the tree ring index (TRI) time series. The first period starts at the 1st July of the previous year with a length of 21 days and then

moves by one day at a time. So, the following segment starts at the 2nd July and ends 21 days later. This continues until the time span of 11th October to 31st October of the current year is reached. Subsequently, the interval increases by one to 22 days and starting again on 1st July of the previous year. A total re-run is done. This keeps going until an interval maximum of 121 days is reached. In each computation step the calculated correlation coefficient is compared with the latest maximum and is getting possibly saved as new maximum together with the linked temporal position and interval width. The whole process is a complete enumeration and so 42218 correlations for each climate parameter are calculated for every year. From the 42218 calculations the five time intervals with the strongest correlations for temperature and precipitation are presented.

Since inter-correlations between the variables can occur (multi-collinearity), a *principle component analysis* (PCA) is applied to the key climate parameters, which were determined in the last step. This converts possibly correlated variables into a set of linearly uncorrelated variables, referred to as *principle components* (PC). The result of the PCA is a scree plot, where the eigenvalues are ordered based on the affiliation to eigenvectors. The highest eigenvalue represents the largest proportion of variance within the predictors. Further, for statistical modelling a *principal component regression* (PCR) follows, which includes the TRI and the results from the PCA. In doing so, regression coefficients are getting estimated and subsequently, based on the principle of matrix multiplication, a data matrix is produced, which is independent from the number of included eigenvectors. The significance of each variable is determined by using the t-test. The t-test serves as a decision criterion and eliminates eigenvectors, if necessary.

The quality of the model performance is evaluated by several criteria, which are as follows:

- Coefficient of determination (R^2)
- Akaike information criterion (AIC) by AKAIKE (1974)
- Normal distribution of the model residuals by using the Kolmogorov-Smirnov test
- Gleichläufigkeit (Glk) between the modelled TRI-series by PCR and the measured TRI-series
- Ratio of sensitivities of modelled TRI-series by PCR/ measured TRI-series

Finally, a sensitivity analysis of individual predictors is conducted, where the effects of climatic variables on deviations of radial increment are pointed up. For that, all variables except the predictor are fixed to their mean (which is 0 due to standardized data) and the deviations of the TRI from 1.0 provoked by the predictor are computed. An overview of the workflow of CLIMTREG is given in figure 13.

Chapter 2: Methodology and materials

In conclusion CLIMTREG is a statistical tool to analyse climate-growth relationships based on intra-annual and yearly moving time intervals of variable width. By applying this program, the borders of monthly variables are overcome and responses of tree growth to climate factors can be examined thoroughly.

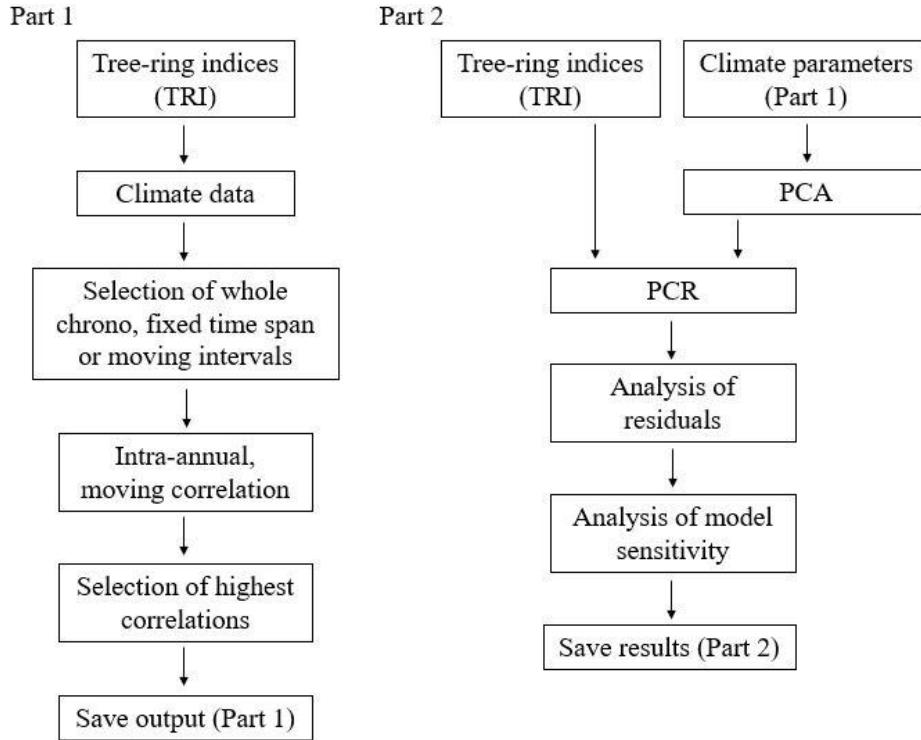


figure 13: Workflow description of program CLIMTREG. The program basically works in two major steps. The first part includes the search algorithm with the intra-annual moving time intervals. The second part contains the PCA, the subsequent PCR and the model evaluation. The workflow description is adapted from BECK ET AL. (2013).

3. Results

3.1. General site descriptions

3.1.1. Inclination and exposition

As described in chapter 2, it was a requirement for site selection that the plots are only exposed to the north (north-east to north-west) to enable best possible homogeneity. Further, the different inclinations of the plots were of interest. Both factors for all 105 plots are presented in figure 14.

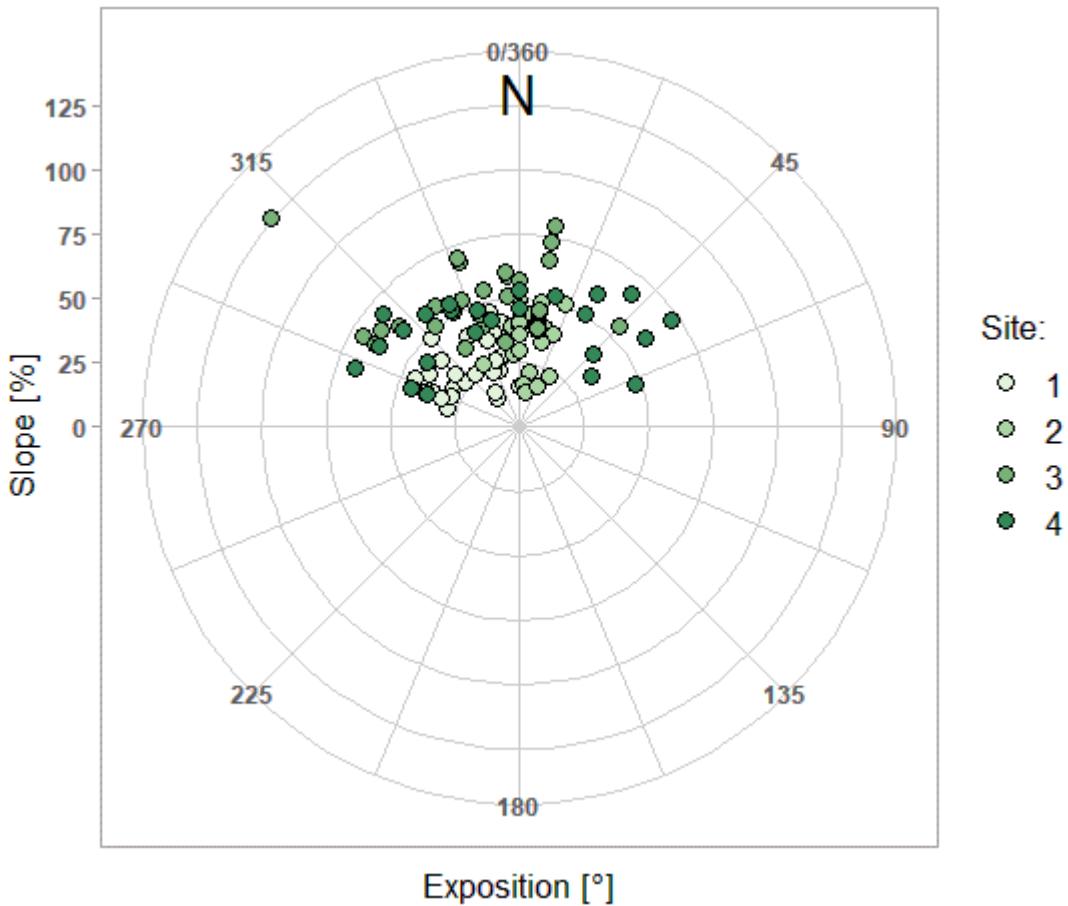


figure 14: Illustration of the exposition and inclination of all 105 plots. The different colours mark the affiliation to the sites. The more the points are away from the centre, the higher is the inclination, ranging from 0 to 125 %.

The recordings showed that all plots are exposed to the north, but slight differences between the sites can be observed. The plots of site 1 were aligned more to north/north-west, while the site 2 plots point more directly to the north. Site 3 and 4 were more spread from north-west to north-east and therefore were less homogeneous than site 1 and 2. But all in all the required homogeneity was given. The inclination ranges from a minimum slope of 14 % at a plot on site 2 to a maximum of

126 % at a plot on site 3. In general site 3 (\varnothing 59 %) and site 4 (\varnothing 53 %) were steeper than site 1 (\varnothing 33 %) and 2 (\varnothing 35 %). Consequently, site 1 and 2 as well as site 3 and 4 were more similar to each other.

3.1.2. Basal area

In forestry a commonly used value for characterizing forest stands is the basal area. figure 15 shows the basal area of the sites as well as the basal area for each site separated by the different tree species that occur in the matured stand. As becomes clearly from this figure, next to silver fir (*Abies alba*) and Norway spruce (*Picea abies*), also European beech (*Fagus sylvatica*) was present in the stands. Since none of the beech trees were dominant or co-dominant they were not considered within the dendroclimatological analysis. Further, only on sites 1 and 2 a mentionable amount of

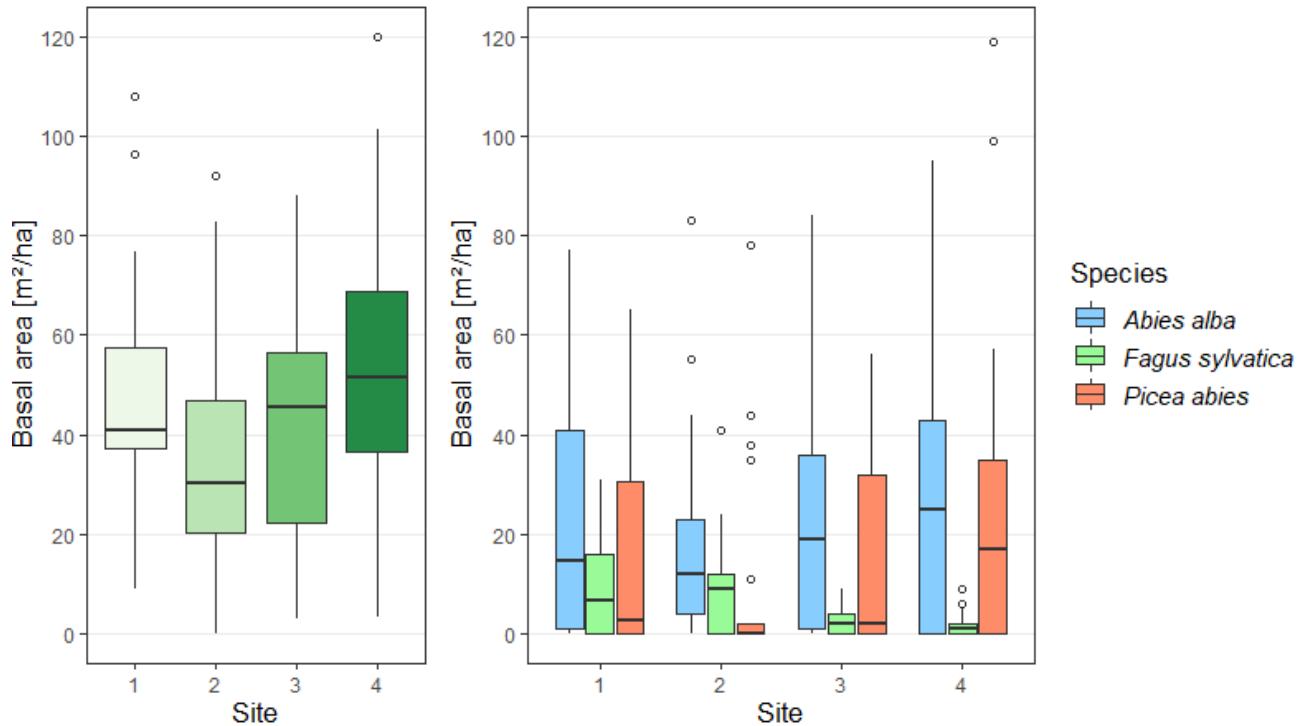


figure 15: Basal area of the sites (left) and separated by tree species (right), based on recordings within the 25 (30) 100 m² circles per site. For every plot the particular basal area has been computed and is presented here as box-and-whisker-plots.

beech trees existed. Basically site 2 had the lowest measured average basal area (35.5 m²/ha), whereas site 4 had the highest one (53.4 m²/ha). Remarkable is the box-whisker-plot of Norway spruce on site 2. There, spruce has a comparatively low average basal area (8.4 m²/ha), because many of the plots have no spruce trees within the 100 m² circles (18 of 25). The plots where spruce trees were existent within the circle indicate high basal area values, resulting in outliers in the box-

whisker-diagram. This is due to the large dimensions of the few spruce trees. So, Site 2 had less, but larger spruces than, for example, beeches. Silver fir had the largest share on every site and seems, based on the basal area information, to dominate the stands. Site 3 and 4 had nearly the same basal area distribution, whereas site 1 and 2 showed similar patterns with higher portions of beech.

3.1.3. Height

For further characterization of the stands the height of the sampling trees was considered. By selecting the trees for their dominance in the stand they represent the highest and largest ones. The

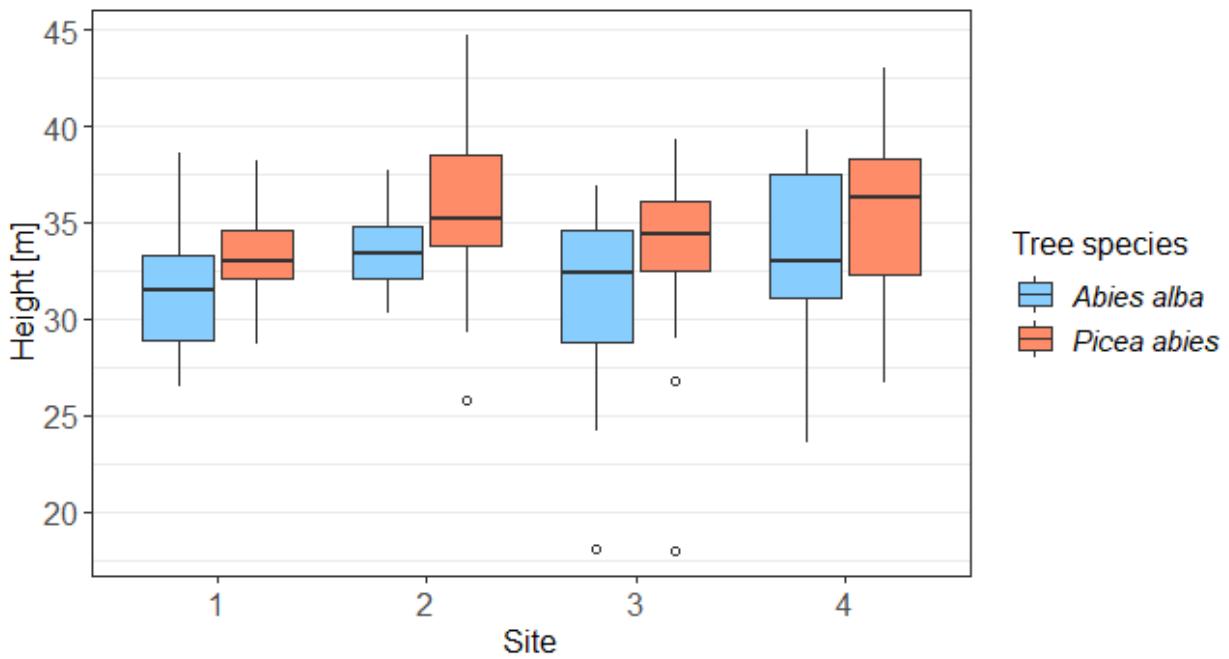


figure 16: Height of the sampled spruce and fir trees presented as box-whisker-diagrams.

arithmetic mean of the height of the highest 100 trees (Oh_{100}) was, in combination with stand age, a common value for yield description. The height measurements of the sampling trees are presented in figure 16. It stands out that *Abies alba* was on every site of slightly lower height than *Picea abies*. The average across all sites was 32.4 m (± 4 m) for silver fir, respectively 34.3 m (± 4.2 m) for Norway spruce (mean height of 71 trees per species \pm standard deviation). The lowest average height of both species can be found on site 1, but the differences between the sites were neglectable. The highest measured tree was a spruce on site 2 with a height of 44.7 m, whereas the smallest one was also a spruce (18 m; site 3). The height measurements on site 4 deviated a little more than on the other sites. In conclusion, Norway spruce was on average higher than silver fir on the research sites. Regarding this, the sites were quite homogeneous.

3.1.4. Age

The age of the stand was estimated from the tree ring measurements. For this, the counted rings of the oldest three trees of each species for every site were viewed (table 1). Only the tree-ring series, where the pith was visible were used for the age estimation.

table 1: Counted rings of the three oldest trees per site and species.

		1	2	3
<i>Abies alba</i>	Site 1	99	95	80
	Site 2	243	91	85
	Site 3	133	119	111
	Site 4	151	128	121
<i>Picea abies</i>	Site 1	140	119	106
	Site 2	136	134	125
	Site 3	139	131	119
	Site 4	166	140	120

The results presented above show that there were differences between and within the species. The dominant fir trees of site 1 were approximately 90 (80-100) years old, whereas the spruce trees of the same site were roughly 30 years older. The age of the Norway spruces was almost the same on every site, ranging from 106 to 166 measured rings. The average age was around 130 years. In contrast to that was the age distribution of the silver firs.

While the oldest measured trees on site 1 were of similar age, the oldest fir on site 2 was 150 years older than the second oldest. This very old silver fir exhibited 243 measured tree rings and was therefore the oldest one of the whole data set obtained within the field work (figure

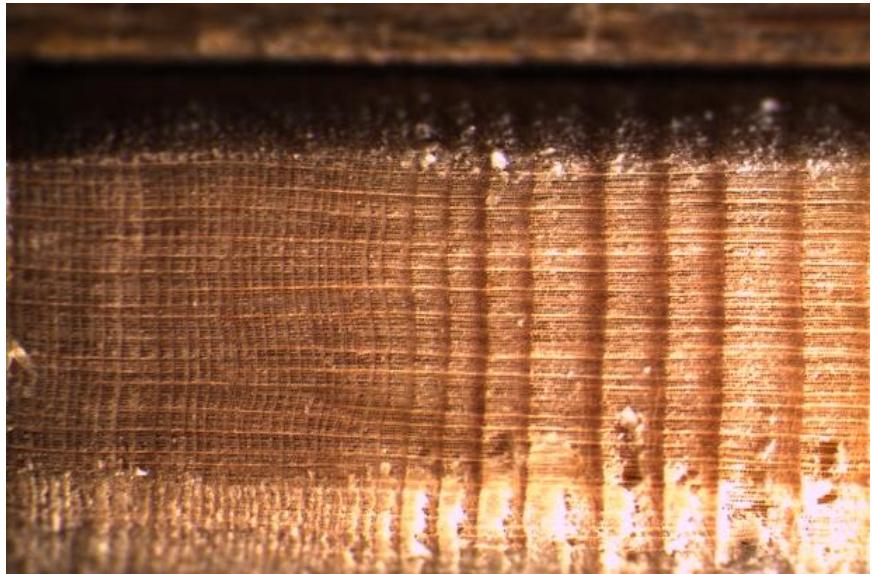


figure 17: Excerpt from the oldest tree of the data set. The recognizable leap in growth is most likely due to forest management activities. Picture is shown in 1.6x magnification.

17). The firs of site 3 had an estimated age of around 120 years, whereas the ones on site 4 were a little bit older (approximately 135 years). Thus, across species, site 3 and 4 were quite similar. Only the silver firs of site 1 and 2 varied.

3.1.5. Determination of yield capacity

For better comprehension and classification, the tree stands were graded according to their yield capacity. For the classification of *Picea abies* the yield table of ASSMANN & FRANZ (1990) was utilized. An average top height of the highest 100 trees per hectare (Oh_{100}) of approximately 34 m and an average age of 130 years resulted in the third highest available yield class 36 (*Oberhöhenbonität* 36).

For *Abies alba* the grading due to HAUSSER (1990) was applied. Based on an average diameter in breast height of 54 cm and an average age of 90 (100) years, the stands are classified as yield class I, the highest yield class for silver fir.

3.2. Characterization of the sampling trees

3.2.1. Stability of the sampling trees

For the evaluation of the stability and vitality of the trees, which were cored for the dendroclimatological analysis, two factors were considered. The first one was the relative crown length (crown ratio). It can be assumed that the higher the crown ratio is, the more vital and stable the trees are. On the research sites, the specimen of *Picea abies* had a higher live crown ratio than silver firs (figure 18). The overall mean was 56 % ($\pm 9\%$) for *Abies alba* and 64 % ($\pm 12\%$) for

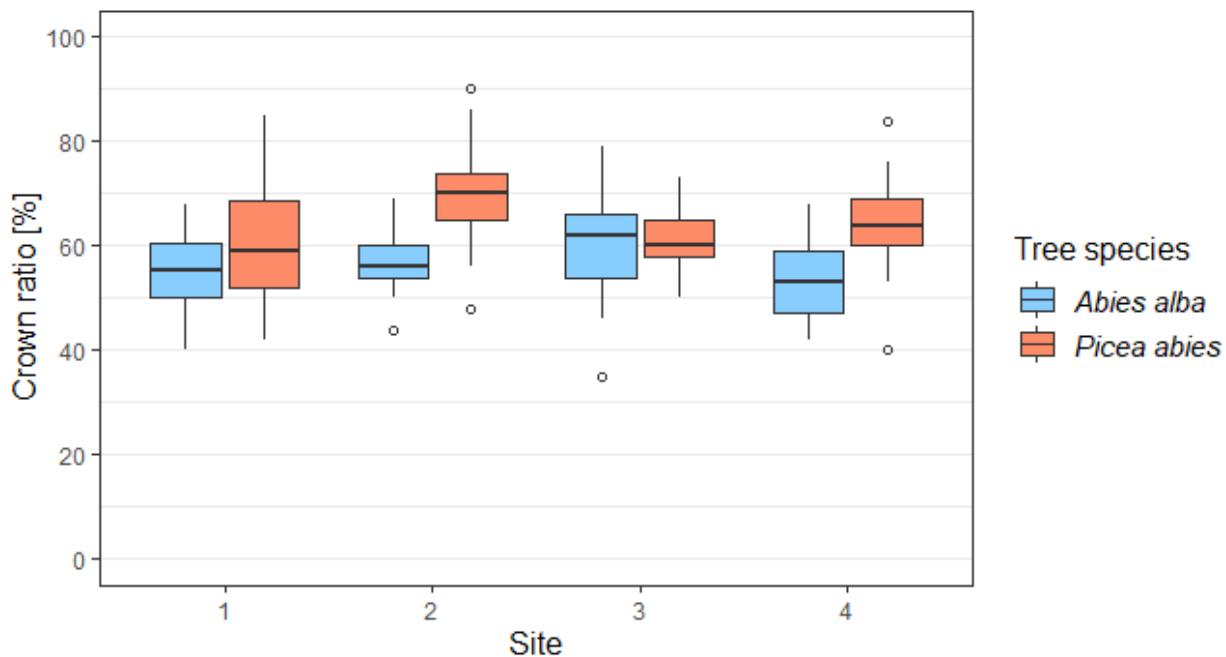


figure 18: Relative crown length (crown ratio) of the sampled fir and spruce trees. Illustrated as box-whisker-plots.

