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ORIGINAL PAPER

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Impact of late frost events on radial growth of common beech (*Fagus sylvatica* L.) in Southern Germany

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Abstract Phenological, temperature, and tree-ring data were used in order to identify and quantify the impact of late frosts on common beech (*Fagus sylvatica* L.) at different altitudes in Southern Germany during the last century. For this intention, dendroecological investigations were made upon trees at the Meteorological Observatory Hohenpeißenberg as well as from seven stands in the Bavarian Forest and 17 stands at the northern fringe of the Alps. From these locations, a considerable number of severe growth minima in the tree-ring series could be related to late frost in the days of or immediately after leaf unfolding. The frequency of frost-related growth minima increases with altitude. In individual years, radial growth can be reduced by more than 90% (stand mean) in relation to the average growth of the ten previous years. Hence, late frosts are considered as important ecological events that strongly affect beech vitality and competitiveness especially at high altitudes. Evidence of significant impacts on radial growth by late frosts distinct before leaf unfolding or with temperatures above −3°C was not found. Also, increasing frequency and intensity of late frosts during recent decades were not ascertained. Hence, the recently observed decreased vitality of common beech accompanied by growth depressions especially at high altitude sites in Central Europe cannot be explained as a consequence of late frost damage.

Keywords Common beech · *Fagus sylvatica* L. · Late frost · Frost damage · Dendroecology

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Introduction

During leaf unfolding, trees and shrubs are most frost sensitive. Common beech (*Fagus sylvatica* L.) is more sensitive to spring frost damage compared to other tree species because of an earlier onset of leaf unfolding (see Lauprecht 1875). Frost below −4°C can kill the developing new shoots, reduce growth, and cause misshapen branching out (Holmsgaard 1962). Flowers and newly formed fruits can even be damaged at a few degrees below zero. According to Walter (1986), new shoots, bursting buds, and unfolding leaves can be affected by slight frost. However, different investigations revealed a frost resistance of these plant tissues between −1 and −4°C (Till 1956; Holmsgaard 1962; Larcher and Häckel 1985; Sakai and Larcher 1987; Mayer et al. 1988).

Intensity and frequency of late frost events influence the geographical range of beech. According to Klötzli (1976), late frosts restrict the advance of beech at the eastern border of its natural range and determine the upper altitudinal limit in exposed mountainous sites. Also, Walter (1986) assumed that the upper altitudinal limit of beech in the Alps is a consequence of late frosts. Estimating the different effects of global climate change raises the question whether climate warming may cause an earlier onset of spring phenophases and, as consequence, the probability of late frost impacts will increase. Model analyses of the influence of climate change on the timing of bud burst of trees in Central Finland indicate an increased risk of frost damage if the predicted warming occurs (Hänninen 1991). No change or even a decreased risk, however, has been concluded in other studies (Murray et al. 1989; Kramer 1994; Menzel

1997). Kramer (1994) explained these contradictory results by the different response of tree species to local climatic conditions. Also for Bavaria, Menzel (1997) assumed that physiological adaptation will prevent an increasing risk and frequency of late frost damage.

Destruction of the foliage by frost is a considerable loss for the tree. Depending on the degree of damage, the formation of new leaves demands a more or less high amount of storage compounds and assimilates. In addition, the lost assimilation area reduces the production capacity. Therefore, years with late frost damage are marked by small tree rings (Schwerdtfeger 1981). Repeatedly, it has been shown that negative pointer years (negPY) (increment minima) in the tree-ring series of beech could be related to late frost impacts (Z'Graggen 1992; Dittmar and Elling 1999; Elling and Dittmar 2003; Schweingruber and Nogler 2003).

One example, well documented for the Bavarian Forest by Elling et al. (1987), was the severe advective late frost in May 1953 which affected many Central European beech chronologies. After an early leaf unfolding, a sudden cold spell between 9th and 14th May with associated minimum temperatures below −6°C at high altitudes caused strong damage in beech trees of different age classes.

For the evaluation of late frost damage, two kinds of frost events must be distinguished. Advective late frosts, caused by a horizontal delivery of cold-air masses, are stronger at high elevations and characterized by damage potential which increase with altitude. However, lower slopes, valleys, depressions, and typical cold-air tailback sites (germ. "Kaltluftstaulagen") are more affected by radiation frost, caused by a strong outgoing terrestrial radiation during cloudless nights. Because of temperature inversions, this kind of late frost affects younger beech trees more than mature ones. In some years, however, both kinds can be significant depending on the weather, site or region (Reif and Papp-Vary 1995).

In the following contribution, phenological, temperature, and tree-ring data of beech stands in Southern Germany were analysed in order to study the impact of late frost events on the radial growth of beech. The damage potential of a late frost is strongly related to the site-specific minimum temperatures and the phenological status of the tree. Hence, evaluations were carried out in the proximity of phenological stations, or data were utilised that had been transformed to the relevant altitudes by regional specific gradients. This investigation focuses on the Bavarian Forest and the northern fringe of the Alps, where several beech stands have been recently dendroecologically investigated by the authors. As several strong growth depressions were repeatedly found in tree-ring series of these sites since the late 1970s (Elling and Dittmar 2003), this study additionally deals with the question whether late frost events are involved in these observed vitality loss and damage processes.

Materials and methods

Beech trees and late frost events at the Meteorological Observatory Hohenpeißenberg

Directly south of the Meteorological Observatory Hohenpeißenberg of the German Weather Service (DWD), several beech trees were sampled for dendrochronological analyses at the end of July 2002. As long-term phenological observation and temperature data are available for this station, the relation between the timing of leaf unfolding, late frost, and signals in tree rings could be analysed for a time span of around 50 years. Wood cores were taken at breast height, in two opposite directions, from six mature beech trees. Tree rings were measured, synchronized, and dated, and climate-growth relationships according to Dittmar and Elling (1999) were analysed. Phenological observations have been carried out at the Hohenpeißenberg station since 1951 with a homogenous time series since 1978. Using the temperature model of Rötzer et al. (2004), the timing of bud burst (i.e. leaf unfolding) was estimated since 1879 in order to investigate late frost impacts over the whole time span of around 100 years represented by the tree-ring data. In this time span, the date of leaf unfolding ranged between the 26th of April and the 23th of May. In order to also take frost impacts before leaf unfolding into account, all days when minimum temperatures fell below −3°C between the 15th of April and the end of June were identified from the Hohenpeißenberg temperature record. According to Mayer et al. (1988), frost below −3°C was chosen as the physiological threshold value for frost damage to sensitive plant tissue. This is in line with the frost hardiness of unfolding leaves detected by Till (1956) and the frost sensitivity of beech leaves according to Tranquillini and Plank (1988). For single-year analyses (interpretation of increment minima), however, frosts above −3°C also were taken into account. Timing of leaf unfolding and late frosts were graphically compared and evaluated by single-year analyses.

Determination of late frost events and their effects on radial growth in Southern Germany

The database for the analyses of late frost impact on radial growth in Southern Germany was a tree-ring series from seven beech stands in the Bavarian Forest and 17 beech stands at the Northern fringe of the Alps. These stands were dendroecologically investigated at the Department of Forest Science and Forestry at the Weihenstephan University of Applied Sciences between 1984 and 2004 (cf. Elling and Dittmar 2003; Dittmar et al. 2003a, b). As forest sites are normally not proximally located to phenological and meteorological stations, site-specific data about leaf unfolding and minimum temperatures are required. For this, regionally specific vertical gradients of leaf unfolding were used. As there is a delay of leaf unfolding with altitude, gradients of 2.3 days (Bavarian Forest) and 1.7 days (Southern Bavaria with Northern Alps) per 100 m altitude, respectively, according to Dittmar and Elling (2006), were applied. For the representation of minimum temperatures and their vertical gradients, data from climate stations with careful exclusion of cold air tailback sites in the two regions were analysed. Data from around 14 phenological and 9 climate stations in the Bavarian Forest and from 40 phenological and 8 climate stations in Southern Bavaria were obtained from DWD and evaluated. As far as they were available, data within the time span 1951–2000 were considered (Table 1).

For the Hohenpeißenberg data, late frosts with damage potential were defined as sudden cold spells reaching temperatures below −3°C after the 15th of April until the end of June. For reconstruction of the temperature situation, the daily minimum air temperature at 2 m above ground was used and, if available, the daily minimum temperature near the ground was also considered. With phenological data from several observation stations, the site- and altitude-specific status of leaf unfolding was estimated for each late frost event and compared with signals in tree rings. Single-year analyses were based on negative pointer and event years selected according to Dittmar and Elling (1999). Negative pointer years (negPY) are defined as growth minima with strong growth reductions (more than 30 or 50%) in relation to the ten previous years occurring in at least 90% of trees. To identify strong signals at single trees also, negative event years (negEY) were selected. They can occur, for example, if only a few trees are strongly affected by late frost damage. Negative event years therefore are defined as especially strong growth reductions (more than 50 or 70%) in relation to the ten previous years occurring in at least two trees. For the strength of the required growth chances (30 or 50% for negPY and 50 or 70% for negEY, respectively), the mean sensitivity of the tree-ring series is considered. The mean sensitivity is a statistical measure of the ring-width changes from year to year (Fritts 1976). Higher threshold values of growth changes are used at mean sensitivities above 0.2 and lower at mean sensitivities at and below 0.2 (Dittmar and Elling 1999). Besides late frosts, information about weather conditions and mast years of beech in the investigated regions were also taken into account as reasons for growth reductions in single years.