Picea abies. In comparison, the crown ratio of silver firs between the sites was quite constant, whereas the crown ratio of spruces fluctuated a bit more from site to site. The spruce trees of site 2 had the highest average crown ratio with 69 % ($\pm 10\%$). Considering the relative crown length, the sampling trees were (very) stable. This is concordant with the results of the relation between tree height and diameter in breast height (h/d-ratio). As can be seen in figure 19 almost every measured tree was considered as very stable or stable. The differences between the tree species and sites were small. Only the fir trees on site 1 had a higher h/d-ratio and therefore seemed to be less stable in comparison. In summary, it is to say that the sampling trees were stable and vital. Besides, the relative crown length as well as the h/d-ratio lead to conclusions about competition. Competition conditions are described in the next section.

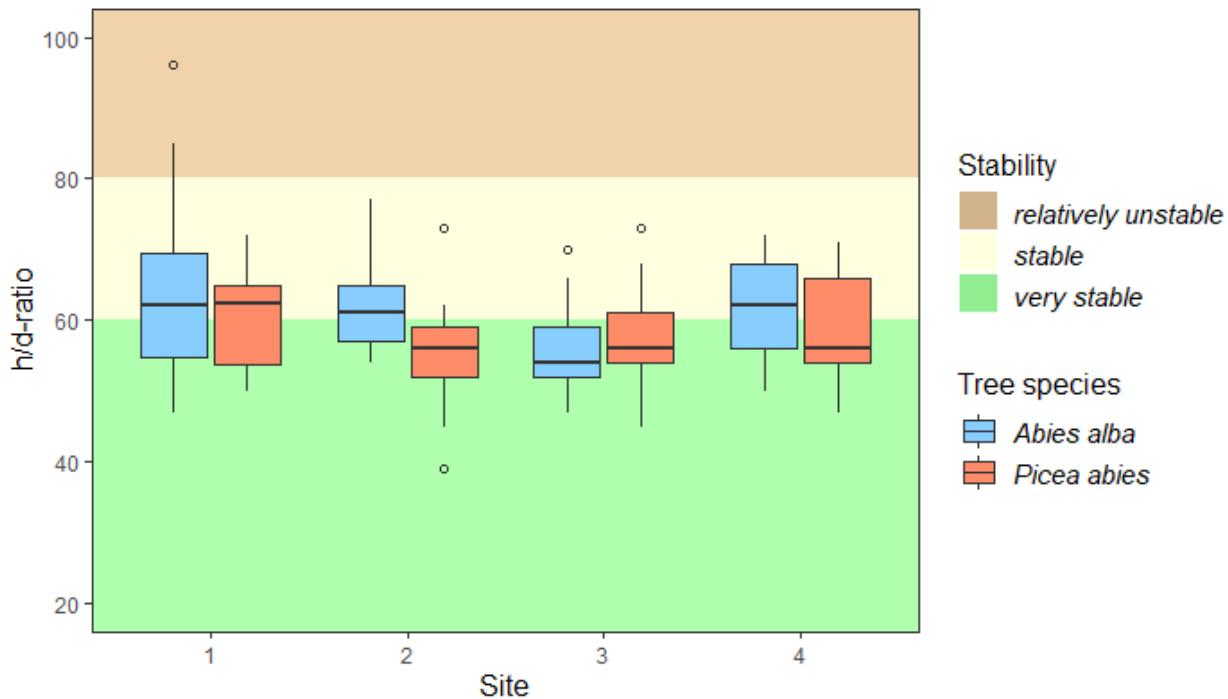


figure 19: Illustrated is the relation of tree height to diameter in breast height of Norway spruce and silver fir trees for every site in form of box-whisker-diagrams. The stability classification is based on publications by ABETZ (1976) and MAYER (1984).

3.2.2. Competition

In order to characterize the sampling trees, it is crucial to have a look on the competition conditions. As already mentioned, crown ratio and h/d-ratio already allow first statements about the competition. The higher the crown ratio and the smaller the h/d-ratio is, the stronger is the dominance within the stand. For a more detailed insight the growing space of each sampling tree

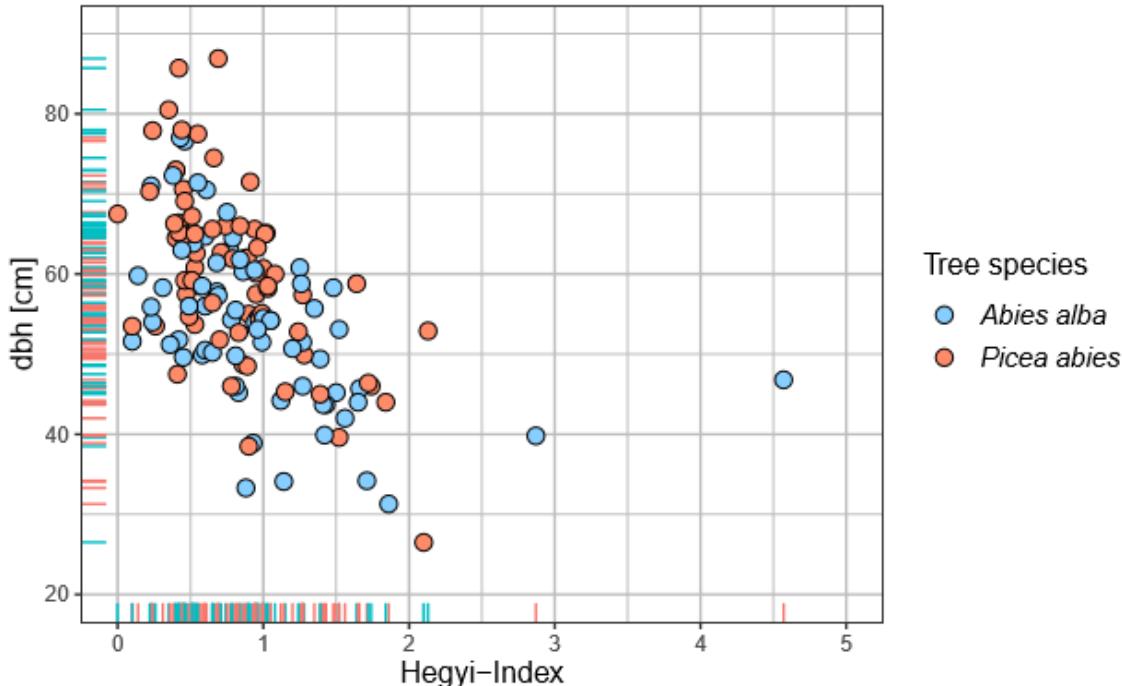


figure 20: The Iterative Hegyi's competition Index (CI) in dependence of diameter in breast height (dbh) of all 142 cored trees. The small lines on the x and y-axis additionally mark the values on the particular axis.

was evaluated by the *Iterative Hegyi's competition Index* (CI). The result is displayed in figure 20. It is recognizable that trees with a larger diameter in breast height (dbh) had smaller CI-values, which indicates less interference from competition. This is confirmed by the computation of the coefficient of correlation ($r = -0.54$). Norway spruces ($\bar{x} = 60 \text{ cm} \pm 11 \text{ cm}$) had a higher mean dbh than silver firs ($\bar{x} = 54 \text{ cm} \pm 9.9 \text{ cm}$), but according to the average competition indices, *Abies alba* ($\bar{x} = 0.95$) and *Picea abies* ($\bar{x} = 0.79$) were not significantly different ($p=0.102$, d.f. = 124.89). Further, the competition indices of silver fir ranged from 0.1 to 4.57, whereas the CI of the specimen of Norway spruce ranged from 0 to 2.13.

3.3. Dendroclimatological analysis

3.3.1. Course of the growth

To see how the firs and spruces grew in the course of time, in figure 21 the development of the basal area increment is plotted. For both species it is recognizable that the basal area increment increased over the years which is common due to the increasing age and diameter. In further consideration differences between the tree species can be made out. The measured tree growth of Norway spruces started 1948 (at least 70 % overlap of all series of all sites) and continued increasing until the mid-1970s. The same goes for the silver firs, in which the measurement started

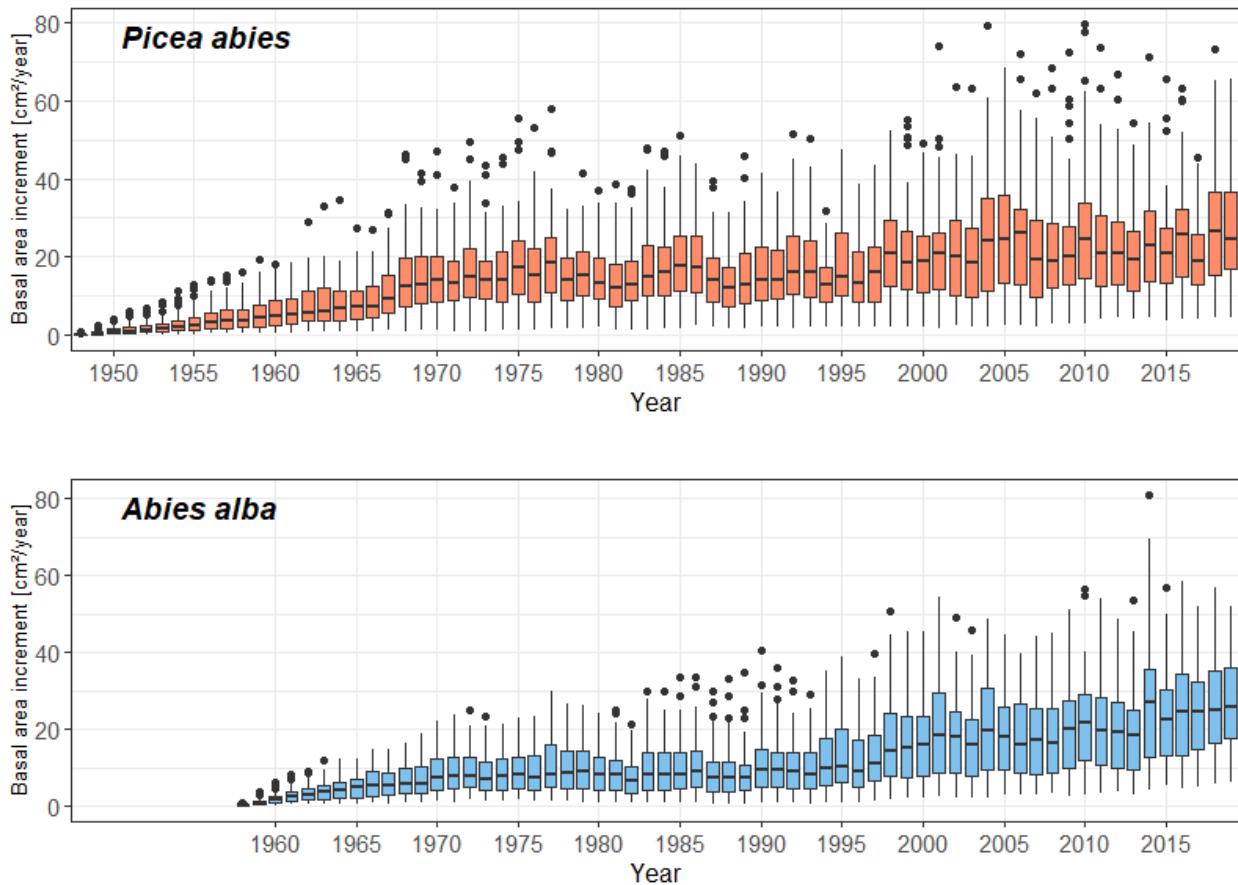


figure 21: Course of the basal area increment of Norway spruce (above, n=68) and silver fir (below, n=67) from 1948, respectively 1958 to 2019. From each of the 135 trees two cores were obtained and averaged to guarantee reliability of the BAI. Presented as box-whisker-diagrams.

ten years later in 1958. Then, in the early 1980s both species recorded growth reductions, followed by an increase of growth from 1983-1986. From 1987-1989 again a significant setback in growth is noticeable. From then the growth of *A. alba* kept increasing constantly up to now with returning growth reductions in the meantime. In the mid-90s (1996), early 2000s (2003) and mid-2010s (2013) several setbacks are measured, whereas for example in 2004 and 2014 exceptionally strong growth can be identified. In return, *P. abies* showed more fluctuations in terms of growth as well as more outliers with stronger growth. Especially the years 1994, 1996, 2003 and 2017 stand out optically as years with a decline in growth. The years with significant growth reactions, referred to as pointer years, are explained in detail later.

3.3.2. Growth fluctuations

In consideration of growth development, it is of interest how the annual growth (annual basal area increment) of the trees differ from one year to another. To visualize this, in figure 23 and figure 22 the year-to-year fluctuations of the basal area increment of *Picea abies* and *Abies alba* is shown for each site. Distinctive is that the fluctuations got stronger with an increasing age, which can be partly attributed to the also increasing basal area, but mainly those fluctuations are caused by external influences like climatic conditions or management activities. Further, it is characteristic that the fluctuations for both species were much stronger on site 1 and 2 than on site 3 and 4.

In general, Norway spruce revealed much more distinctive fluctuations (several times up to $>10 \text{ cm}^2 \text{ year}^{-1}$) than silver fir (once close to $10 \text{ cm}^2 \text{ year}^{-1}$). On all sites, *P. abies* fluctuated more intense and the fluctuations started to become stronger and stronger from 1970 on. *A. alba* however started later (somewhere between 1980 and 1990) and the deviations were less intense. The in chapter 3.3.4 explained results of the pointer year analysis are concordant to the negative and positive fluctuations. Besides, due to the increasing fluctuations in time the figures remind of a trumpet shape.

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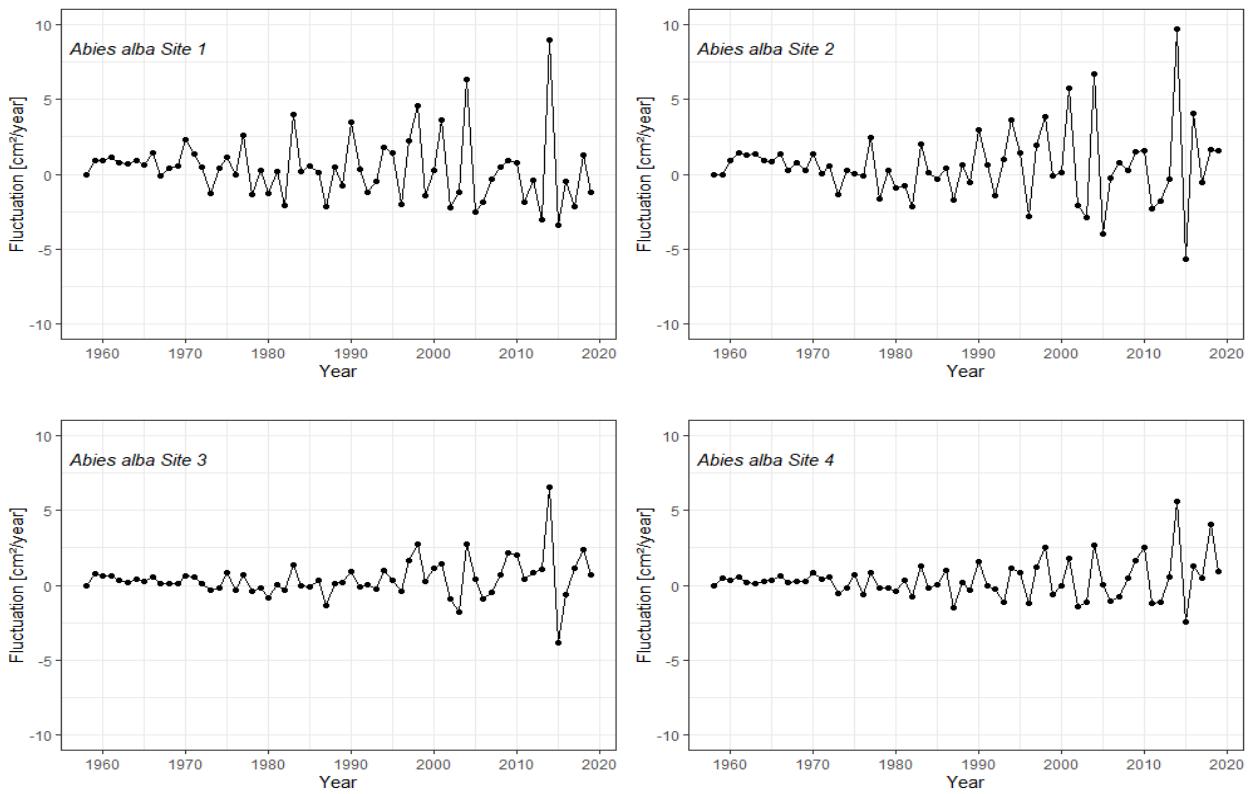


figure 23: Year to year fluctuations of *Abies alba* separated by site.

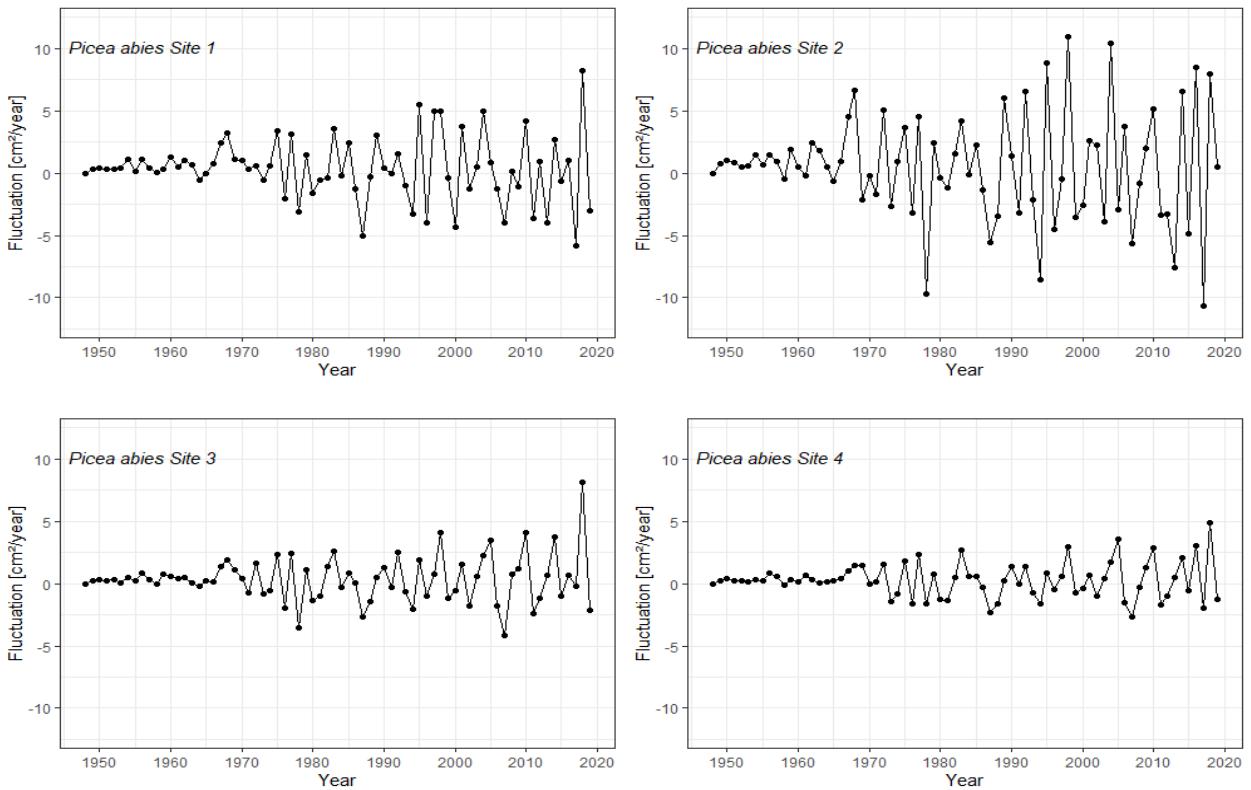


figure 22: Year to year fluctuations of *Picea abies* separated by site.

3.3.3. Chronology characteristics

Overall, 284 increment cores were obtained during field work and were later prepared and measured in the laboratory. 270 cores were included in the analysis. Some samples were omitted due to missing rings, rotten wood or insignificance within the chronology. For the standardization of the raw ring width data, exponential smoothing and cardinal splines were applied as methods of detrending. The decision criteria which method was used for further analysis were EPS, SNR and mean signal strength of the resulting chronologies. The selection was made individually for every chronology. For the obtained data set, the method of exponential smoothing was always more advantageous compared to cardinal splines. Based on the resultant detrended tree ring indices, mean chronologies were built for each site and species. Those are presented in figure 24 & figure 25. In addition, the general information as well as statistical criteria of all mean index chronologies are shown in table 2. Of the 71 obtained silver fir increment series four got omitted, whereas three of the 71 Norway spruce increment series got excluded from further analysis due to lack of significance within the chronology. The chronologies of Norway spruce, where at least 70 % of the series were present, reached further back than the silver fir chronologies. The shortest chronologies go back to 1958 (*A. alba*), respectively 1948 (*P. abies*). The average annual tree ring width of both species was approximately the same, but site 1 and 2 revealed larger average tree ring widths (close to 3 mm) for fir and spruce than on site 3 and 4 (close to 2 mm).

Mean sensitivities were broadly similar within the same tree species, but the chronologies of Norway spruces (0.173-0.199) showed a higher mean sensitivity than of the silver firs (0.125-0.167). So, the percentual change in ring width from one ring to subsequent one was higher within *Picea abies*. The Gleichläufigkeit reached values around 60-65 %. This means that the growth signs for consecutive years of each chronology agree to 60-65 %. SNR and EPS (including the mean signal strength) serve as quality measure for the chronologies. First, the signal-to-noise ratio ranged between approximately 13-23 for *Abies alba* and 11-15 for *Picea abies*. This means that in case of *Abies alba*, for example on site 1, the climate signal is 23 times stronger than the noise. As can be seen from the table, the SNR of the silver fir chronologies were always higher than for the equivalent Norway spruce chronologies. Besides, for both species site 1 and 2 had a higher SNR than site 3 and 4. The EPS of each chronology ranged between 0.915 and 0.958, whereas the EPS of silver fir were slightly higher.