Late frosts with an obvious damage potential in a specific region and altitudinal belt were selected in a second step to estimate the amount of radial growth reduction in the affected years. The 1,000 m altitudinal belt (940–1,060 m a.s.l.) at the Northern Alps was chosen for these analyses as it is well represented by eight of the study sites. At these altitudes, late frost events after leaf unfolding (with minimum temperatures below −3°C) occurred in the years 1928, 1953, and 1991. For these years, changes of ring widths at all trees in relation to the ring width of the previous year and of the average of the ten previous years, respectively, were calculated.

Results

Late frosts and radial growth of beech at the Meteorological Observatory Hohenpeißenberg

Several, but only a few serious, minima are visible in the radial growth series of the ca. 100-year-old beech trees growing at the Meteorological Observatory Hohenpeißenberg (Fig. 1). Although, in comparison to

Table 1 Climate stations selected for T_{min} gradients in the two study regions

No.	Climate station	Altitude (m a.s.l.)	Time span
Bavarian forest with upper Palatinate Forest			
1	Regensburg	366	1951–1999
2	Passau-Oberhaus	409	1951–1996
3	Oberviechtach	595	1951–1999
4	Zwieselberg	615	1965–1999
5	Grainet-Rehberg	655	1957–1999
6	Altglashütte	750	1954–1987
7	Waldhäuser	940	1972–2000
8	Mauth-Finsterau	1,004	1951–1956
9	Gr. Falkenstein	1,317	1951–1982
April: $T_{min} = 4.59 - 0.43\ A_{100\ m}$, $p < 0.001$, $n = 322$			
May: $T_{min} = 8.84 - 0.41\ A_{100\ m}$, $p < 0.001$, $n = 322$			
Bavarian Alps (northern fringe)			
1	Bruckmühl-Oberwall	549	1959–1981
2	Traunstein-Axdorf	635	1972–2000
3	Bad Kohlgrub	850	1951–1999
4	Mittenwald	920	1951–1999
5	Hohenpeißenberg	977	1951–2000
6	Oy-Mittelberg	1,010	1951–1993
7	Rauschberg (Ruhpolding)	1,640	1963–1998
8	Wendelstein	1,832	1951–2000
April: $T_{min} = 5.54 - 0.43\ A_{100\ m}$, $p < 0.001$, $n = 364$			
May: $T_{min} = 9.45 - 0.40\ A_{100\ m}$, $p < 0.001$, $n = 364$			

T_{min} = minimum temperature at 2 m above ground
A_{100m} = altitude in 100-metre steps

similar altitudinal environments at the northern fringe of the Alps, the climate at Hohenpeißenberg (977 m a.s.l.) is more favourable with regard to temperature and radiation, it can be characterized as typical mountainous (Attmannspacher 1981). Single-factor correlations according to Dittmar and Elling (1999) with temperature, precipitation, and radiation data for the period 1901–2000 revealed no primary growth limiting factor. This suggests that growth conditions are generally favourable and from year to year different growth influences are effective. Five of the nine growth minima during the last century coincide with late frost around or after the date of leaf unfolding: 1903, 1906, 1928, 1953, and 1984 (Table 2). The latter four are defined as negPY. It is interesting to note that not all growth minima are related to late frosts, but in every year with a late frost after leaf unfolding, a negative response in the tree rings was found (Fig. 1). The only exception here is 1927 where the minimum in the succeeding year (1928) can be explained as response to late frost events in May 1927 and 1928 (see below).

In 1984, besides late frost impacts, small ring widths might also have been caused by fructification. According to von Schönborn (1969), both factors can be effective together in particular years. Strong fructification (Eicke 1996) is assumed to be the main reason for increment minima in 1995. Evidence of late frost impacts as reported by Reif and Papp-Vary (1995) in South-West Germany between the 14th and 15th of May were not found in the temperature data at Hohenpeißenberg. There the last frost below −2°C was recorded on the 15th of April, 1995. The pointer years 1933 and 1967 are related to cool and cool-wet weather conditions during the vegetation period, respectively. Late frost impacts can be excluded. For the minimum in 1940, no satisfying explanation was found.