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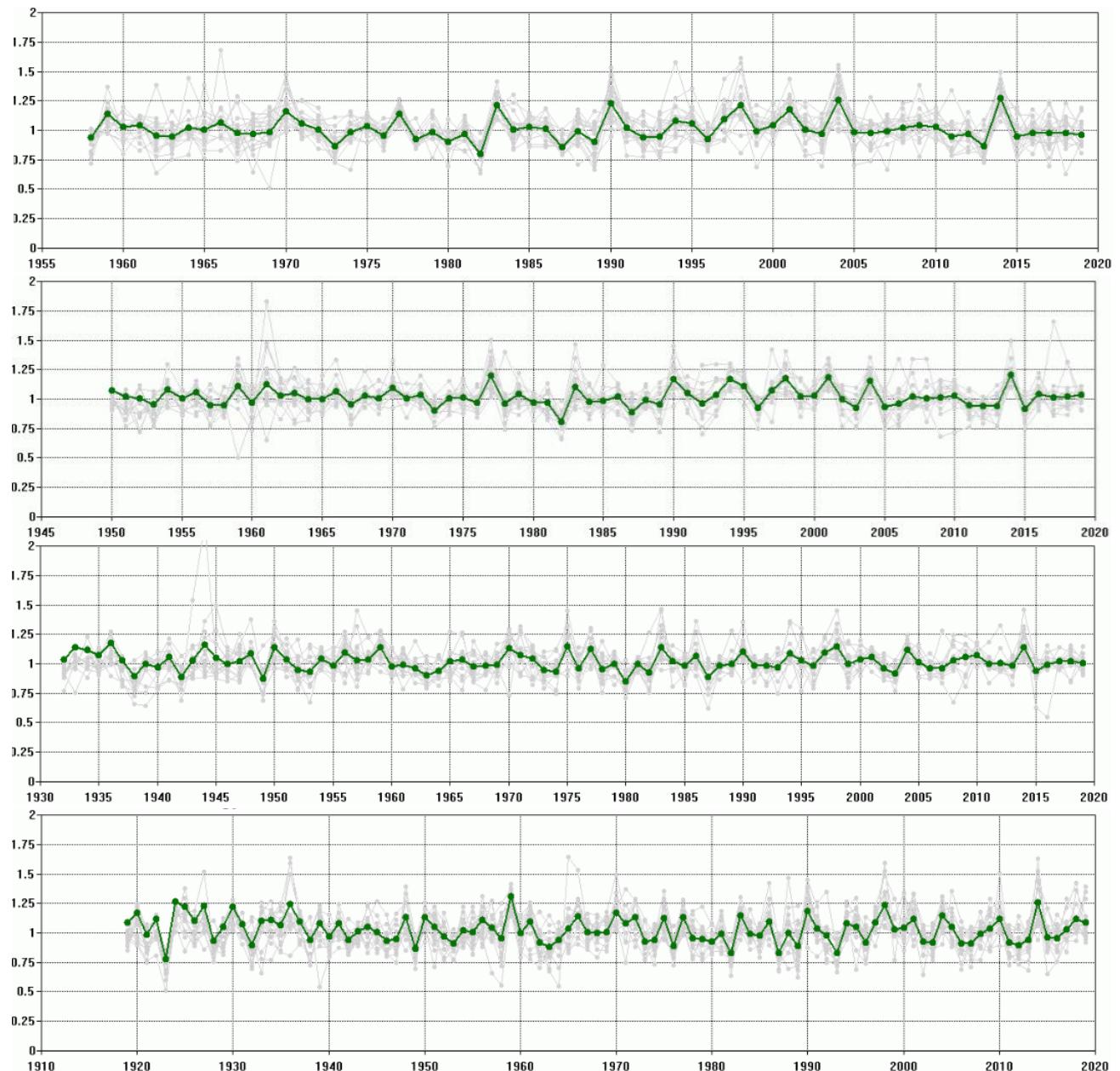


figure 24: Computed mean index chronologies of *Abies alba* for each site. Listed according to the order of the site numbers: 1, 2, 3, 4. The red line marks the mean index chronology, whereas the grey lines display the tree ring indices which are included in the chronology. Note the different time scales on the x-axis

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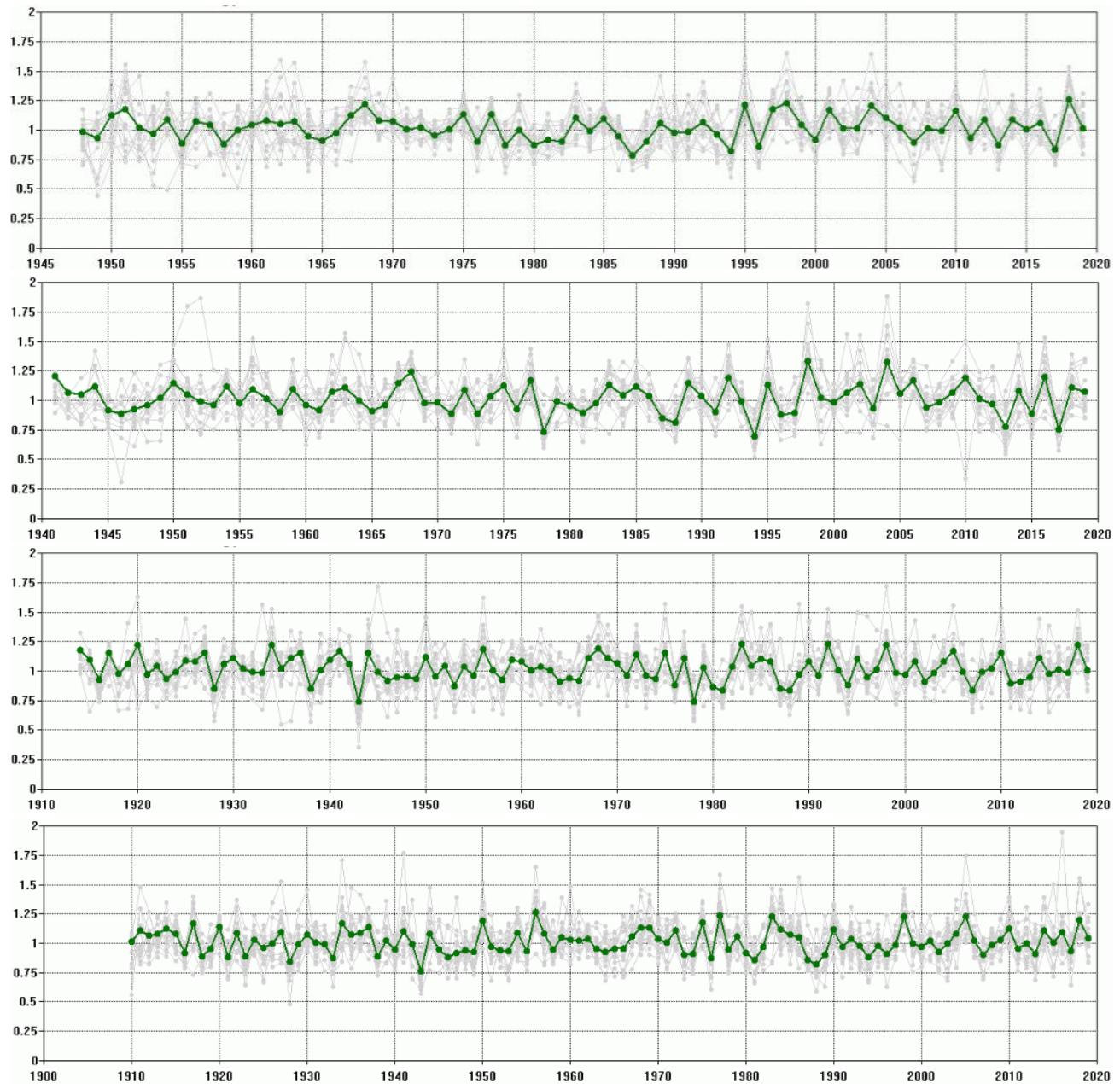


figure 25: Computed mean index chronologies of *Picea abies* for each site. Listed according to the order of the site numbers: 1, 2, 3, 4. The red line marks the mean index chronology, whereas the grey lines display the tree ring indices which are included in the chronology. Note the different time scales on the x-axis

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table 2: Overview of general information and statistical parameters of all built chronologies. Annual tree ring width [mm]= shown as mean \pm standard deviation. Every tree got cored twice in opposite direction, rectangular to the slope.

Tree Species	Site	Number of cored trees	Annual tree ring width [mm]	Period with minimum 70 % presence	Series with significant signal strength	Mean sensitivity	Applied detrending method
<i>Abies alba</i>	1	20	2.95 ± 1.05	1958-2019	19	0.158	Exponential Smoothing
	2	17	2.91 ± 1.09	1950-2019	16	0.134	Exponential Smoothing
	3	17	2.24 ± 1.13	1932-2019	15	0.125	Exponential Smoothing
	4	17	2.13 ± 0.90	1919-2019	17	0.167	Exponential Smoothing
<i>Picea abies</i>	1	20	2.67 ± 1.07	1948-2019	18	0.197	Exponential Smoothing
	2	17	3.13 ± 1.16	1941-2019	17	0.199	Exponential Smoothing
	3	17	2.15 ± 0.81	1914-2019	16	0.181	Exponential Smoothing
	4	17	2.03 ± 0.96	1910-2019	17	0.173	Exponential Smoothing

Tree Species	Site	Mean signal strength of the chronology	Signal-to-noise ratio (SNR)	Expressed population signal (EPS)	Gleichläufigkeit (Glk)
<i>Abies alba</i>	1	0.548	23.107	0.958	62.5
	2	0.540	18.836	0.949	62.9
	3	0.473	13.489	0.930	60.1
	4	0.432	12.957	0.928	63.5
<i>Picea abies</i>	1	0.456	15.119	0.937	59.7
	2	0.457	14.320	0.934	64.4
	3	0.434	12.298	0.924	62.8
	4	0.389	10.855	0.915	60.9

3.3.4. Pointer year analysis

Based on the mean index chronologies of each site and species, the negative and positive pointer years were determined. The summarized results are illustrated in table 3. The summary begins at year 1958, because from that point of time on all chronologies from both species were present. Several things from this figure are worth mentioning: The year 1977 was a significant (1x highly significant) positive pointer year for both species on all four sites, whereas the year 2014 was only a positive significant (2x highly significant) pointer year for *Abies alba*. 1998 and 2004 were in general for both species conducive to growth. In contrast to that is the year 1987, which stands out due to a striking setback in growth. *Abies alba* (1x highly significant) and *Picea abies* (2x highly significant) show both negative significant pointer values for that particular year across all sites. The year 1982 should also be mentioned, since within this year only silver fir has experienced negative growth reactions. Highly significant pointer values can be seen on three of the four sites. The equivalent year in which only Norway spruce recorded negative growth is the year 2017 (1x highly significant, 2x significant). Below, the chronologies with the tagged pointer years of fir and spruce on site 1 are compared as an example to get a more detailed insight (figure 26). The other chronologies including the pointer years are attached in the appendix (figure 42 & figure 43).

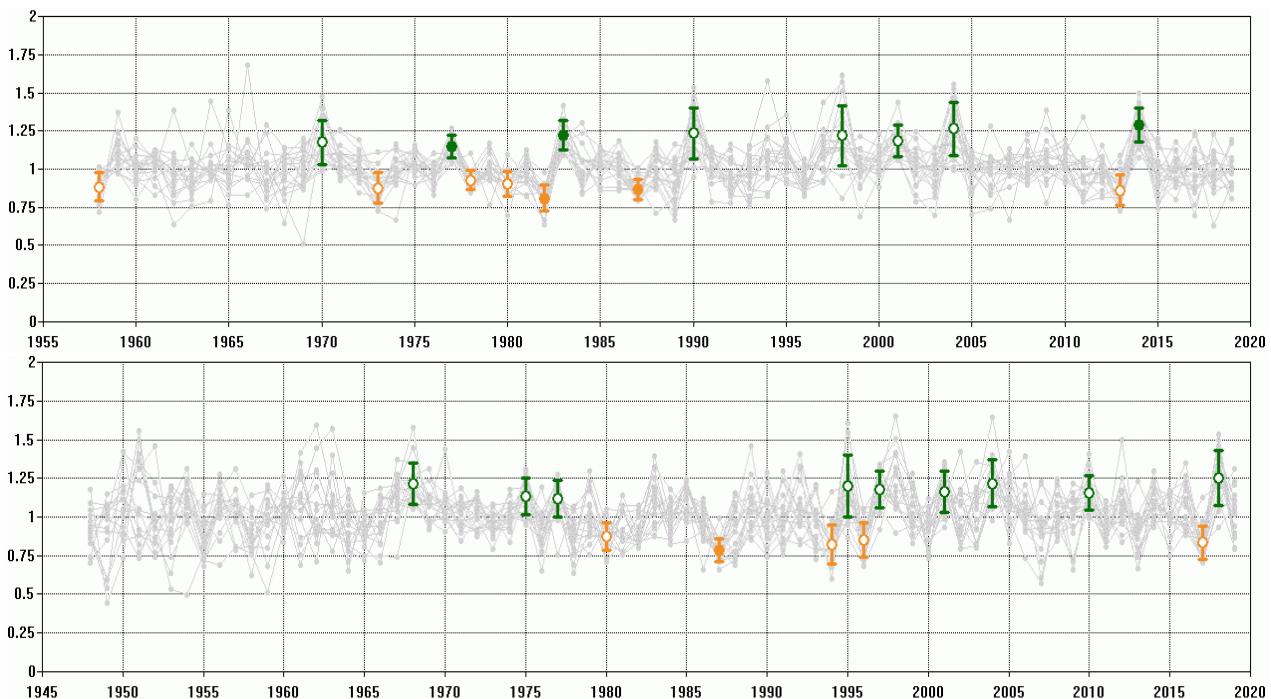


figure 26: Illustrated are the tree ring index series with the corresponding pointer years of silver fir since 1958 (above), respectively of Norway spruce since 1948 (below) for site 1. Orange colour indicates negative pointer years, whereas dark green colour represents positive pointer years. Empty circles correspond to significant pointer values and filled circles to highly significant pointer values. In addition, whiskers are attached to the circles indicating the variability. Note the different time scales on the x-axis.

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table 3: Overview of the positive and negative pointer years from 1958 to 2019. Years with distinctive characteristics are marked bold.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
<i>Abies alba</i>	Site 1																					
	Site 2																					
	Site 3																					
	Site 4																					
<i>Picea abies</i>	Site 1																					
	Site 2																					
	Site 3																					
	Site 4																					

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<i>Abies alba</i>	Site 1																					
	Site 2																					
	Site 3																					
	Site 4																					
<i>Picea abies</i>	Site 1																					
	Site 2																					
	Site 3																					
	Site 4																					

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
<i>Abies alba</i>	Site 1																	
	Site 2																	
	Site 3																	
	Site 4																	
<i>Picea abies</i>	Site 1																	
	Site 2																	
	Site 3																	
	Site 4																	

 Highly significant negative pointer year
 Significant negative pointer year

 Highly significant positive pointer year
 Significant positive pointer year

According to the results, 1987 was the year in which both species showed clearly negative growth reactions on all sites. For this reason, 1987 becomes the focus of further analyses.

3.3.5. Evaluation of possible extreme climatic events

For the determination and quantification of extreme climatic events two indices were applied on the obtained climate data set, the *DeMartonne aridity-humidity index* and the *standardized precipitation evapotranspiration index*. To begin with, the DMI, respectively the DMI of the vegetation period (DMI_{ijja}) over the course of the years are illustrated in figure 27. It can be seen that the mean of the DMI was close to 5, indicating cool and wet conditions. The DMI_{ijja} on the other hand with a mean of 0.92 indicates relatively dry and warm conditions. For both, the late 1940s, 1980s and late 1990s showed drier and warmer conditions than the average. But no striking outliers were shown. Whether the DMI nor the DMI_{ijja} revealed mentionable drought events that happened in the year 1987, which was determined as the year with the most distinctive negative growth reaction.

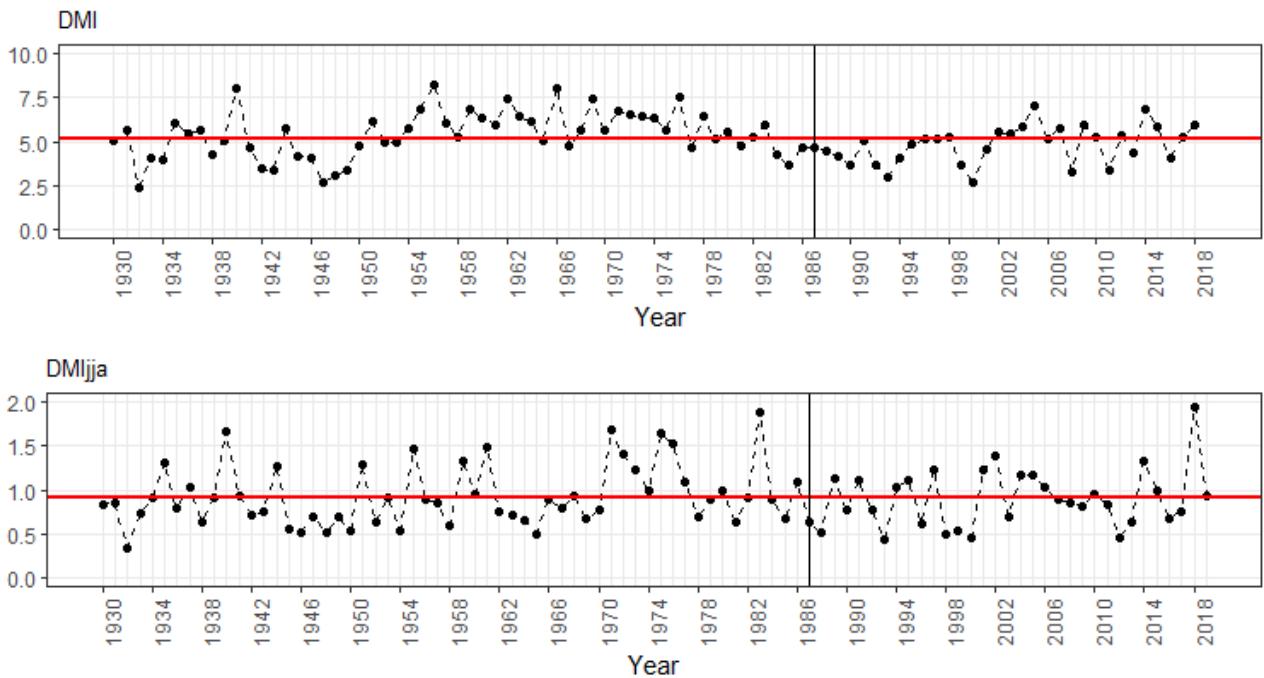


figure 27: DeMartonne aridity-humidity index (DMI) and the DMI of the vegetation period (DMI_{ijja}) for the period 1930–2019. The vertical lines tag the year negative pointer year 1987, whereas the red horizontal line indicates the long-term mean. Note the different scaling on the y-axis.

The same results were achieved by the SPEI, which is shown in figure 29. No significant dry conditions, respectively drought events were observed for the year 1987 or years before. In contrast

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to the DMI, SPEI showed a dry period for the year 2015. But according to the pointer year analysis this year was not a significant negative pointer year.

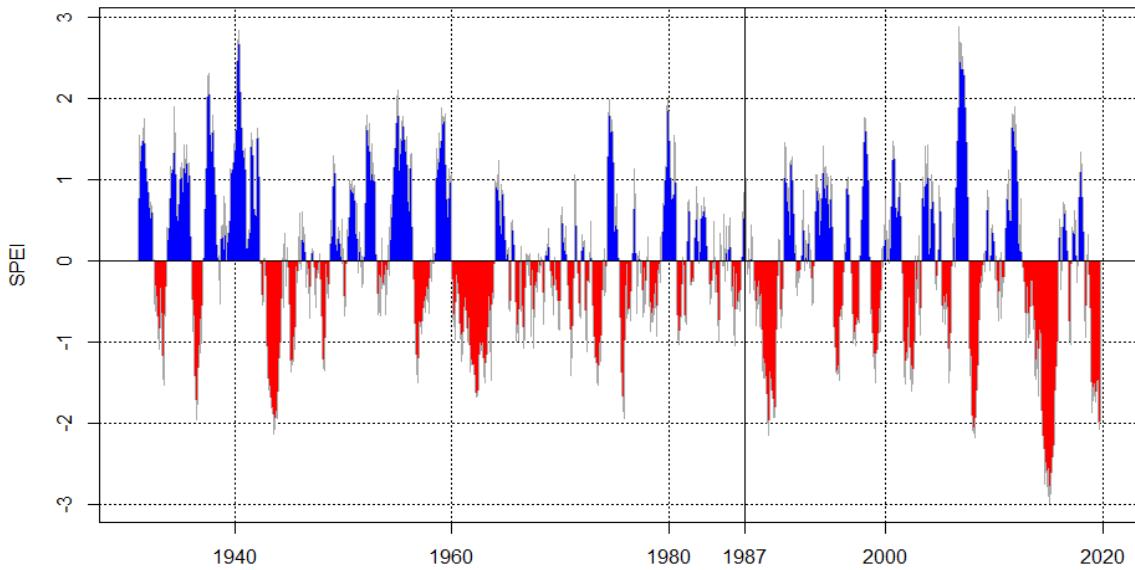


figure 29: Spatial distribution of 12-month SPEI over the course of 1930-2019. Blue colour indicates wet periods, whereas red colour stands for dry periods. The year 1987 is tagged due to the results of the pointer year analysis.

Based on those results, it can be assumed that an extreme drought event was not the source for the growth setback in 1987. To find possible causes, this particular year was observed in more detail. In this regard a Walther-Lieth-diagram was made taking only the year 1987 into account. The result is shown below in figure 28. It can be recognized that frost events occurred until May and the monthly mean temperature was below 0 °C in January and March. In March daily minimum temperatures of -23.6 °C were reached. In seven months of the year frost events were noted. Further, August and September had low precipitation. Especially the month of September was a dry and arid month with a precipitation sum

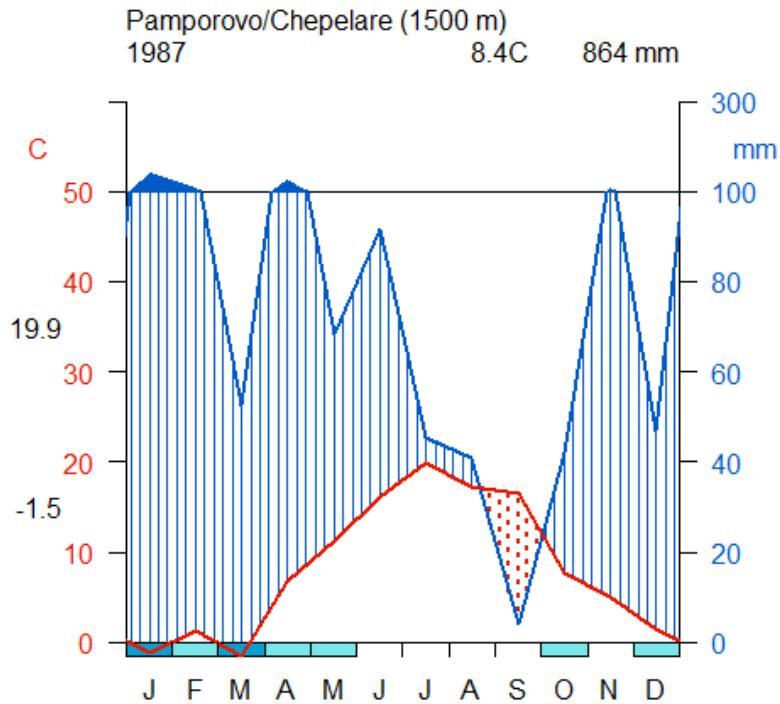


figure 28: Walther-Lieth diagram for the year 1987.

of only 3.9 mm. In summary, the year 1987 is characterized by a cold and long winter with many frost events and a dry late summer.

3.3.6. Growth response to disturbance in 1987

Of special interest is, how Norway spruce and silver fir responded to the disturbance back in 1987 and if there were any differences between the species response. Hence, the resistance, recovery and resilience of both tree species were examined while considering a triannual period before and after the stress event. In figure 30 the growth response of both tree species is shown.

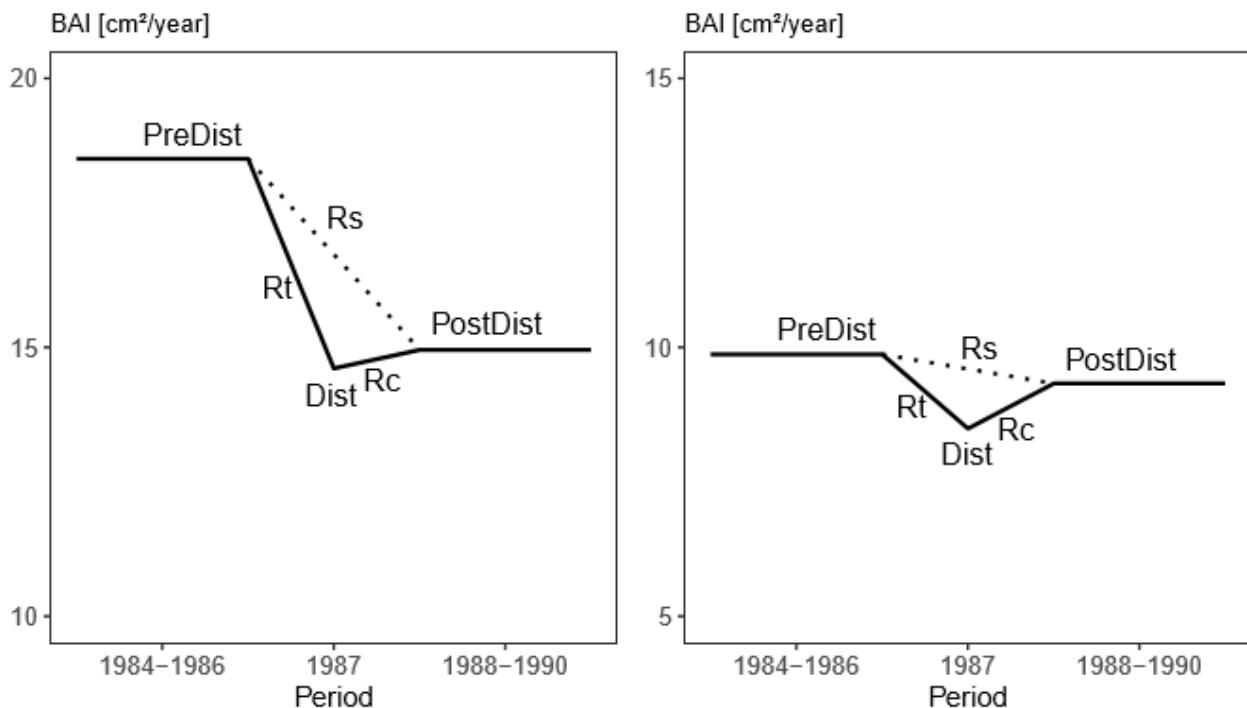


figure 30: Growth response of Norway spruce (left) and silver fir (right) to the stress event in 1987. Characterized by growth in a triannual period before (PreDist), the year of the stress event (Dist) and a triannual period after the disturbance (PostDist) (modified after LLORET ET AL. (2011) and PRETZSCH ET AL. (2013)). Indices for resistance, Rt = Dist/PreDist, recovery, Rc = PostDist/PreDist and resilience, Rs = PostDist/PreDist are applied to describe the stress response patterns. Note the different scaling on the y-axis.

Picea abies had an overall higher mean basal area increment of $18.5 \text{ cm}^2 \text{ year}^{-1}$ in the period before the disturbance than *Abies alba* ($9.9 \text{ cm}^2 \text{ year}^{-1}$). During the event of disturbance, the annual growth dropped down to $14.6 \text{ cm}^2 \text{ year}^{-1}$ for spruce and to $8.5 \text{ cm}^2 \text{ year}^{-1}$ for fir. Despite the growth reduction, the BAI of spruce was still clearly higher than that of fir. After the stress event, the annual basal area increment increased again to $14.9 \text{ cm}^2 \text{ year}^{-1}$ (*P. abies*), respectively $9.3 \text{ cm}^2 \text{ year}^{-1}$ (*A. alba*). For a more detailed insight into the stress reactions of all measured trees, in figure 31 resistance and resilience are considered. In A, the annual basal area increment in 1987

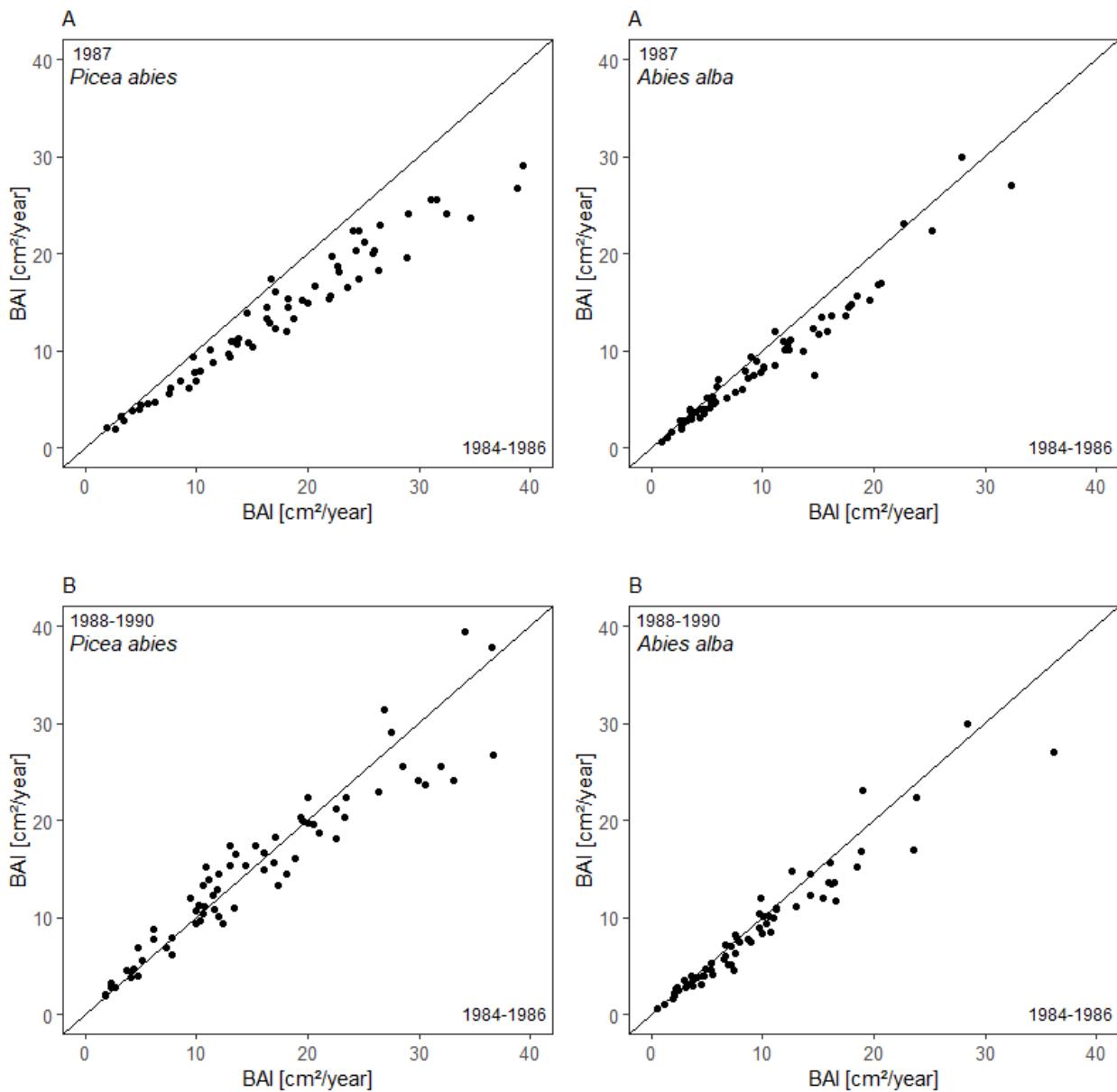


figure 31: Resistance (A) and resilience (B) of Norway spruce (left) and silver fir (right) regarding the year of disturbance 1987. (A) Relationship between annual growth (BAI in $\text{cm}^2 \text{ year}^{-1}$) in 1987 and in the triannual reference period 1984-1986. (B) Relationship between annual growth in the three-year period after 1987 and in the three-year reference period. Based on figures presented by PRETZSCH ET AL. (2013).

is plotted over the mean basal area increment in the period before the disturbance (1984-1986). Every point corresponds to one tree. Assuming that the disturbance did not influence the growth of the trees, the points would match with the bisector line. This would indicate an optimal resistance. Almost all points within the scatterplot for spruce and fir are below the bisector line. Especially the spruce trees depart significantly from the bisector line. This indicates that the trees, and foremost Norway spruce, were negatively affected by the disturbance. In part B of the figure it is shown how well those trees endure the effects of the disturbance. The mean basal area increment in the triannual period after the disturbance (1988-1990) is plotted over the mean growth in the reference

period 1984-1986. Points directly on or close to the bisector line suggest perfect resilience, whereas observations below the line are a sign for continuous growth reduction after the disturbance. Symbols above the line indicate that the growth after the disturbance exceeds the growth in the reference period. While the observations for fir are very close to the bisector line, the observations for spruce fluctuate much more. Most of the points are below the line, but many points are over it as well. So, the impact of the disturbance negatively influenced many spruces in terms of growth in following years. But a mentionable amount showed good resilience and even exceeded the growth level before the event. Silver fir trees were less affected, and a large proportion reached the reference growth level. This leads to the conclusion that spruce is much more affected by the disturbance than silver fir.

The relative growth response is given in figure 32. Basal area increment of *P. abies* decreased in 1987 by 21 % ($R_t, \bar{x} = 0.79$) compared to the reference period 1984-1986, while *A. alba* recorded an average decrease by 14 % ($R_t, \bar{x} = 0.86$). The differences in terms of resistance between the species were significant ($p = 0.0006$, d.f. = 122.7). Silver fir ($R_c, \bar{x} = 1.10$) recovered significantly better than Norway spruce ($R_c, \bar{x} = 1.0$) ($p = 0.001$, d.f. = 131.98).

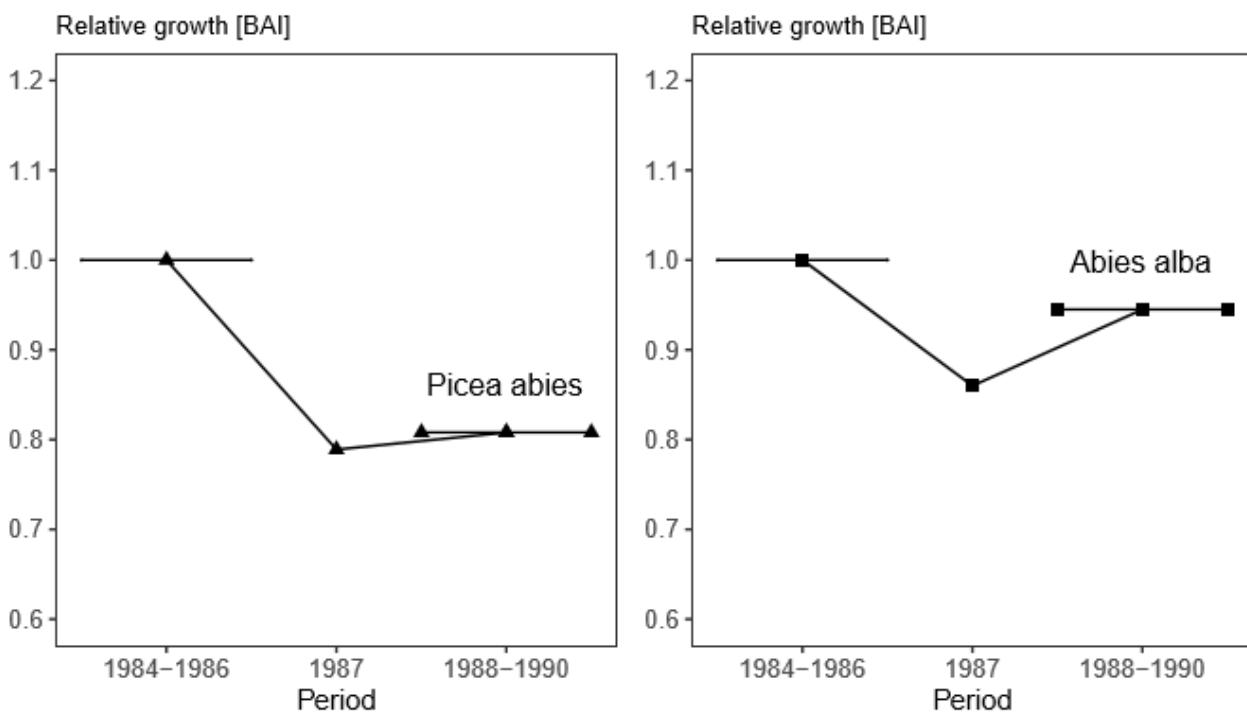


figure 32: Species-specific growth responses to the disturbance in the year 1987. The growth reaction is shown in relation to the mean growth level of the triannual reference period 1984-1986 before the disturbance (reference line = 1.0). The courses represent the growth in the year of disturbance 1987, and in the period of recovery 1988-1990 in relationship to the reference period before the event. Reaction of *P. abies* on the left, respectively *A. alba* on the right side.

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Within the three-year period after the stress event, fir reached 95 % ($Rs = 0.95$) and spruce 81 % ($Rs = 0.81$) of the annual growth level of the reference period. Hereby, the overall difference between the tree species was highly significant ($p = <0.0001$, d.f. = 131.29).

It becomes clear, that Norway spruce had an overall higher annual growth, but the growth reduction due to the stress event was significantly stronger than of silver fir. Besides, the recovery of the spruces was also significantly lower than of the fir trees. So, spruce reacted more sensitive to the disturbance and growth was affected for a longer period.

It is also important whether there were differences between the sites in terms of growth reactions. In this regard, figure 33 represents the resistance and resilience of all trees of both species in dependence of the sites. The dotted line indicates optimal resistance, respectively resilience. In case

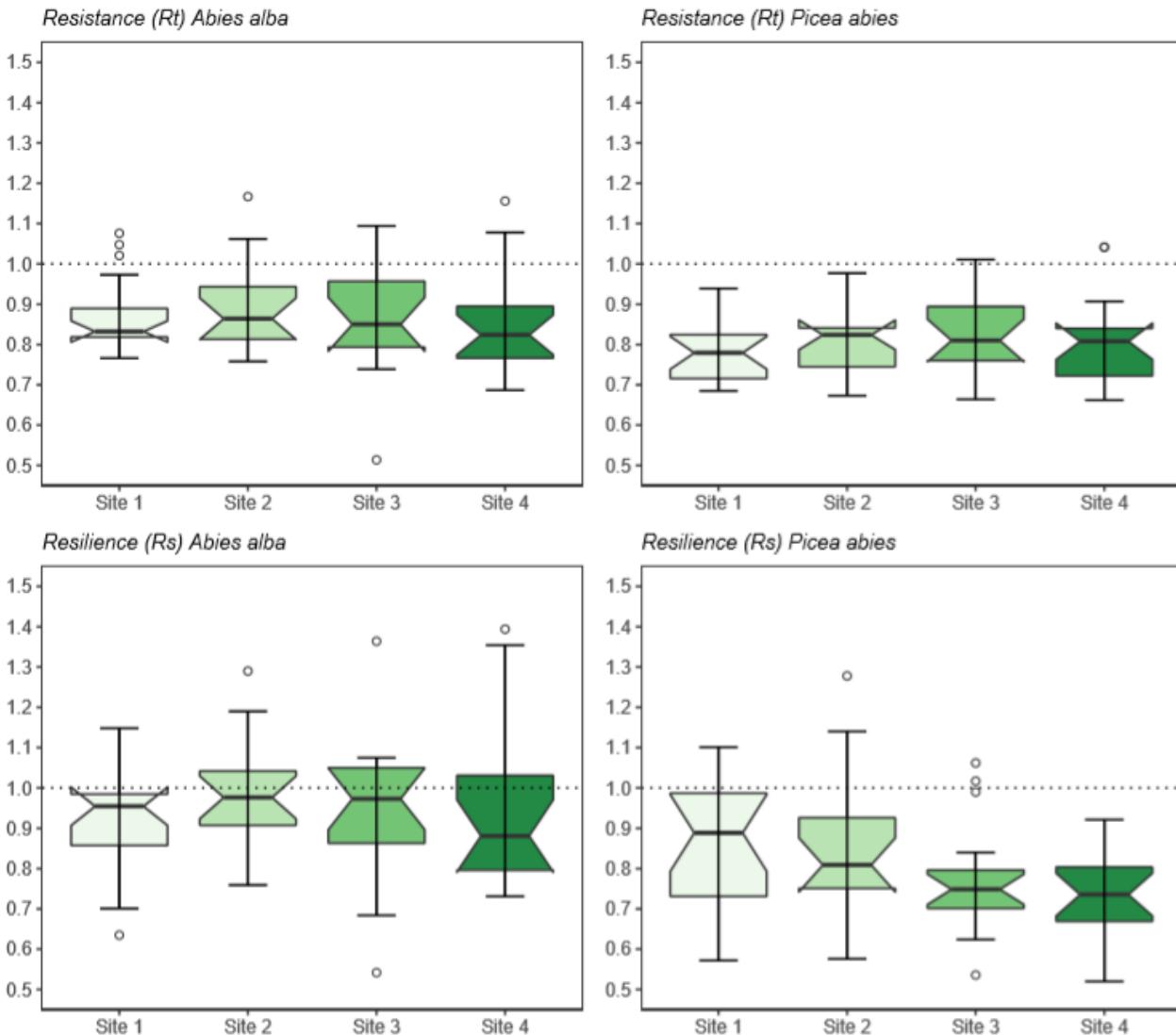


figure 33: Resistance (above) and resilience (below) of silver fir (left) and Norway spruce (right) in dependence on the sites regarding the stress event in 1987. Presented as notched box-whisker-diagrams. The notch marks the 95 % confidence interval of the median.

of resistance, values below this threshold imply that the trees were negatively influenced by the stress event in 1987, whereas values above this line even indicate increased growth. For resilience, observations above the line show that the trees had higher growth in the period after the event than during the three-year reference period before the disturbance. If the values are below the line than in the following years, the trees were still negatively affected. The data is presented in form of notched box-whisker plots at which the notch corresponds to the 95 % interval of the median. It is considered proven, that if the notches do not overlap the median differs. It can be seen, there were differences between tree species and sites. As already described, overall *A. alba* showed a significantly higher resistance and resilience than *P. abies*. Considering the sites, however, there were no significant deviations regarding resistance and resilience. But there were noticeable discrepancies in respect of resilience of Norway spruce trees on site 4 in comparison to all fir sites. The Norway spruces on this site differed significantly from site 1 ($p = 0.002$), 2 ($p < 0.001$), 3 ($p = 0.002$) and 4 ($p = 0.002$) of *A. alba*. There were no significant differences between site 1 and 2 of *P. abies* and sites 1-4 of *A. alba*. That site 3 and 4 of Norway spruce had comparatively low resilience values can also be derived from figure 33. The disparity of those sites in comparison to site 1 and 2, however, is not significant. To mention is that no spruce tree on site 4 and only a small amount on site 3 reached the growth level of the reference period after the disturbance. Overall, silver fir had a higher resistance and resilience and did not differ regarding site, whereas Norway spruce reacted, especially on site 3 and 4, more sensitive to the stress event.

3.3.7. Determination of the climate-growth relationship of *P. abies* and *A. alba*

Not only the response to disturbances is of interest, but also the general relationship between tree growth and climate. In this regard program CLIMTREG was utilized to detect which climate variables in which time periods influence the growth of Norway spruce and silver fir in the Western Rhodopes. In the following section all results regarding correlations between climate variables and tree growth is described. Statistical values for the evaluation of the performance quality of each model are listed in the appendix (table 4).

3.3.7.1. Climate-growth relationship of *Abies alba* (1958-1987)

Concerning the influence of climate variables, a similar picture emerged at all four sites for silver fir. The climate parameter, which correlated in the period 1958-1987 the highest to the tree ring index (TRI), was temperature. The time intervals in which the temperature affected tree growth coincided between all sites. This is presented in detail in figure 34. It becomes clear that in the months of November (previous year) to early April (current year) the mean temperature show high positive correlations towards the growth of the fir trees. This indicates that with a higher temperature the growth increased and vice versa. For example, on site 4 the tree ring index positively correlated quite strong) with the mean temperature of wintertime, respectively the time spans of 4th November- 8th February ($r = 0.63$) and 20th February- 3rd May ($r = 0.69$). Similar time spans with likewise high correlations can be noticed for the other three sites (Site 1: $r = 0.61$; Site 2: $r = 0.67$; Site 3: $r = 0.65$). Further, on all sites negative correlations of the previous year July temperature to the growth of silver fir can be noticed, whereas the correlations were less strong (Site 1: $r = -0.47$; Site 2: $r = -0.39$; Site 3: -0.39 ; Site 4: -0.38) in comparison to the winter temperatures. Furthermore, the mean temperature of the current year mid-September to end of October also showed very high negative correlations on all sites (Site 1: $r = -0.54$; Site 2: $r = -0.59$; Site 3: -0.50 ; Site 4: -0.58). This negative relation means that the higher the temperatures in this time interval was, the lower was the growth. Therefore, it can be concluded that high temperatures in winter positively influenced growth, whereat a reverse situation can be noticed for July and late summer temperatures. Regarding the influence of precipitation on growth, it can be said that early summer precipitation between end of May and end of July of the current year was important for *Abies alba* (appendix; figure 44). The precipitation within this time span is on all sites positively correlated with the tree ring indices, the growth of the firs (Site 1: $r = 0.65$; Site 2: $r = 0.49$; Site 3: $r = 0.60$; Site 4: $r = 0.63$). However, precipitation in late winter (mid-February to mid-March) showed negative correlations (Site 1: $r = -0.47$; Site 2: $r = -0.44$; Site 3: $r = -0.47$; Site 4: $r = -0.48$). Furthermore, several connections between the growth of *A. alba* and relative humidity was noticed (figure 35). At each of the four sites, there were negative correlations between relative humidity and the TRI for the time span between mid-February and mid-April (Site 1: $r = -0.49$; Site 2: $r = -0.54$; Site 3: $r = -0.38$; Site 4: $r = -0.43$) as well as October of the current and the previous year. Positive correlations were observed for June/ July (Site 1: $r = 0.51$; Site 2: $r = 0.53$; Site 3: $r = 0.60$; Site 4: $r = 0.54$).