Late frosts before leaf unfolding, therefore, seem to be only relevant if they occur near to the date of (i.e. a few days before) leaf unfolding and when temperatures are distinctly below −3°C. Earlier and/or weaker frost may be responsible for the weaker (but not identified as pointer or event years) minima in the years 1945 and 1957. Late frosts in two subsequent years after and during leaf unfolding occurred in 1927/1928 and caused an especially severe growth reduction in 1928. In 2000, the investigated beech trees at Hohenpeißenberg were cut below the crown at 4–5 m stem height. Hence, tree-ring widths are strongly decreased after 2000 and no ring was built in some of the trees in 2001.

Late frosts and their impacts on radial growth of beech in the Bavarian Forest and Southern Bavaria

Late frost events and their impacts on radial growth were accordingly analysed in the Bavarian Forest and in Southern Bavaria. As data from several phenological and meteorological stations were taken into account, both data sets were visualized in separate diagrams for certain years (Figs. 2, 4). They contain the date of leaf unfolding

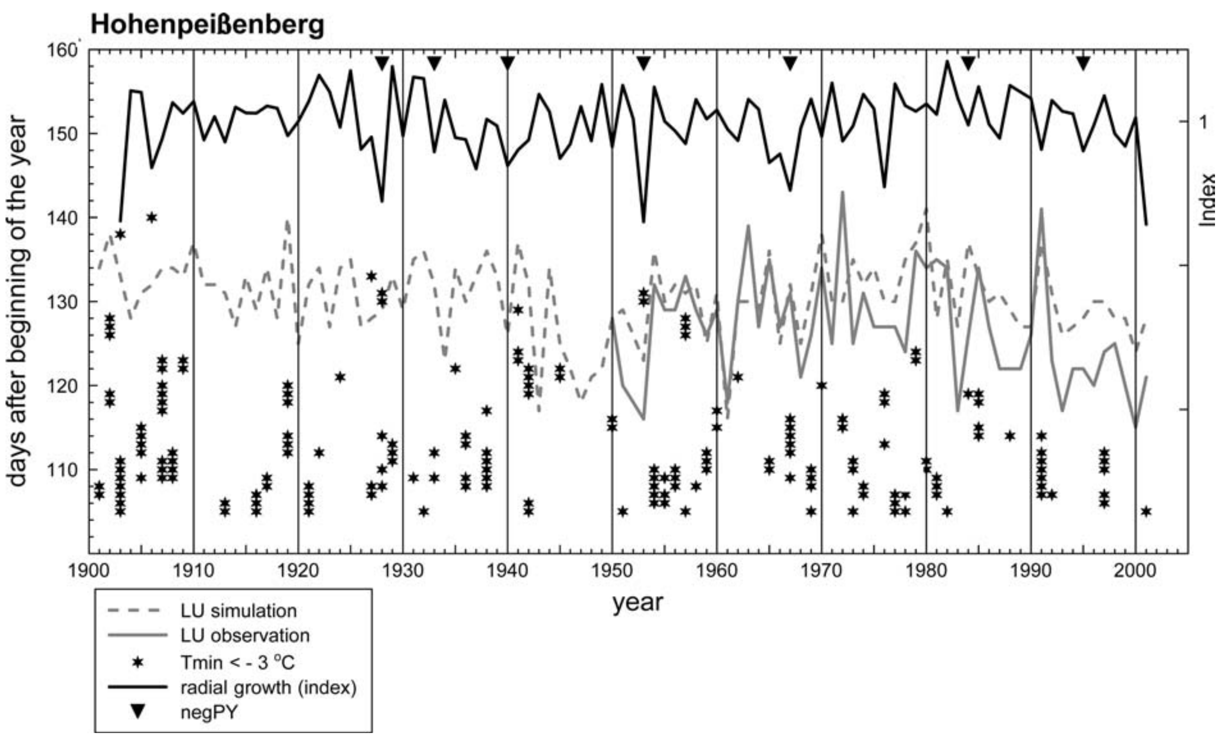


Fig. 1 Timing of leaf unfolding, occurrence of frost events in spring, and radial growth of beech at the mountain Hohenpeißenberg. Timing of leaf unfolding (*LU*) was simulated according to Rötzer et al. (2004). Radial growth of six beech trees is plotted as mean index curve (residual chronology) and negative pointer years (*negPY*) are selected according to Dittmar and Elling (1999)

Table 2 Single-year analyses of radial growth minima of beech trees growing at the Meteorological Observatory Hohenpeißenberg (977 m a.s.l.)