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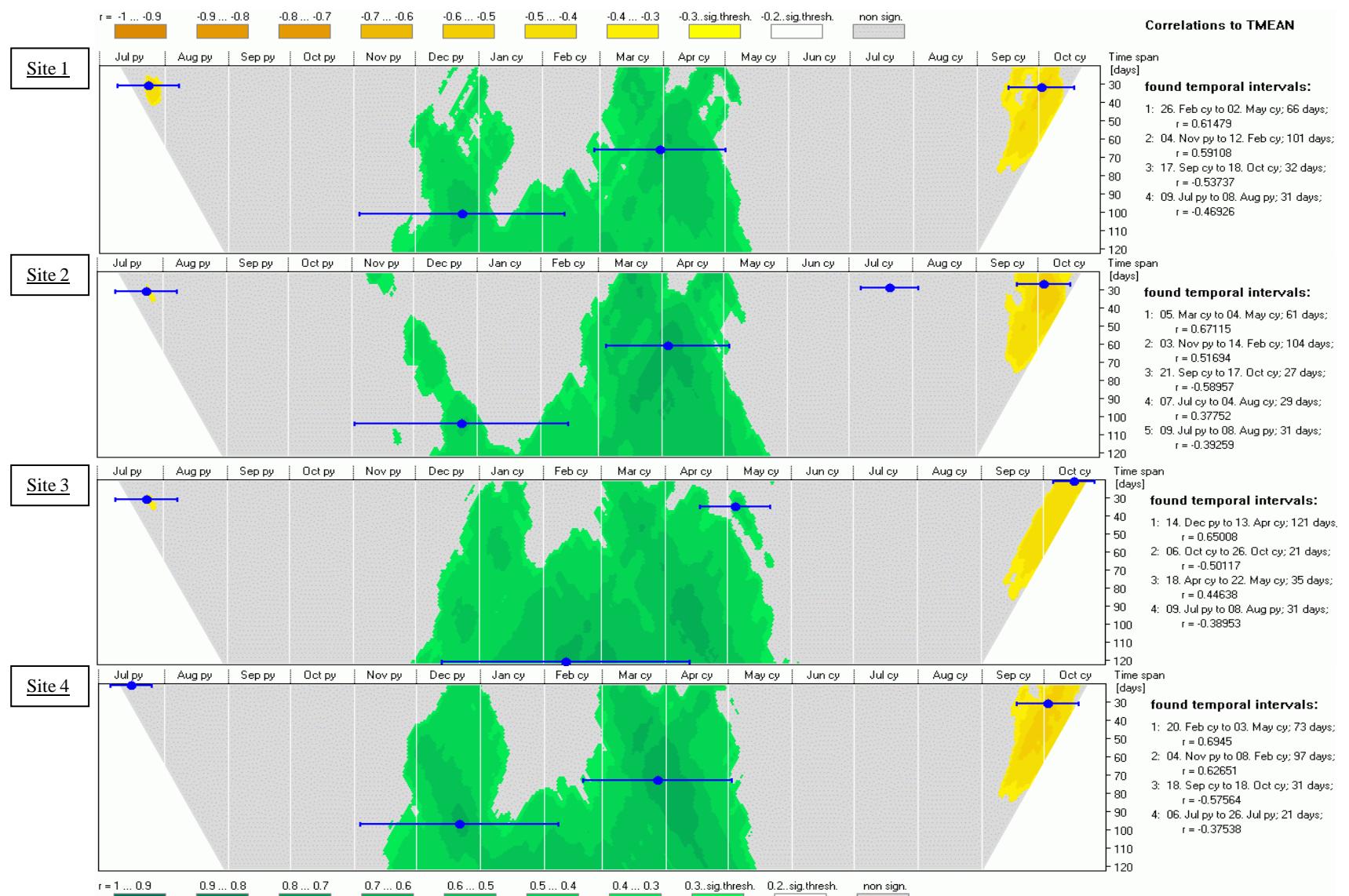


figure 34: Time intervals with the highest correlations of mean temperature to the tree ring indices of *Abies alba* for each site (period 1958-1987). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

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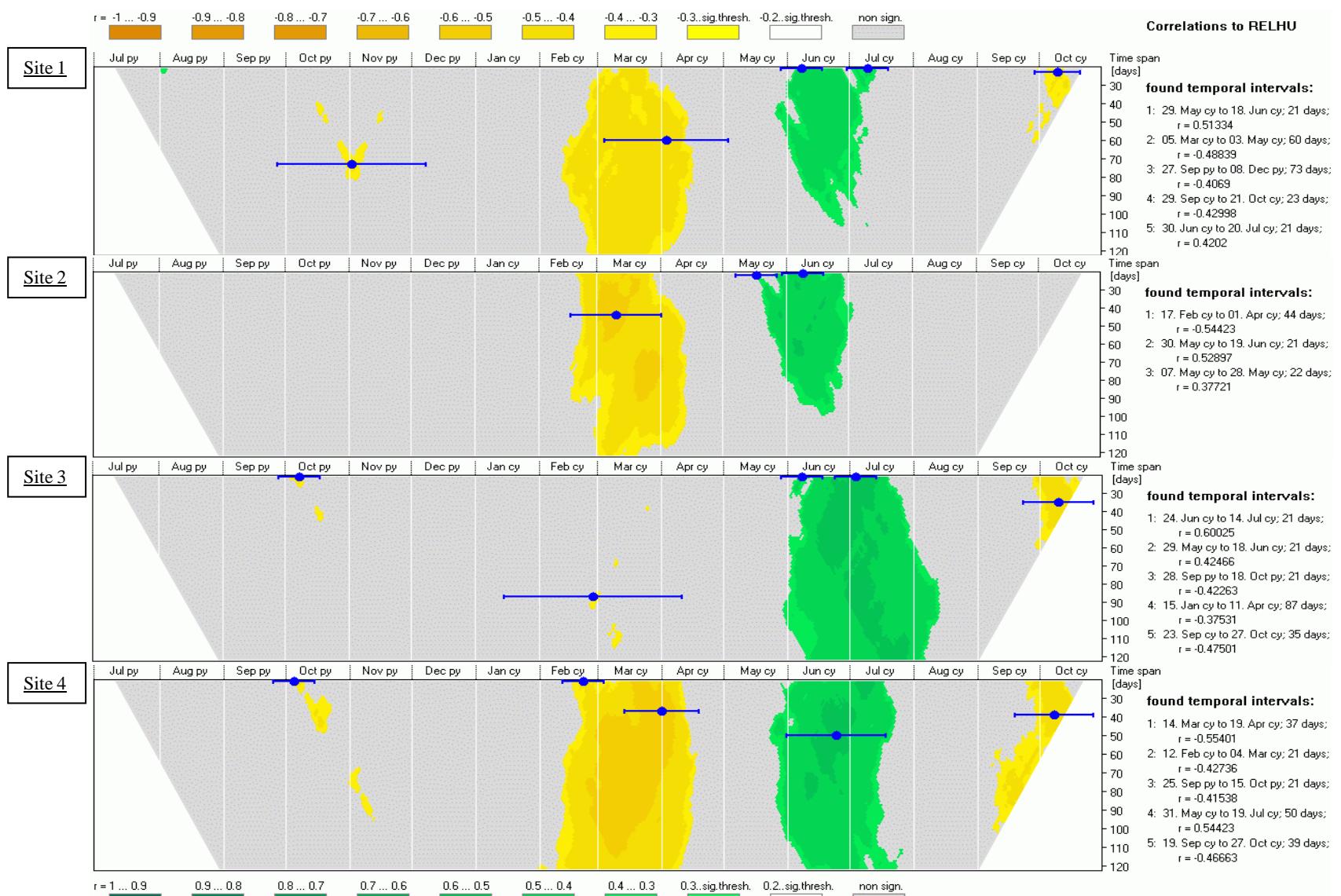


figure 35: Time intervals with the highest correlations of relative humidity to the tree ring indices of *Abies alba* for each site (period 1958-1987). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

3.3.7.2. Climate-growth relationship of *Picea abies* (1958-1987)

In case of Norway spruce, in the period 1958-1987 the growth highly correlated positive with mean temperature in springtime, respectively from late March to end of May on all sites (Site 1: $r = 0.74$; Site 2: $r = 0.62$; Site 3: $r = 0.68$; Site 4: $r = 0.70$). Furthermore, at site 2, 3 and 4 negative relationship between the temperature and TRI was noticed. There, the late summer/ autumn temperatures (end of September and October) of the current year (Site 2: $r = -0.37$; Site 3: $r = -0.50$; Site 4: $r = -0.57$) correlated negatively with growth. For a better understanding, the temperature-growth relationship of *Picea abies* is given in figure 36.

In terms of precipitation Norway spruce showed positive correlations during summertime (Site 1: $r = 0.54$; Site 2: $r = 0.53$; Site 3: $r = 0.66$; Site 4: $r = 0.60$). The precipitation within end of March and end of May, on the other hand, was related negatively to growth on all four sites (Site 1: $r = -0.56$; Site 2: $r = -0.56$; Site 3: $r = -0.52$; Site 4: $r = -0.47$). In figure 37, the relationship between precipitation and the growth of *Picea abies* is presented in detail for all four sites. The results regarding relative humidity coincide with the ones from precipitation for summertime, in which a negative relationship was determined (Site 1: $r = -0.46$; Site 2: $r = -0.50$; Site 3: $r = -0.47$; Site 4: $r = -0.39$). In addition, a positive relationship between relative humidity and tree growth was identified for December of the previous year (correlations ranged between 0.40 and 0.58) (figure 46 in the appendix).

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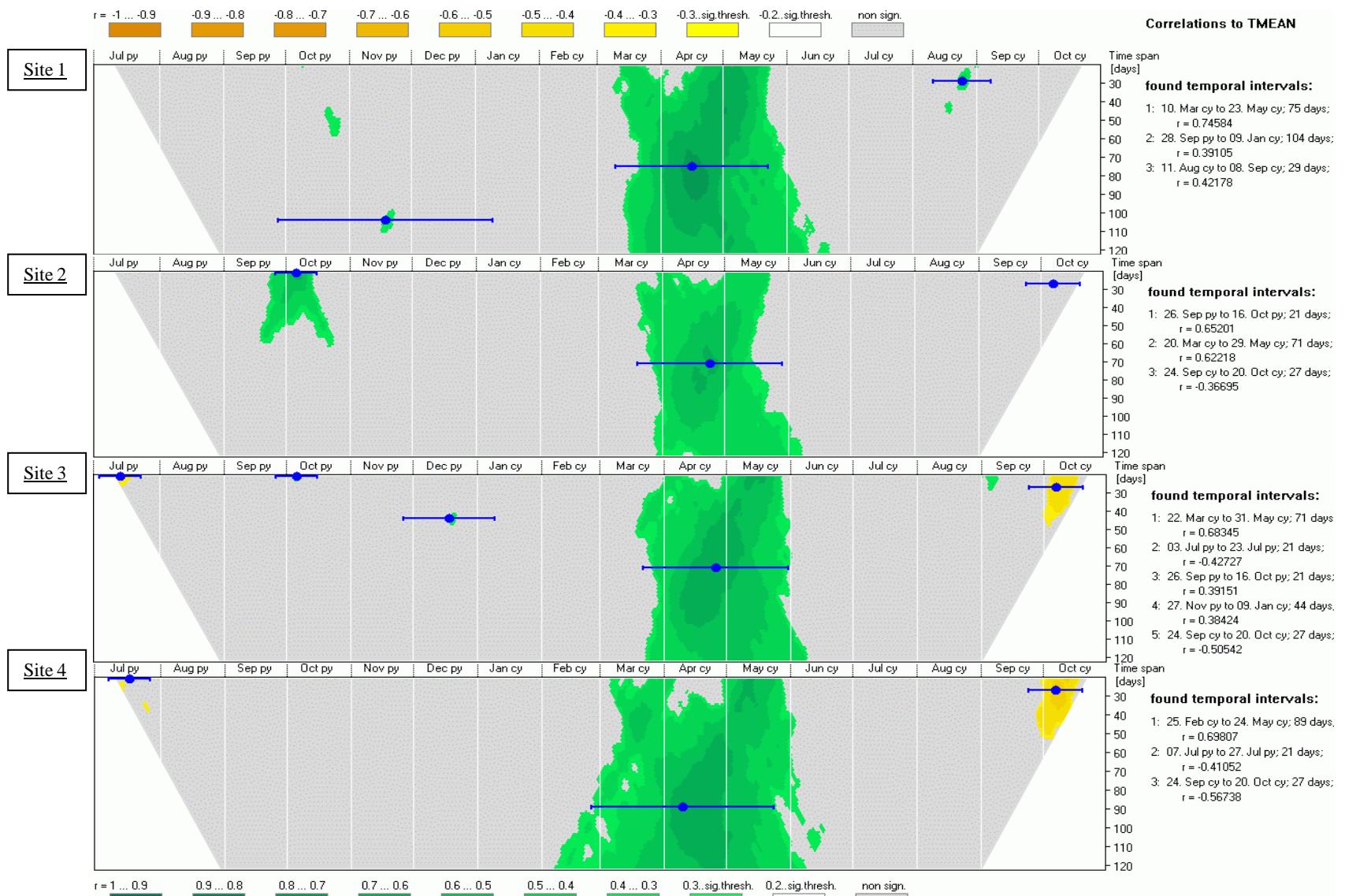


figure 36: Time intervals with the highest correlations of mean temperature to the tree ring indices of *Picea abies* for each site (period 1958-1987). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

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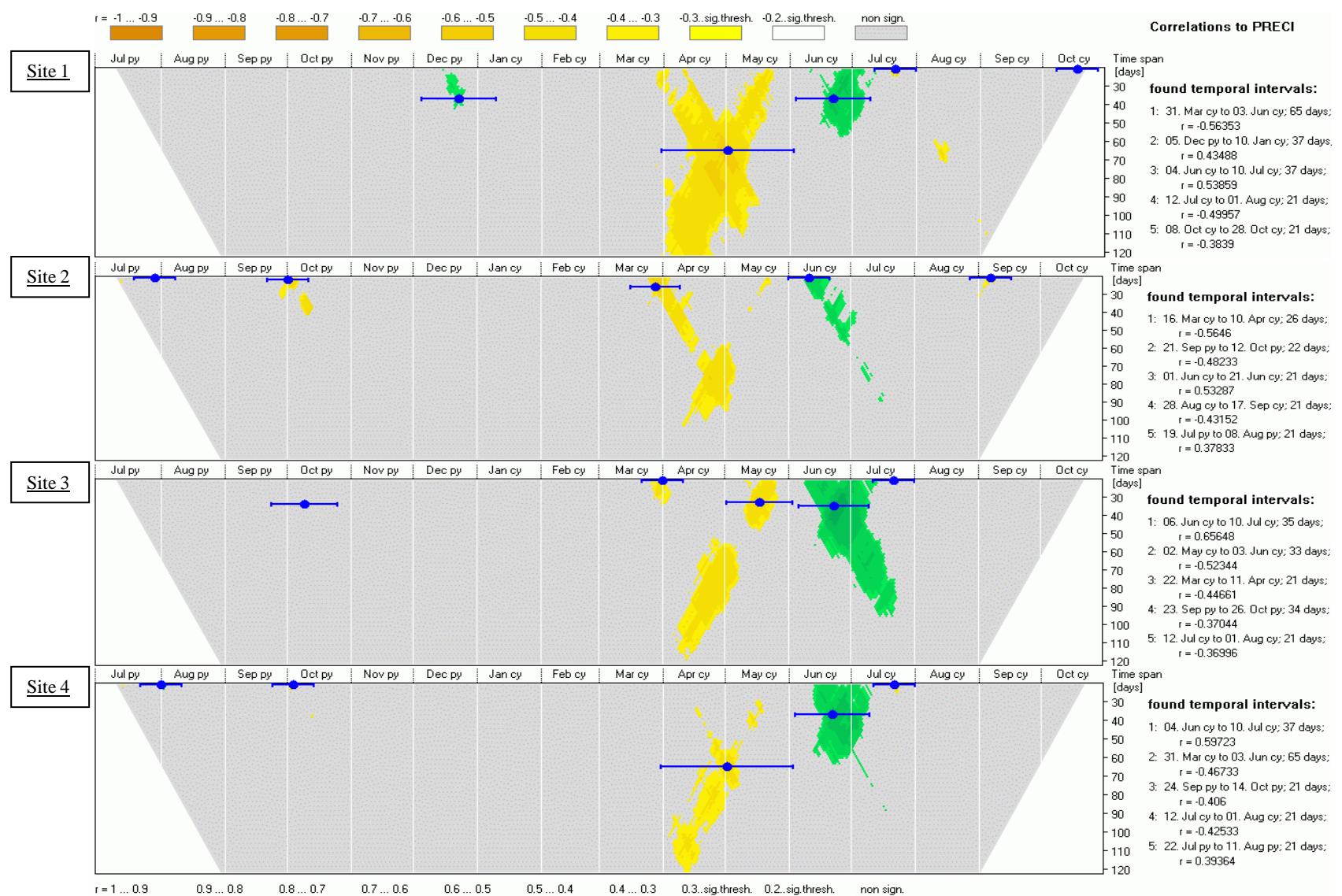


figure 37: Time intervals with the highest correlations of mean temperature to the tree ring indices of *Picea abies* for each site (period 1958-1987). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

3.3.7.3. Climate-growth relationship of *A.alba* over the past 30 years (1987-2016)

In consideration of the last 30 years (1987-2016), differences were spotted in comparison to the first 30 years between 1958 and 1987. First, for silver fir, the positive relationship between mean winter temperature and growth was less strong for the past 30 years (Site 1: $r = 0.49$; Site 2: $r = 0.61$; Site 3: $r = 0.52$; Site 4: $r = 0.56$). Besides, the time span in which the positive correlations were observed was shorter as in the first 30 years and only ranged from mid-December until end of March. Negative effects of previous July temperature or late summer temperatures of the current year weren't noticed (figure 38).

Particularly prominent were the strong correlations between the growth of *Abies alba* and the relative humidity, which can be seen in figure 39. While positive correlations for the period 1958-1987 were found for June and July, strong correlations were detected earlier in the year between mid-April and mid-May (Site 1: $r = 0.74$; Site 2: $r = 0.72$; Site 3: $r = 0.59$; Site 4: $r = 0.58$) in the last 30 years of the observation. The negative relationship between relative humidity in spring and the TRI, which was noticed for the first 30 years, was also identified for 1987-2016 and showed approximately the same correlations. However, the correlated time span was much shorter (only March).

Over the past 30 years, precipitation in April, June and July has shown a positive relationship with tree growth. In comparison, the correlating time spans are much shorter and less strong. Negative correlations of late winter precipitation were only detected for site 1 and 2. Overall, the precipitation results show a less distinctive image than in the first 30 years (figure 45 in the appendix).

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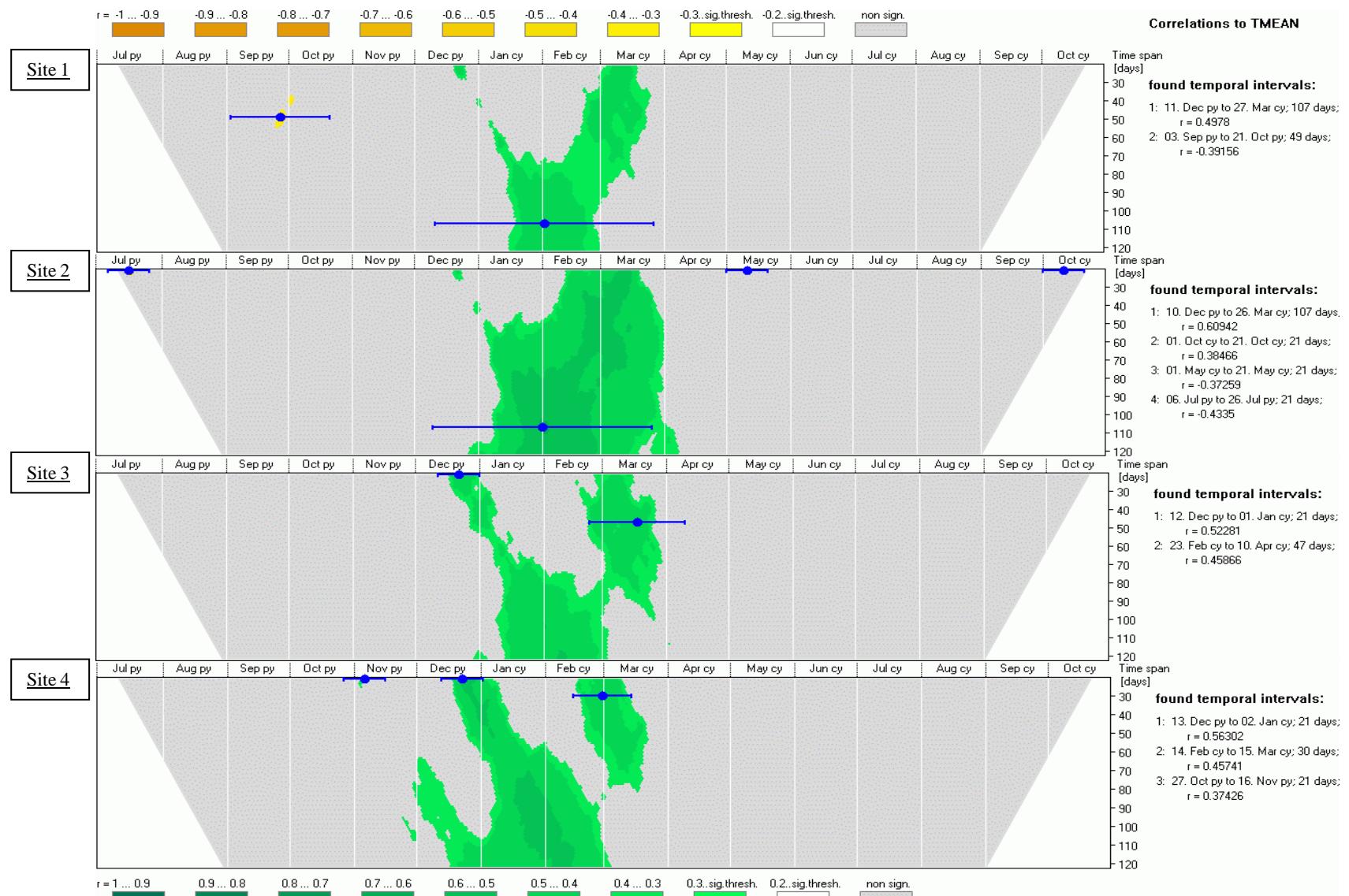


figure 38: Time intervals with the highest correlations of mean temperature to the tree ring indices of *Abies alba* for each site (period 1987-2016). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

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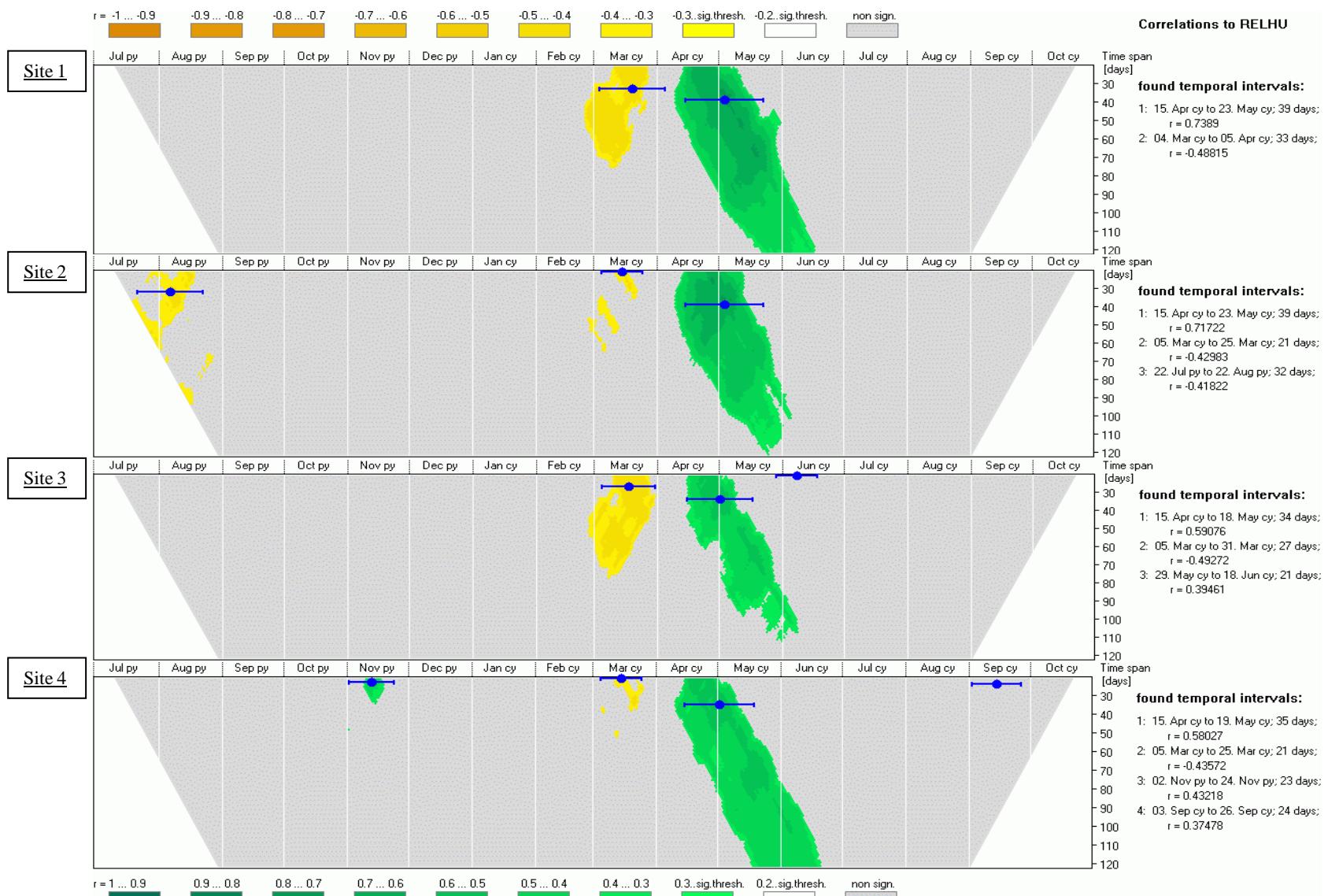


figure 39: Time intervals with the highest correlations of relative humidity to the tree ring indices of *Abies alba* for each site (period 1987-2016). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

3.3.7.4. Climate-growth relationship of *P.abies* over the past 30 years (1987-2016)

Comparisons between the past 30 years of the observation and the first 30 years reveal shifts and changes in the relationship between the climate variables and tree growth. While for 1958-1987 temperature was identified for positively influencing growth in springtime, this relationship was not noticed for the period 1987-2016. In general, mean temperature showed barely any correlations towards growth (figure 40).

For the relative humidity, on the other hand, a shift of the correlating time spans was to observe. While in the first 30 years relative humidity in March-May had a strong negative relation to growth, this relationship was only noticed for a short time frame in end of March in the last 30 years. However, the correlations were higher (Site 1: $r = -0.52$; Site 2: $r = -0.52$; Site 3: $r = -0.44$; Site 4: $r = -0.54$). The positive correlations between winter humidity and growth was not observed for 1987-2016. Instead, relative humidity in May and June indicated a strong positive relationship to the TRI (Site 1: $r = 0.50$; Site 2: $r = 0.64$; Site 3: $r = 0.56$; Site 4: $r = 0.54$). Further, on all sites positive correlations were also determined for September of the current year (figure 47 in the appendix).

In terms of precipitation Norway spruce showed positive correlations during summertime (Site 1: $r = 0.60$; Site 2: $r = 0.46$; Site 3: $r = 0.43$; Site 4: $r = 0.45$) over the last 30 years. The precipitation at the end of March and early April, on the other hand, was related negatively to growth on all four sites (Site 1: $r = -0.44$; Site 2: $r = -0.66$; Site 3: $r = -0.53$; Site 4: $r = -0.59$). It concludes that the influence of precipitation in summertime was less strong in the last 30 years, whereas the detected negative relationship of spring precipitation was approximately the same as in the period 1958-1987 (figure 41).

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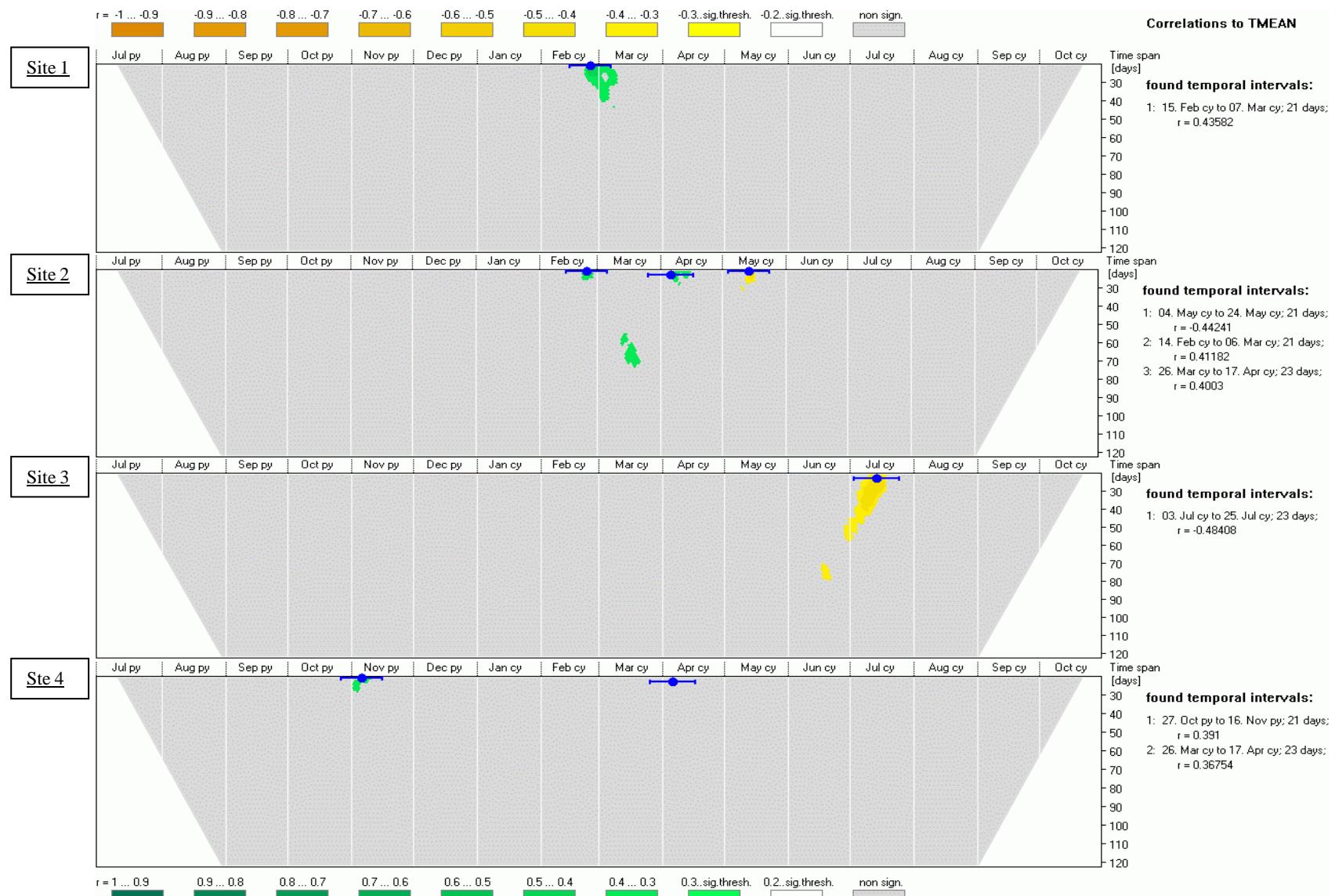


figure 40: Time intervals with the highest correlations of mean temperature to the tree ring indices of *Picea abies* for each site (period 1987-2016). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: cy = current year; py = previous year. Computed with program CLIMTREG.

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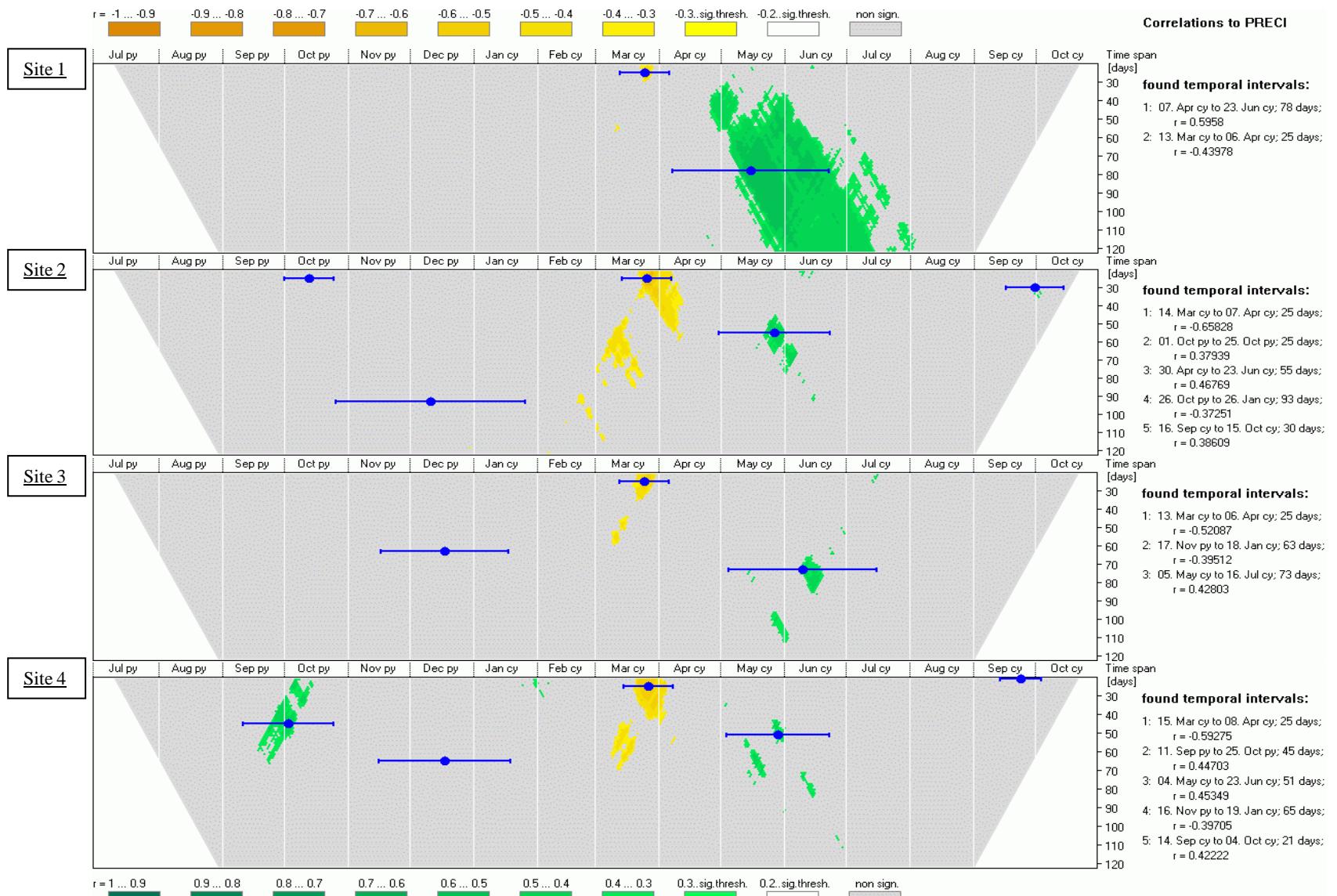


figure 41: Time intervals with the highest correlations of precipitation to the tree ring indices of *Picea abies* for each site (period 1987-2016). The centres of the determined time intervals are distinguished by circles, whereas the time spans are shown by horizontal bars. The white vertical lines indicate monthly boundaries. The colours represent the significance levels. The associated colour coding is listed above and below the figure. Explanation of the variable designations: *cy* = current year; *py* = previous year. Computed with program CLIMTREG.

4. Discussion and conclusions

The aim of the study was to provide insight into the growth of *Picea abies* (H. KARST) and *Abies alba* (MILL.) in mixed stands at the edge of their natural distribution range in the western Rhodope Mountains, Bulgaria. Of special interest were growth responses to disturbances, such as drought, as well as the climate-growth relationship of these two species. This study is intended to contribute closing the current gaps in knowledge and tries to anticipate possible developments under ongoing climate change. For this, 284 increment cores were extracted from 71 silver firs and 71 Norway spruces at four sites in the area of Pamporovo/ Smolyan. The cores were prepared, measured and analysed in terms of growth responses towards disturbances, respectively changes in climate in the process.

4.1. Stand classification

Mixed fir-spruce (-beech) stands are considered as one of the most productive forest ecosystems in Europe. In Bulgaria, under perfect conditions the growing stock can even exceed $1400/m^3\ ha^{-1}$. The study sites were situated at approximately 1550 m a.s.l. and are therefore in the common elevation range for Norway spruce (1300-1900 m a.s.l.) and silver fir (1000-1600 m a.s.l.) in the Western Rhodopes (PANAYOTOV & YURUKOV, 2016). The typical age for Norway spruce in mixed mountain forests in Bulgaria is around 100-120 years. The usual age for silver fir on the other hand is between 80-100 years (~30%), respectively 120-200 years (~42%) (PANAYOTOV & YURUKOV, 2016; PANAYOTOV ET AL., 2016). The stands in which this study was conducted are therefore within the typical age range of these forests. Both species are therefore still in an age with high annual increment. This was also confirmed by the time course of the basal area increment. The higher number of outliers compared to fir are probably due to the opportunistic behaviour of the spruce trees. For instance, NIKOLOVA ET AL. (2016) noticed in the Swiss Alps that *P. abies* can benefit from release felling quite well, especially in northern exposition. Because the stands in which the field work was carried out were managed, salient annual growth changes can be also due to management effects.

The mean tree ring width was similar for fir and spruce, ranging from 2.03 to 3.13 mm/year depending on the site. Other observations from the nearby Pirin mountain range as well as from central and north Romania showed lower average tree ring width for Norway spruce (PANAYOTOV

ET AL., 2009). The reasons for this are probably the higher age of the sampled trees in Romania (chronologies started at 1800) and the higher elevation of the spruces in the Pirin Mountains. Latter were sampled at the upper tree line at 1850 m a.s.l. For *Abies alba*, little lower mean ring widths at a similar age were observed at its western distribution limit in the Spanish Pyrenees. On the other hand, at its eastern distribution limit, which is located in the East Carpathian Mountains in Romania, the measured mean ring widths were in the same range as in the Rhodopes (GAZOL ET AL., 2015). Corresponding examinations of mixed fir-spruce stands from the Vosges mountains, France, showed similar mean ring width on mesic and humid sites, although the altitude was substantially lower (around 950 m a.s.l.) (LEBOURGEOIS ET AL., 2013).

In consideration of the yield classification from pure stands in Bavaria, the assumption can be made that the trees were vigorously growing (HAUSSER, 1990; ASSMANN & FRANZ, 1990). However, the application of those yield tables is quite limited for mixed stands in the Western Rhodopes and can only be used for a rough classification.

Within this field study the height of the dominant fir and spruce trees was measured. Silver fir reached a maximum tree height of 39.8 m (\varnothing 32.4 m) and Norway spruce 44.7 m (\varnothing 34.3 m). In general, *A. alba* was observed to be able to reach a maximum height of 55-60 m (FARJON, 2010). Therefore, silver fir is the tallest tree species of the genus *Abies* in Europe (MAURI ET AL., 2016; EUFORGEN, 2009a). *P. abies* is also known to reach similar heights of close to 60 m (CAUDULLO ET AL., 2016). For Bulgaria in particular, PANAYOTOV & YURUKOV (2016) described maximum heights of approximately 55-60 m for both, silver fir and Norway spruce. These heights were measured in the Parangalitsa reserve in the Rila National Park. There, high relative humidity and deep brown forest soils ensure perfect environmental conditions for growth (PANAYOTOV ET AL., 2016). Thus, in the south-west of Bulgaria, silver fir and Norway spruce are able to reach their growth limit in terms of height. The trees on the study sites, however, were not that high. Probably due to a shallower soil and foremost because of intense forest management.

By evaluating the live crown length as well as the h/d-ratio it was concluded that the examined trees were vital and (very) stable. The reason for the high stability is probably due to intense forest management activities on a regular basis that can be observed throughout the forests in that area (MAYER, 1984; ZLATANOV ET AL., 2017). Besides, the relative crown length as well as the h/d-ratio lead to conclusions about competition, because the h/d-ratio is constrained by the average past competition status of the trees (BERT, 1993). In this regard, the calculations of the *Iterative Hegyi's competition Index CI* for both species show that the sampling trees were dominant within the stand

and competition played a minor role in terms of growth over the past several years. Compared to HÄRTL (2008), in which the CI of spruce was determined at sites with different thinning intensities, it can be seen that the low average CI value of *Abies alba* ($\bar{x} = 0.95$) corresponds to that of strong low thinning (0.9), whereas the low mean CI value of *Picea abies* ($\bar{x} = 0.79$) corresponds to late Z-thinning (0.8). This indicates that there were strong and frequent interventions in the past and, hence, also confirms the assumptions that were derived from the h/d-ratio results. In addition, the calculated basal area suggests that strong interventions have taken place in the past, too, especially on site 2, where only a basal area of 35.5 m²/ha was determined. However, a basal area of 53.4 m²/ha was measured on site 4, which indicates that the interventions, respectively disturbances, were less intense there.

4.2. Chronology characteristics

In the study, 17-20 trees were sampled per site. This is concordant with the suggested minimum number of 15-20 trees per site as recommended by MÉRIAN & LEBOURGEOIS (2011) and SCHWEINGRUBER (1996). Based on the 284 obtained increment cores, eight mean chronologies (one chronology for each species and site) were built after growth trends and autocorrelation were removed from the tree ring series. The reliability of the mean site chronologies is verified by high expressed population signals, which exceed the recommended threshold of 0.85 by far (WIGLEY ET AL., 1984). This indicates a strong common signal as well as a high quality of the constructed chronologies. It means that the signal in the chronology is expressed well and thus that the sample chronology is satisfactorily representing the population. To a certain degree, the high quality of the chronologies is supported by the signal-to-noise ratios (DEWITT & AMES, 1978; BRIFFA & JONES, 1992). Hereby it is to mention that within the silver fir chronologies, the climatic signal was more present than within the corresponding Norway spruce chronologies. It follows that according to the SNR, the quality of the silver fir chronologies was better. Comparatively low SNR values below 15 indicate that, next to climate, other factors play an important role for tree growth in those stands (BECK, personal communication). The Gleichläufigkeit, which ranged between 60 % and 65 % for both species is comparatively low, but reaches the recommended threshold of 60 % by BAILLIE & PILCHER (1973).

The mean sensitivities of the chronologies differed between Norway spruce and silver fir. In general, *Picea abies* showed higher sensitivities. It can be therefore concluded that the Norway

spruce trees in the stands showed a higher presence of high-frequency variance and reacted stronger to environmental factors than silver fir. Hence, the relationship between radial growth and the limiting factors is more prominent within the *Picea abies* increment series. In general, the computed mean sensitivities were not high, but acceptable. Only the ones on site 2 and 3 of *Abies alba* seemed to be not very sensitive. The reason for the lower sensitivity of *A. alba* could be greater advantages of mixing with other species such as *P. abies* and *F. sylvatica*. In this regard LEBOURGEOIS ET AL. (2013) observed lower sensitivities to summer droughts if silver fir was mixed with other species. PANAYOTOV ET AL. (2011), who examined *Picea abies* tree-rings regarding extreme climate conditions in Vitosha and Pirin Mountains, Bulgaria, generated similar mean sensitivities. MÄKINEN ET AL. (2003), who examined high-frequency variation of *P. abies* alongside a gradient throughout Germany, Finland and Norway came to the conclusion that trees under average conditions, as given in the study stands, show weaker responses towards climatic alterations.

In comparison to chronologies from the lowlands in Bavaria (DIETRICH ET AL., unpublished) the mean sensitivities are relatively low. But this may be due to the difference in altitude. Referring to this, ZANG ET AL. (2014), DITTMAR ET AL. (2012) as well as VAN DER MAATEN-THEUNISSEN ET AL. (2013) described a decrease of MS of silver fir and Norway spruce with an increase in altitude. WILSON & HOPFMUELLER (2001) on the other hand observed an increase of MS from intermediate towards lower and higher altitudes in which the chronologies at lower elevations still had the highest mean sensitivities. In the study of DITTMAR ET AL. (2012), the MS of Norway spruce dropped down from a very high value of 0.48 at an altitude below 500 m a.s.l. to 0.10 at an altitude above 1200 m a.s.l. Comparatively to this, the calculated mean sensitivities for Norway spruce in the Western Rhodopes at an altitude of approximately 1550 m a.s.l. are quite high (0.173-0.199). In addition, KAHLE ET AL. (2005) found higher MS of *Picea abies* outside its natural distribution range in south-western Germany. The observed slightly higher MS of Norway spruce in comparison to silver fir is confirmed by VAN DER MAATEN-THEUNISSEN ET AL. (2013) at high altitudes but not by DITTMAR ET AL. (2012).

Those findings indicate that silver fir and Norway spruce have in general a higher climate-sensitivity at low elevations and outside their natural distribution range.

The higher mean sensitivities are concordant with the findings from the analysis of the year-to-year fluctuations. With progress in time, for both tree species an increase in the intensity of the fluctuations was observed. Overall, Norway spruce showed stronger fluctuations. This affirms the

higher sensitivity of *Picea abies* towards external influences for these stands. From 1980/1990 in particular, fluctuations became significantly stronger. This fact was also described by DIETRICH ET AL. (unpublished), who examined the effects of water shortage and drought on different tree species throughout Bavaria, Germany. There, for Norway spruce as well as European beech increasing short-term year-to-year fluctuations in basal area increment were observed since the 90s. For silver fir, though, these effects weren't noticed. According to DIETRICH ET AL. (unpublished), the reason for positive peaks in the following year of a disturbance (like for spruce in 2017; this study) is due to a quick recovery, respectively high resilience. But the reasons for the fluctuations can be manifold. Because of forest management activities in the stands over the past years, those kinds of influences cannot be excluded, and the applicability of the year-to-year analysis is limited. The general increase in fluctuations, however, is not solely due to forest management. Therefore, DIETRICH ET AL. (unpublished) refers to CARPENTER & BROCK (2006), by clarifying that increasing fluctuations in biological systems are well known characteristics for disturbances and can be signs of transitions to long-term reorganizations. Meaning that the forest ecosystems are likely to face changes in these stands in the Western Rhodopes. This can be observed for many parts in Europe. A driving factor in many regions is present climate change (IPCC, 2014; EEA, 2010; GONZALEZ ET AL., 2010).

4.3. Growth responses towards the disturbances in 1987

Based on the pointer year analysis, 1987 was identified as the year with the most significant growth reductions for both species at all sites over the past 60 years. This year's detailed climate analysis using the SPEI and DMI indices showed no signs of significant drought events. But the climate data revealed that 1987 was characterized by a cold and long winter with late and strong frost events as well as a dry late summer. However, the reason for the significant negative growth response of the trees is so far unclear. Though, PANAYOTOV ET AL. (2016) mentioned that the nearby Trigrad region (air-line distance of approximately 20 km) was afflicted by a famous drought in 1987/1988. For the period 1987-1989, PANAYOTOV ET AL. (2010) described a very dry June, an above-average July temperature and a dry November and December of the previous year at the adjacent Pirin mountain range. At lower elevations, at the Thracian Lowland as well as the Danube Plain, the period between 1982 and 1994 was determined as the driest period in the 20th century in Bulgaria (KOLEVA & ALEXANDROV, 2008). Overall, the 80s and 90s in Bulgaria and Romania were

characterized by a long drought (PANAYOTOV ET AL., 2009). Over the course of the year, especially the months of July, August and September are considered as the driest (KOLEVA & ALEXANDROV, 2008). This has also been confirmed by the analysis of the data obtained from the climate station in Chepelare, close to the study sites. Accordingly, it is possible that late frost, drought as well as a combination of both is the reason for the setback in growth in 1987 and the subsequent years.

To measure the tree's stress response, the basal area increment (BAI) was used as an indicator, because of the fact that any measured growth reduction at breast height has a clear reference to disturbances and losses in aboveground productivity. However, equating the BAI with overall tree growth must be treated with caution due to different stress responses throughout the entire tree (PRETZSCH ET AL., 2013). In this context, dendroclimatic studies have shown that the climate sensitivity changes along the tree stem (BOURIAUD ET AL., 2005; VAN DER MAATEN-THEUNISSEN & BOURIAUD, 2012). BOURIAUD ET AL. (2005) described a decrease of climate sensitivity with an increase in stem height. On the other hand, VAN DER MAATEN-THEUNISSEN & BOURIAUD (2012) found out that a trees' response at different stem heights to climate changed with altitude, tree species and the time in the year in which the stress event occurred. Therefore, they concluded that growth at breast height seems to be biased to a certain degree. In addition, the stress response of trees differs with age (CANDEL-PÉREZ ET AL., 2012; ČERMÁK ET AL., 2019), size (ZANG ET AL., 2012), elevation (CANDEL-PÉREZ ET AL., 2012; VAN DER MAATEN-THEUNISSEN & BOURIAUD, 2012) and mixture (PRETZSCH ET AL., 2013). The application of the so-called Lloret-Indices was controversially discussed recently (SCHWARZ ET AL., 2019), but was still used due to its simple, yet efficient way to assess a trees' response to disturbances.

As already mentioned, a drought event in 1987 could have caused the growth decline. Occurring drought stress in trees causes the reduction of the cell turgor and interferes with cell enlargement and metabolism. Indirectly, the synthesis with auxin and carbohydrates is decreased which results in decelerating their translocation to the cambium (KRAMER & BOYER, 1999; PICHLER & OBERHUBER, 2007). Finally, this leads to a reduction of the annual increment. In the course of this study it was found that Norway spruce reacted more sensitive to the disturbance than silver fir. Overall, *A. alba* showed higher resistance, recovery and resilience than *P. abies*. This is concordant with the findings by DĂNESCU ET AL. (2018), who examined growth reactions of these two species to episodic drought in mixed stands in southwestern Germany. According to them, fir had a significantly higher increment resistance and resilience. With diminishing intensity of the drought, the resistance of silver fir increased, whereas for Norway spruce the resistance was constantly low,

even at less intense droughts. For Bavaria, DIETRICH ET AL. (unpublished) detected very low resistance for Norway spruce at low elevations with a warm and dry climate. The resistance increased towards the cooler and wetter end of the gradient and was similar to the resistance determined in this study. Fir, though, did only show a growth decline at warm and dry sites and not in mountainous regions with a cool and wet climate. This is contrary to the findings from the Western Rhodopes, where silver fir also showed a growth decline, even if the increment loss was low. BOSELA ET AL. (2016) indicated that the last glacial period created two different genetically distinct lineages of *Abies alba*, which seem to differ regarding their response to drought. The Balkan lineage was more prone to drought at the beginning of the growing season, whereas the western lineage was more sensitive to summer drought. These findings were not confirmed by the results of this thesis. A reason for this could be the very high winter precipitations in the Rhodopes, which ensure a sufficient water supply in spring.

The generally high resistance of *A. alba* towards drought, especially at high elevations, was observed for southern Germany (ELLING ET AL., 2009; ZANG ET AL., 2014; VITALI ET AL., 2017), Italy (CARRER ET AL., 2010) and the French Alps (DESPLANQUE ET AL., 1999). VITASSE ET AL. (2019) mentioned three possible explanations for the high resistance. First, the primary growth cessation usually already happens in early July, whereas most of the droughts occur in July and August (and September in the Western Rhodopes). Secondly, fir often grows naturally on deep soils and can benefit from its deep taproot by utilizing water from a greater soil volume (DESPLANQUE ET AL., 1998; VITALI ET AL., 2017). Third, *Abies alba* responds with rapid stomata closure if there is a vapour-pressure deficit increase. Therefore, the transpiration is controlled efficiently. This behaviour is considered as an avoidance strategy (CARRER ET AL., 2010; VITASSE ET AL., 2019).

Norway spruce, on the other hand, has been proven to be prone to drought stress throughout Europe (DESPLANQUE ET AL., 1999; SAVVA ET AL., 2006; BOURIAUD & POPA, 2009; ZANG ET AL., 2014; VITALI ET AL., 2017). It is considered as an isohydric species, which reduces its water consumption already in the early stages of drought events by closing its stomata (PRETZSCH ET AL., 2013; ZANG ET AL., 2014). This preventive strategy, however, could lead to facilitation of neighbouring species by allocating resources. But in short drought periods, isohydric species can avoid damage and recover quickly (PRETZSCH ET AL., 2013). DIETRICH ET AL. (unpublished), for example, described such a quick recovery, respectively high resilience, for Norway spruce at low elevations in Bavaria in the following years after drought. In contrast to that, ZANG ET AL. (2014) as well as DĂNESCU ET

AL. (2018) observed that most of the spruce trees indicated a prolonged growth decline after the same drought years and concluded that this is a sign of drought intolerance. The same was noticed for silver fir in the French Alps (ROLLAND ET AL., 1999). Such a continuing growth reduction was also recognized for the chronologies of both species, fir and spruce, within this study. Further, ZANG ET AL. (2014) determined a full recovery, respectively an even distribution of resilience, for silver fir and European beech. Following ZANG ET AL. (2011), NIKOLOVA ET AL. (2011) and ZANG ET AL. (2014) the low resilience of Norway spruce is due to a strong preconditioning through the climate of the previous year as well as alterations in the root-shoot allometry, which are considered as a direct response towards dry conditions.

Next to species specific response to drought another reason for a higher resistance and resilience of *Abies alba* can be effects of mixture. In this regard, PRETZSCH ET AL. (2013) described no positive effect for *Picea abies* if occurring in mixed stands. Silver fir, though, seems to be affected positively in terms of drought resistance by growing in mixed forest stands (VITALI ET AL., 2018). But BOSELA ET AL. (2018) emphasized that growing in a mixture has its limits and does not shield trees from influences of long-term changes of environmental conditions, such as climate change. All studies mentioned above refer to the droughts in 1976 and 2003, which were severe in Central Europe. In Bulgaria, for instance, 1976 was considered as a cool and wet year and is therefore in complete contrast to Central Europe due to a very different climate regime (PANAYOTOV ET AL., 2010).

The second possible explanation for the growth decline in 1987 were the strong frost events that occurred from January until end of May. Frost events can abbreviate the growing season, damage the needles and affect the fitness negatively. Therefore, it is important for the trees to remain in the frost hardened stage long enough. But late spring frosts can occur after bud burst and can cause growth decline (VITASSE ET AL., 2009; LEINONEN & HÄNNINEN, 2002). For the mountainous areas in south Bulgaria, negative impacts of unusually cold winters and frost events have been described recently (PANAYOTOV ET AL., 2011; PANAYOTOV ET AL., 2016; PANAYOTOV ET AL., 2019), but no particular frost years were mentioned. Even though an increase of temperature was observed for the south Bulgarian mountainsides (PANAYOTOV ET AL., 2019), frost events are not decreasing or getting less severe. Instead, Europe is witnessing a general increase of late spring frosts (ZOHNER ET AL., 2020).

Silver fir has been noticed reducing growth due to frost, especially in spring, and is therefore considered as susceptible towards frost events (BECKER, 1989; ROLLAND, 1993; ROLLAND ET AL.,

1999; BOURIAUD & POPA, 2009). ROLLAND ET AL. (1999) even observed that frost events in the French Alps had a stronger negative impact on tree growth at dry and high altitude sites than drought. Regardless, it has been determined that silver fir trees from higher provenances have a higher resistance to frost than provenances from the lowlands (LARSEN, 1986; VITASSE ET AL., 2019). Due to the limitation by frost, ROLLAND ET AL. (1999) referred to *Abies alba* as an ‘oceanic’ species. In comparison, Norway spruce is well adapted to cold winters and is considered to be less prone to early winter and late spring frost events (LEBOURGEOIS, 2007; BEGOVIĆ ET AL., 2020). Further, SCHWEINGRUBER & MÜLLER (1992) examined the impact of a winter frost event in Switzerland on the growth of silver fir and Norway spruce and determined that it took 3 to 4 years for fir and 2 to 3 years for spruce to recover from this disturbance.

In consideration of this, it would be expected that fir had a stronger and longer lasting growth decline than spruce if a late frost incident was the reason for the negative pointer year in 1987. However, spruce showed a significantly higher setback, making it more likely that drought or a combination of both, drought and frost, were responsible.

In conclusion, *P. abies* is more sensitive to drought, whereas *A. alba* is more susceptible to late frost. From this study resulted that Norway spruce reacted more sensitive to the disturbance in 1987 than silver fir. Although no significant drought event was determined by the applied indices, related examinations from close by revealed a drought period at 1987. Detailed examinations of the daily climate data also disclosed frost events until end of May. Therefore, it can be concluded that 1987 was a year with unfavourable growing conditions. Considering the development of the intensity and frequency of extreme events in the presence of climate change, further growth setbacks can be expected for the Western Rhodopes.

4.4. Influence of climate on growth of *P. abies* and *A. alba*

Xylogenesis, the cell formation in woody plants, takes place at different times within a year. Basically, cell formation happens in five major stages: cell division, cell enlargement, deposition of the secondary wall, lignification of the cell wall and the programmed cell death. In general, the cambial activity is considered starting in early April and lasting until August, whereas the maximum growth is expected to happen sometime around summer solstice. Cell enlargement begins in mid of April and ends at the end of August, whereas the cell thickening ranges from May to November (RATHGEBER ET AL., 2016). In the Bulgarian mountains, the process of cell formation

has been described to last from mid of May until October for coniferous species (IVANOVA, 2016). This is also coherent with the observed time period of xylogenesis for *Picea abies* in Europe, described by ROSSI ET AL. (2008). In addition, *Abies alba* has been mentioned for having a significant longer wood formation period than *Picea abies* (GRIČAR & ČUFAR, 2008; VITALI ET AL., 2017). For the growth of a tree, respectively the xylogenesis, climate plays a major role. In this regard, RATHGEBER ET AL. (2016) mentioned that, for instance, temperature has a direct control on cambial cell division, whereas water shortage can affect cell enlargement. It has been noticed that reaching certain climatic threshold values is crucial for the tree ring development of conifers (ROSSI ET AL., 2008) and because of that the variation within each month is of high interest. Therefore, program CLIMTREG was utilized to examine the climate-growth relationship based on intra-annual daily and yearly moving time intervals with variable width (BECK ET AL., 2013). For this study the influence of the climatic parameter temperature, precipitation and relative humidity on growth has been examined for the periods 1958-1987 and 1987-2016 in the Western Rhodopes.

4.4.1. Temperature

First of all, it should be noted that positive correlations between winter temperature and growth were observed for *Abies alba* within both periods, although the correlations were significantly more pronounced in the first 30 years. There, the temperature within the time span between mid-November and end of April showed strong correlations. In the last 30 years, the affecting time span was much shorter, ranging from mid-December to end of March. In comparison, the effect of increasing growth with higher temperature was limited to spring for *Picea abies*. Regarding this, in the period 1958-1987 a very strong relationship was identified for the time interval March to end of May. Though, this significant relation was barely observed for the period 1987-2016.

The results for Norway spruce in the first 30 years indicate that higher temperatures in the beginning of the growing season, when cambial activity and cell development starts, influenced growth positively. This is concordant with findings by GRIČAR ET AL. (2007), who described that temperature is the decisive factor for growth in the beginning of the growing season. According to them, elevated temperatures in this period increases the rate of cell division. Similar results were achieved by SAVVA ET AL. (2006), who found significant influence of temperature in March and April in the Tatra Mountains, Poland. In general, it has been reported for conifers that the cambial

cell production was affected more by the minimum than by the maximum temperature (DESLAURIERS & MORIN, 2005; ROSSI ET AL., 2008). According to MÄKINEN ET AL. (2003), the observation that high temperatures in spring encourages growth was observed for warmer regions, while the opposite was true for cooler regions. Besides, at higher elevations, where low air temperature is the significant limiting factor, a positive influence of temperature was noticed throughout the growing season across the distribution range (DESPLANQUE ET AL., 1998; FRANK & ESPER, 2005; SAVVA ET AL., 2006; BOURIAUD & POPA, 2009). In this regard, SAVVA ET AL. (2006) recognized a stronger impact of summer temperatures on growth with an increase in elevation. The positive impact of high winter temperatures on the growth of silver fir has been observed in other regions too, like the Eastern Carpathian Mountains (BOURIAUD & POPA, 2009), the European Alps (ROLLAND, 1993; DESPLANQUE ET AL., 1998; FRANK & ESPER, 2005) and the Black Forest in Germany (VAN DER MAATEN-THEUNISSEN & BOURIAUD, 2012). Furthermore, other conifer species in the nearby Pirin mountains in Bulgaria have also been noticed to show this kind of growth response (PANAYOTOV ET AL., 2010). From a physiological perspective, winter temperature is not able to affect the cambial activity, because it is during the dormancy of the trees (PANAYOTOV ET AL., 2010; RATHGEBER ET AL., 2016). However, a positive relationship between winter temperature and tree growth indicates, that milder winters are good for growth. In consideration that silver fir is susceptible to winter frosts and harsh winters, milder conditions are beneficial (ROLLAND, 1993; ROLLAND ET AL., 1999; FRANK & ESPER, 2005). PANAYOTOV ET AL. (2010), on the other hand, mentioned that in milder winters the chance is higher that precipitation falls in form of rainfall or wet snow, which can contribute to a higher soil moisture after snowmelt and can therefore be an advantageous prerequisite for cambial activity in the beginning of the growing season. In addition, FRITTS (1976) complemented that high winter temperatures can reduce snow cover, promote moisture infiltration and cause high net photosynthesis. Besides, the positive relationship between temperature and growth of silver fir in wintertime also indicates that the lower the temperature was, the narrower was the ring width, respectively the lower was the growth. FRITTS (1976) agrees, mentioning that low temperatures can delay the beginning of the growing season which leads to a reduced ring width. This confirms the negative impact of harsh and cold winters with frosts on growth, which has been described for silver fir (ROLLAND, 1993; BOURIAUD & POPA, 2009).

A negative effect of late summer temperatures of the current year (mid-September and October) on the growth of both species, silver fir and Norway spruce, was determined. The reason for this inverse relationship is that temperature is the driving force behind water diffusion and therefore,

high temperatures can lead to high evapotranspiration and cause water stress (FRITTS, 1976). The negative effects were more pronounced in the fir chronologies. In contrast to that, BOURIAUD & POPA (2009) detected a higher response to temperature for Norway spruce for the current and the previous growing season, whereas silver fir was mentioned as less sensitive. A physiological preconditioning by the previous year climate was barely noticed for Norway spruce, which is inconsistent to other studies from Central Europe (DESPLANQUE ET AL., 1998; BOURIAUD & POPA, 2009; ZANG ET AL., 2011; RYBNÍČEK ET AL., 2010). For instance, ZANG ET AL. (2011) described a strong influence of late summer temperatures of the previous year. Within this thesis, late summer temperatures showed only correlations with the current year for Norway spruce. At this time in the year, in terms of cell formation, only the cessation of the xylem cell enlargement as well as secondary wall deposition happens (RATHGEBER ET AL., 2016). For silver fir, on the other hand, a preconditioning by the previous year July and early August temperature was observed. ROLLAND ET AL. (1999) also described that drought in the previous year August affected the growth of silver fir in the French Alps negatively. As the climate data from station Chepelare/Pamporovo revealed, August was the driest month of the year in the past. In addition, CARRER ET AL. (2010) examined growth responses of *Abies alba* to climate towards the southern distribution limit, located in Italy, and found out that previous year summer temperature (July, August and September) was one of the main drivers for growth. Similar results were also achieved by GAZOL ET AL. (2015) at its eastern distribution limit. ROLLAND (1993) concluded for the inner Alps that previous year August temperature and rainfall are crucial for tree growth as the water reserves are at their lowest point at this time of the year. As already mentioned, the physiological preconditioning by the previous year climate, respectively temperature, can affect a trees vitality in terms of frost hardiness, storage of nutrients and drought resistance amongst others (FRITTS, 1976). Therefore, preconditioning by the previous year July and August temperature on the growth of silver fir could have led to a higher frost susceptibility in wintertime and spring of the subsequent year. The climate data revealed that, like 1987, 1986 was also marked by a very dry late summer (low precipitation in September and October). It is possible that this could have influenced the frost hardiness and led to a higher susceptibility towards the strong late frost events from January until May in 1987.

Overall, it can be inferred that the temperature correlations found for silver fir within this study are congruent with other studies conducted in different parts of its distribution range. The reason for the differences between the periods 1958-1987 and 1987-2016 regarding the temperature-growth relationship, however, cannot be determined. A possible explanation is that other non-climatic

factors got more important over the last 30 years, which lead to a decrease of the correlations. For example, during field work, several windthrow in the forests were spotted. Furthermore, ZLATANOV ET AL. (2017) mentioned a continuously increase of harvest intensity which could also derogate the climatic signal.

4.4.2. Precipitation

Correlations between precipitation and growth of *Abies alba* were identified for late spring and early summer. In detail, precipitation from mid-February until early April indicated a negative effect on growth, whereas precipitation in June and July caused a positive growth response. Within the first 30 years, the correlations were significantly more pronounced than in the last 30 years, where the negative impact of the late winter precipitation was not observed anymore. Instead, positive correlations of April and May precipitation were noticed. In the Eastern Carpathian Mountains, BOURIAUD & POPA (2009) also determined a positive influence of spring (April and May) and July rainfall for fir. The same observations were made in the Alps by ROLLAND (1993). Its ability to take advantage of spring rainfall is seen as a reason for the lower sensitivity to drought (DEPLANQUE ET AL., 1999; BOURIAUD & POPA, 2009; ZANG ET AL., 2011). The distinguished positive effect of early summer rainfall was also found for silver fir at its western distribution limit in the Spanish Pyrenees (GAZOL ET AL., 2015), in the Alps (ROLLAND, 1993) and in the Black Forest in Germany (VAN DER MAATEN-THEUNISSEN & BOURIAUD, 2012). At this time of the year, cambial activity is still high and maximum growth occurs (RATHGEBER ET AL., 2016). However, a positive influence of high precipitation in the previous year summer as mentioned by DEPLANQUE ET AL. (1998) or GAZOL ET AL. (2015) was not noticed. As mentioned before, a negative influence of precipitation in the time interval between February and early April was determined. VAN DER MAATEN-THEUNISSEN & BOURIAUD (2012) also found a negative impact of precipitation in May on growth of high-altitude silver fir trees.

In comparison with temperature it seems that precipitation had a lower influence in a shorter time period. Other examinations from Central and Northern Europe indicated that at low altitude mountain areas precipitation influenced growth more, whereas at high elevated areas temperature was more limiting (DITTMAR & ELLING, 1999; MÄKINEN ET AL., 2002). GAZOL ET AL. (2015) described that silver fir populations in Mediterranean regions depended more on sufficient water supply, whereas in Romania a stronger response to temperature was noticed. Besides, climate data

analyses in combination with bioclimatic modelling showed that silver fir requires rainfall above 600-700 mm year⁻¹ and above 90-120 mm in the three warmest summer months combined (TINNER ET AL., 2013; VITASSE ET AL., 2019). Because of that relatively low demands towards precipitation, VITASSE ET AL. (2019) assumed that silver fir has high potential to thrive under predicted climatic changes.

The growth of Norway spruce showed strong positive correlations to rainfall in June and July for both periods, 1958-1987 and 1987-2016, coinciding with the results for silver fir. In addition, a strong negative precipitation-growth relationship was noted for the period from late March to late May in the first 30 years. This relationship somehow changed in the last 30 years. Precipitation in May now had a positive influence, whereas the negative correlations were only seen for mid-March to early April. The positive relationship between early summer precipitation and growth was observed across the distribution range, from the Carpathians (BOURIAUD & POPA, 2009) to the lowlands and mountains of Bavaria (ZANG ET AL., 2011), the inner alpine dry valleys (SCHUSTER & OBERHUBER, 2013), the Black Forest (VAN DER MAATEN-THEUNISSEN & BOURIAUD, 2012), the Swiss Alps (BÜNTGEN ET AL., 2006) and across the mountain range in Slovakia and Czech Republic (RYBNÍČEK ET AL., 2010; SITKOVA ET AL., 2018). The relevance of early summer precipitation can be explained by the fact that June is considered as the month with the most active wood formation at high altitudes near the treeline (ROSSI ET AL., 2006). As with the silver fir trees, negative correlations between spring precipitation and growth were determined. However, they were not confirmed by other studies. A spurious statistical relationship could be the reason for the negative correlations between growth of both species and precipitation. Since precipitation in spring often occurs as snowfall in the Rhodopes, another explanation could be that a deep snow layer prolongs the period in which the forest soil is covered with snow, which can delay the start of the cambial activity of the trees (FRITTS, 1976). Some studies revealed influences of the previous year precipitation on growth of *Picea abies* (BOURIAUD & POPA, 2009; RYBNÍČEK ET AL., 2010), but this was also not observed within this study. In conclusion it can be said that early summer precipitation was one of the most important factors for the growth of both species, Norway spruce and silver fir, in the Rhodope Mountains. Spring precipitation correlated negatively probably due to heavy snowfall, which delayed the start of the growing season.

4.4.3. Relative humidity

Relative air humidity, as sign to what degree the air is saturated with water vapor, is highly dependent on temperature and has a close relationship to precipitation (SCHWEINGRUBER, 1996). For silver fir, in the first 30 years, positive correlations between relative humidity in June and July as well as strong negative correlations to humidity in late winter and spring (February, March and early April) were observed. In the last 30 years, the positive correlations increased significantly and were noticed earlier in the year from mid-April until mid-June. In general, *Abies alba* is considered as an ‘oceanic’ species which prefers high air humidity (ROLLAND ET AL., 1999; PANAYOTOV ET AL., 2016; VITASSE ET AL., 2019) and reacts sensitive if it is too low (GUICHERD, 1994; VITASSE ET AL., 2019). According to VITASSE ET AL. (2019) silver fir is in need of high air humidity for photosynthesis, amongst others, to be able to compete with other species. That is why *Abies alba* is mostly found on north exposed slopes at its southern distribution limit. The Western Rhodopes accommodate the southeasternmost margin distribution limit of *Abies alba*, where observations confirmed that only on north exposed sites silver fir trees occurred.

As for silver fir, a negative relationship between relative humidity and tree growth was identified for Norway spruce in March and April in the first 30 years as well as in the last 30 years. Besides, the first 30 years indicated positive correlations with previous year December, which were not present in the last 30 years anymore. Instead, a relationship to May and June humidity was spotted. In comparison, the correlations for *A. alba* were significantly stronger, confirming the higher importance of relative humidity towards the growth of silver fir (VITASSE ET AL., 2019).

Comparable literature does not exist regarding specific time intervals in which relative humidity affects growth of Norway spruce and silver fir. However, considering the precipitation and temperature results, conclusions can be made. For both species, at the beginning of the growing season as well as in early summer high humidity was favourable. As already described above, this period is crucial for tree growth. There, high temperatures in combination with high humidity imply perfect conditions for growth. On the other hand, high relative humidity in combination with very low temperatures in late winter and spring is affecting growth negatively because of possibly indicating deep snow cover, hoarfrost and late frost. Therefore, the results from relative humidity underline the achieved results from precipitation and temperature.

4.5. Conclusions, constraints and possible future developments

In summary, within this master thesis mixed fir-spruce stands at the southeasternmost margin of their distribution range were examined regarding the characteristics of the stands, the response to disturbances and the climate-growth relationship. 1987 was retrospectively identified as the year in which both species showed a significant growth reduction on every site. Norway spruce showed a more sensitive response, whereas silver fir had a significantly higher resistance. The climatic data as well as observations from nearby regions revealed unfavourable conditions, in terms of strong late frosts and a very dry late summer, for that particular year. Overall, temperature in wintertime and in previous year July was noticed to affect growth of silver fir, whereas temperature in spring determined the growth of Norway spruce. In consideration of water supply, early summer precipitation affected growth positively, whereas spring precipitation had a negative impact.

Considering the predicted climatic changes for south-east Europe and the Western Rhodopes in particular, the projected shift of the current tree composition, as already described by ZLATANOV ET AL. (2017) and PANAYOTOV ET AL. (2019) for that region, can be to a certain extend confirmed by the results of this study. As it is evident that climatic changes will first affect the species that are prone to those changes, Norway spruce will be especially affected. Climatic extremes and disturbances, such as drought, are considered to increase, and therefore the share of Norway spruce trees in the tree composition will decrease due to its lower resistance, e.g. in comparison to silver fir. Likely, winter temperatures will increase, whereof *Abies alba* could benefit, as it was observed in the past that higher temperatures in winter affected its growth positively. In general, it is predicted that silver will thrive under climate change and could to some extend replace Norway spruce in many parts of Europe, including the Rhodope Mountains (TINNER ET AL., 2013; MAURI ET AL., 2016; ZLATANOV ET AL., 2017; PANAYOTOV ET AL., 2019). But its late frost susceptibility and the requirements regarding soil and humidity will still limit its area-wide distribution.

Based on this study, only local statements can be made, since no gradient was examined due to the extensive workload. Another limitation is that the study sites were located in forest stands which were managed intensively over the past 30 years. In order to obtain a clear climate signal that is as free as possible from disturbing signals (noise), an unmanaged forest area would be beneficial. In order to deepen the knowledge gained, further studies should be carried out on the subject. A similar study involving a local gradient with more sampling trees per site and located in an unmanaged forest would be particularly advantageous to limit the constraints of this study.

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Appendix

Pointer year analysis

In the following the results of the pointer year analysis for each site and species are listed.

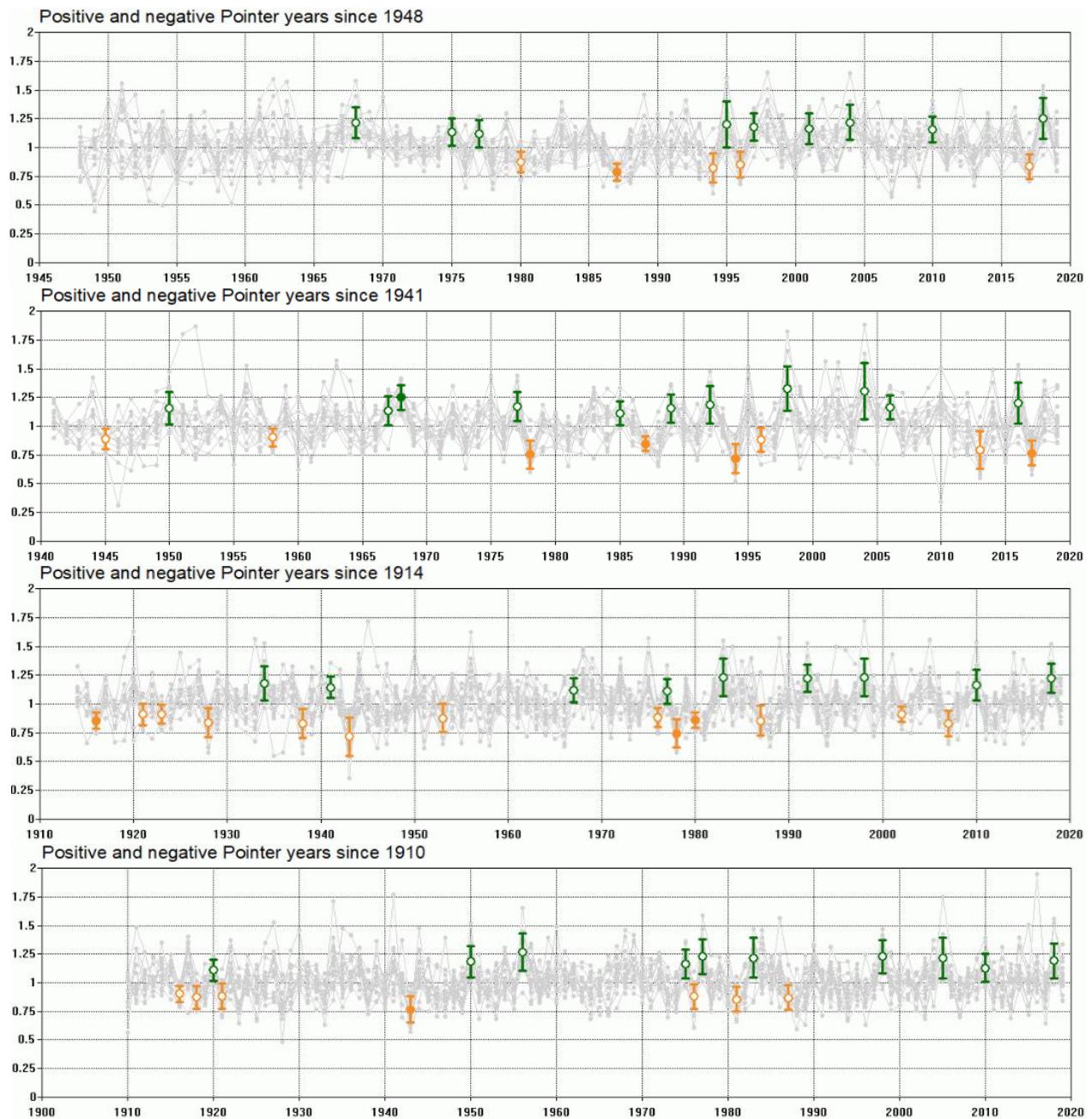
Abies alba



figure 42: Result of the pointer year analysis for silver fir. Listed according to the order of the site numbers: 1,2,3,4. Note the different time scales.

Appendix

Picea abies



**figure 43: Result of the pointer year analysis for Norway spruce. Listed according to the order of the site numbers:1,2,3,4.
Note the different time scales**

Analysis of the climate-growth relationship

The following pages show the results that have been achieved with Climtregr and have not yet been shown in the thesis.

Appendix

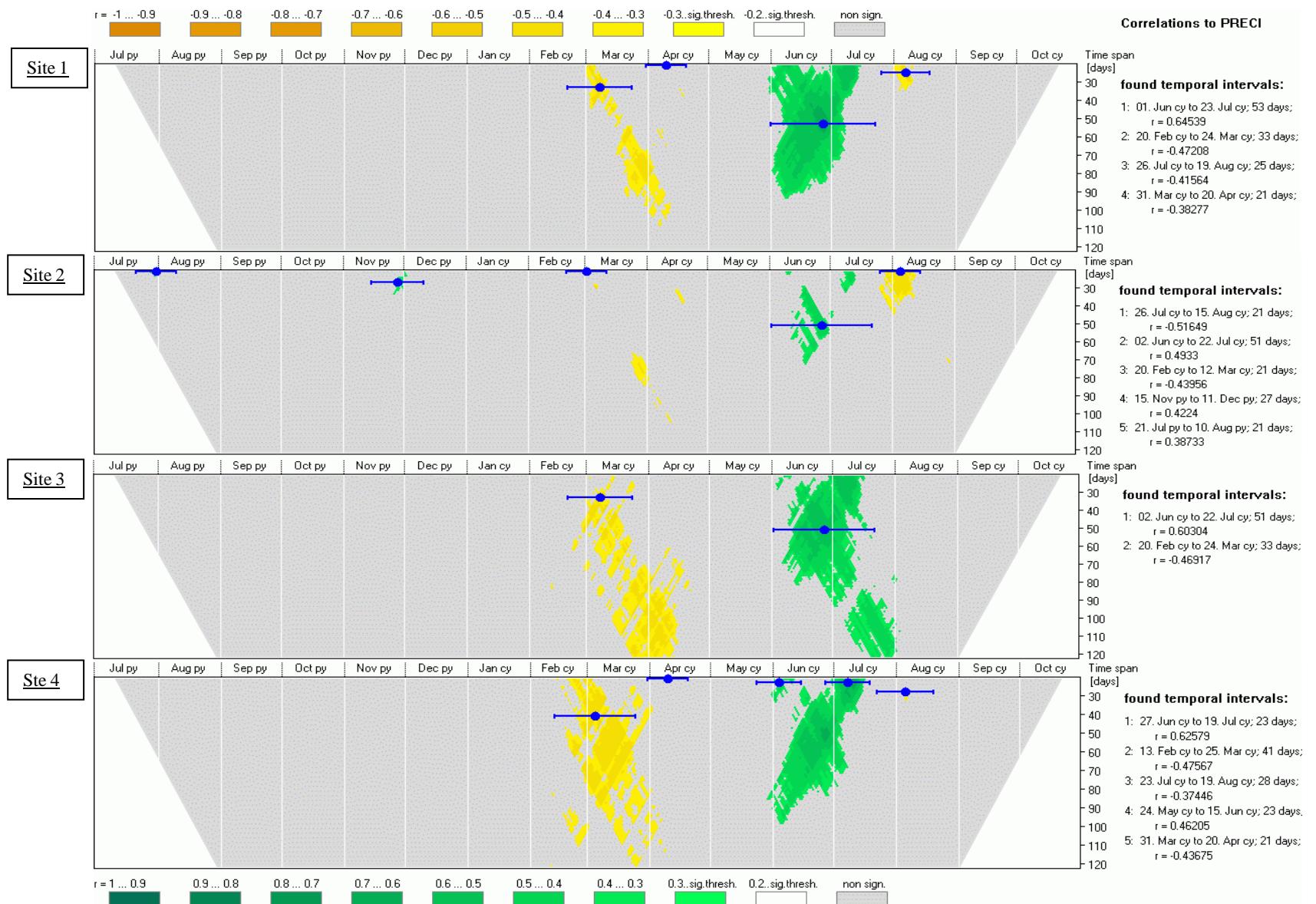


figure 44: Time intervals with the highest correlations of precipitation to the tree ring indices of *Abies alba* for each site (period 1958-1987).

Appendix

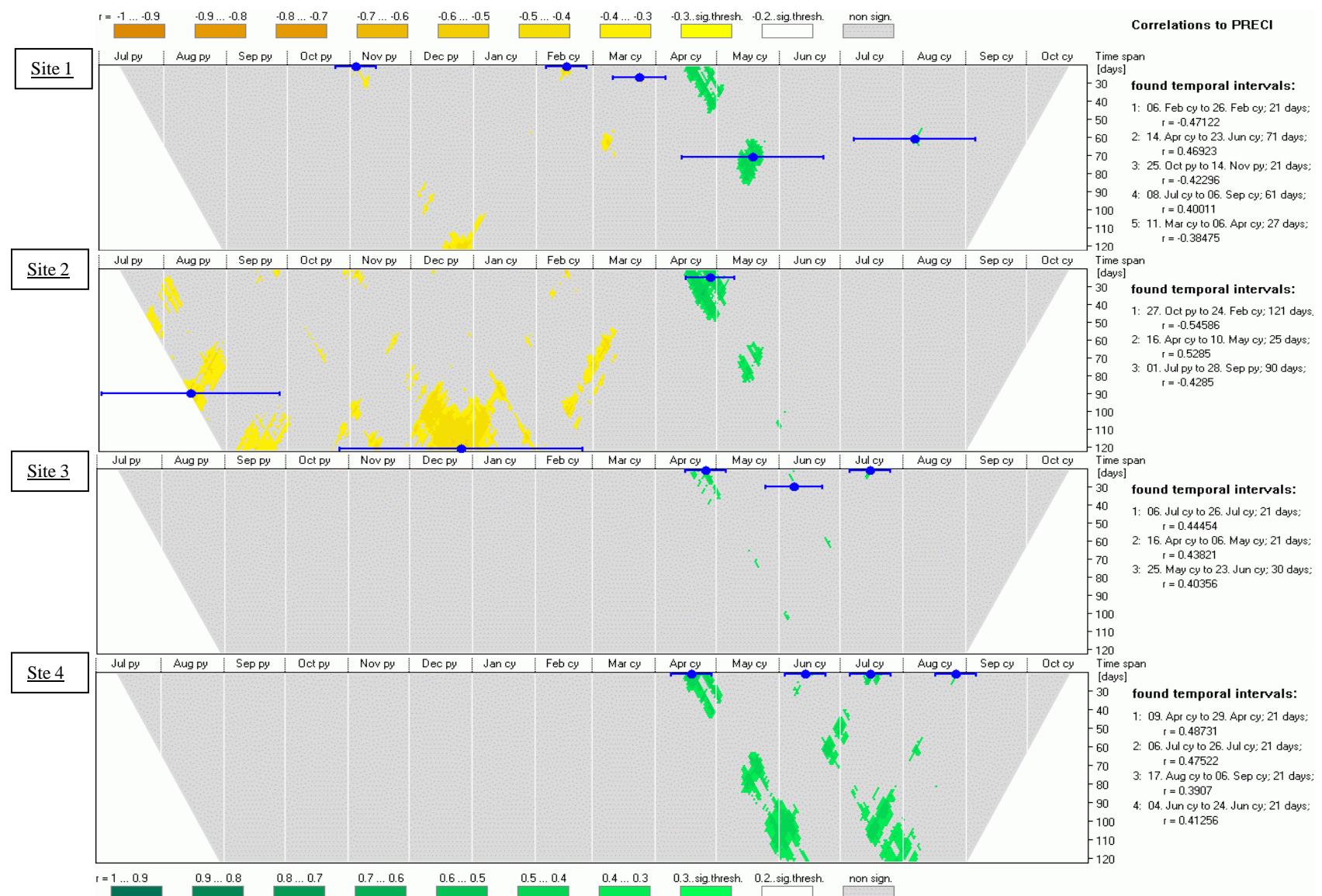


figure 45: Time intervals with the highest correlations of precipitation to the tree ring indices of *Abies alba* for each site (period 1987-2016).

Appendix

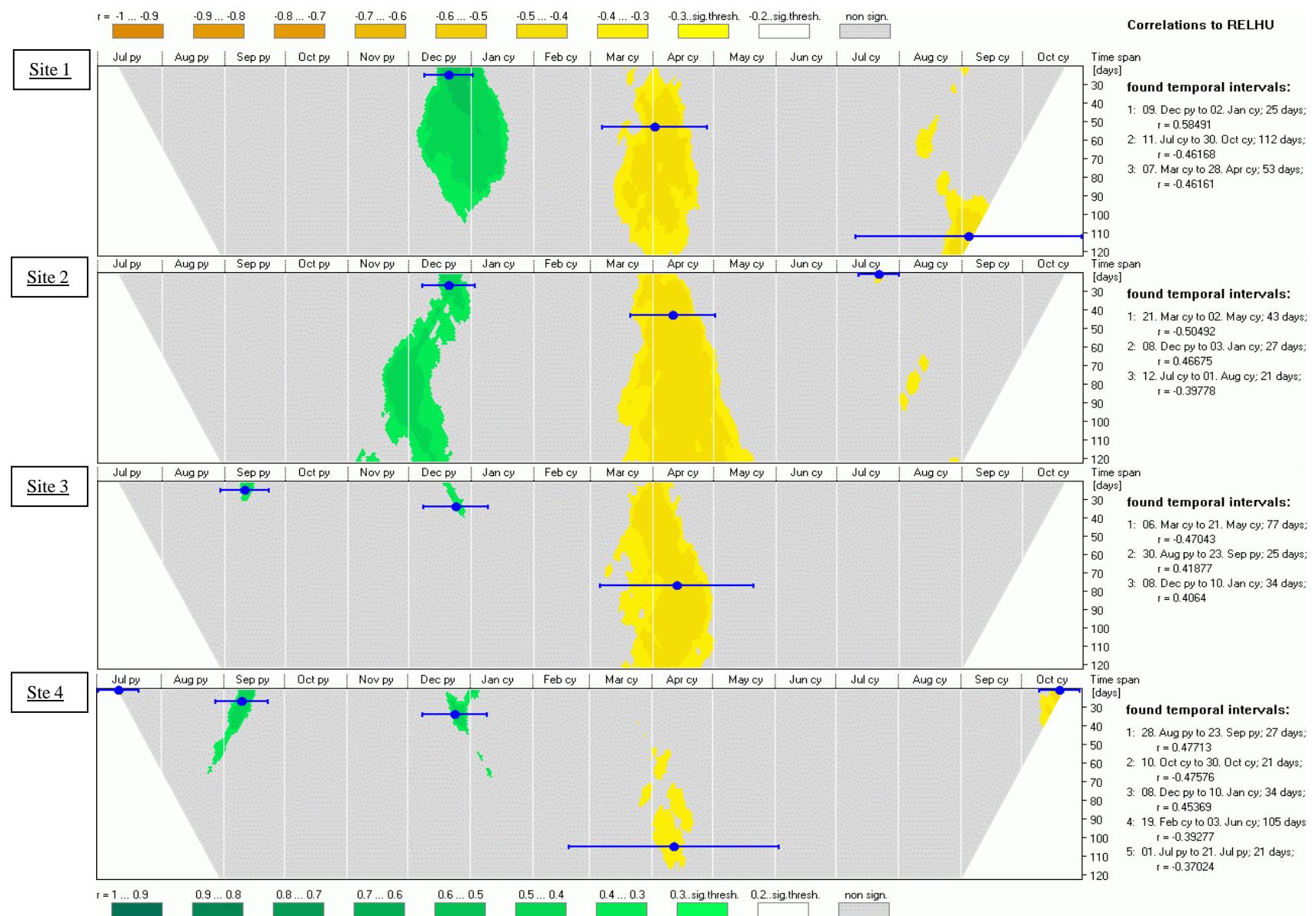


figure 46: Time intervals with the highest correlations of relative humidity to the tree ring indices of *Picea abies* for each site (period 1958-1987).

Appendix

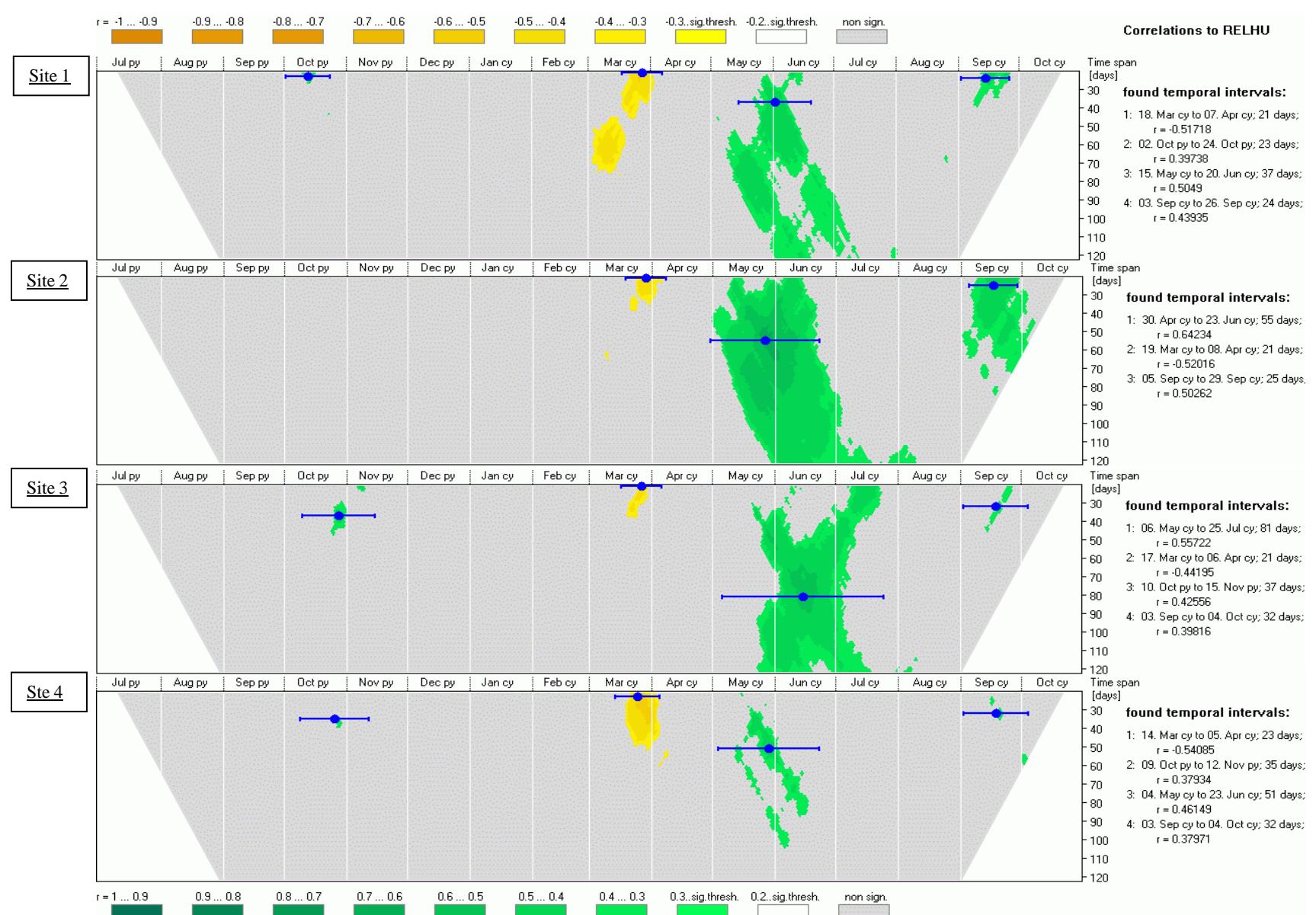


figure 47: Time intervals with the highest correlations of relative humidity to the tree ring indices of *Picea abies* for each site (period 1987-2016).

Appendix

Results from the principal component regression

table 4: Statistical values for the evaluation of the performance quality of each model resulting from the principal component regression.

Tree species: Period: Site:	<i>Abies alba</i>							
	1958-1987				1987-2016			
	1	2	3	4	1	2	3	4
Coefficient of determination (R^2)	0.85	0.80	0.85	0.91	0.86	0.79	0.79	0.91
Akaike information criterion (AIC)	-6.43	-6.57	-6.77	-6.36	-6.16	-6.16	-6.86	-6.47
Gleichläufigkeit (Glk) between the modelled TRI-series by PCR and the measured TRI series	89.65%	86.20%	86.20%	96.55%	96.55%	82.75%	86.20%	89.65%
Ratio of sensitivities of modelled TRI-series by PCR/ measured TRI-series	0.85	0.91	0.91	0.98	0.96	0.98	0.95	0.97

Tree species: Period: Site:	<i>Picea abies</i>							
	1958-1987				1987-2016			
	1	2	3	4	1	2	3	4
Coefficient of determination (R^2)	0.82	0.82	0.87	0.87	0.72	0.75	0.84	0.82
Akaike information criterion (AIC)	-6.15	-5.86	-6.00	-6.28	-5.35	-4.89	-5.97	-6.16
Gleichläufigkeit (Glk) between the modelled TRI-series by PCR and the measured TRI series	89.65%	86.20%	82.75%	75.86%	86.20%	82.75%	89.65%	89.65%
Ratio of sensitivities of modelled TRI-series by PCR/ measured TRI-series	1.02	0.88	0.93	0.95	0.88	0.79	0.89	0.84

Declaration in lieu of an oath

for the master's thesis

English

I hereby declare that this master's thesis was done by myself and that only the sources and tools listed were used. The work was not submitted to any other examination authority in the same or similar form.

Deutsch

Hiermit erkläre ich, dass die vorliegende Masterarbeit von mir selbst angefertigt wurde, und nur die aufgeführten Quellen und Hilfsmittel Verwendung fanden. Die Arbeit wurde in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt.

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Matrikelnummer: 03698312

Titel: Climate-growth relationships in mixed fir-spruce stands in the Western Rhodopes, Bulgaria

Ort, Datum

Unterschrift