Year[a]	Beginning of leaf unfolding[b]	Late frost (date, T^{c}_{min})	Interpretation of the growth minimum
1903	13th May	18th–20th May, −3.2°C	Late frost
1906	13th May	20th May, −6.6°C	Late frost
1928	12th May	11th–14th May, −4.1°C	Late frost (+ late frost in the previous year on 15th May, $T_{min}=-3.9$°C)
1933	12th May	Last frost: 24th April	Unfavourable weather conditions: low temperatures and high precipitation during May and June
1940	10th May	Last frost below −2°C: 14th April	? no sufficient explanation
1953	26th April	8th–11th May, −3.5°C	Late frost
1967	11th May	Last frost below −2°C: 27th April	? unfavourable weather conditions during June: low temperatures and high precipitation
1984	6th May	29th April, −4.9°C	Late frost and/or fructification in South Bavaria (StSPL 1997)
1995	2nd May	Last frost below −2°C: 15th April (14th/15th May: −0.4°C)	Strong fructification at the northern fringe of the Alps (according to Eicke 1996) (late frost according to Reif and Papp-Vary (1995), not effective at Hohenpeißenberg)

[a]Pointer years (after 1911) according to Dittmar and Elling (1999)
[b]Before 1951: simulated according to Rötzer et al. (2004), after 1951: observation data
[c]Daily minimum temperature at 2 m above ground at the Meteorological Observatory Hohenpeißenberg

observed at different phenological stations extrapolated into higher altitudes with the regionally specific averaged long-term delay of leaf unfolding with altitude (grey area and left axis). The right axis shows measured minimum temperatures at different climate stations with the average altitudinal decrease of the minimum temperature during the days of late frost represented as a regression line. During days of late frost, we repeatedly found a steeper decrease of minimum temperatures in comparison to the long-term average decrease in April and May (0.42°C/100 m, see Table 1).

Data for the year 1952 in the Bavarian Forest show that beech trees were already foliaged up to high altitude sites until the late frost of 20th May (Fig. 2a). Minimum temperatures, however, fell below the −3°C threshold value only above 950–1,000 m a.s.l. Consequently, only beech stands at altitudes above 1,000 m a.s.l. could be affected by late frost damage. Another situation occurred during spring 1953 (Fig. 2b). An unusually early leaf unfolding (see also Elling et al. 1987) resulted in the beech trees being foliaged up to higher altitudes before the 9th to 13th of May while the late frost occurred. Damaging temperature values during these days had already reached above 800–850 m a.s.l. Common beech was strongly affected by the late frost in 1953 not only in the Bavarian Forest but also in other German regions (Siegl 1954; Dittmar and Elling 1999; Dittmar et al. 2003a).

Impacts of the late frosts of 1952 and 1953 on radial growth of beech at different altitudes in the Bavarian Forest can be verified by the analysis of tree-ring series (Fig. 3). According to Fig. 2a, the late frost in May 1952 had no damage potential at altitudes below 1,000 m a.s.l. in the Bavarian Forest. At two investigated sites below 1,000 m a.s.l., no signals were detected for this year; in fact at the lower site, even above-average ring widths were measured (Fig. 3a, b). A strong minimum, however, was found in the tree-ring series of beech at the high altitude site between 1,180 and 1,200 m a.s.l. (Fig. 3c). The specific situation in spring 1953 is accordingly reported in the tree rings: the strongest signals are visible at altitudes around 1,000 m a.s.l. (Fig. 3b). Below this altitudinal belt, frost was obviously weaker (Fig. 3a). Above 1,100 m a.s.l., because of a delayed leaf unfolding, probably not all trees were affected (Fig. 3c). Also at the northern fringe of the Alps, late frost events in 1952 and 1953 accordingly caused altitude-specific growth patterns (cf. Fig. 5).

Two late frost events at the northern fringe of the Alps during the second half of the 1970s are presented in Fig. 4. Until the late frost on 30th April 1976, leaf unfolding of beech had reached altitudes up to around 700 m a.s.l. Temperatures below −3°C, however, were reached at almost all climate stations, even at low altitudes (Munich: T_{min} −4.0°C). During 1976, repeatedly strong growth reductions were observed, especially at low altitudes. This response was mostly related to the warm and dry weather conditions during the vegetation period in 1976 (König and Mayer 1989). Our results, however, suggest that besides water deficiency, damage by late frosts also has to be taken into account as reason for increment reduction in 1976 at lower altitudes, especially in Southern Bavaria, where the drought was not so severe and long lasting as in other Central European regions.

A quite different situation occurred during the spring of 1978. Leaf unfolding showed a high variability between different observational stations indicating a local specific onset of the vegetation period in this year (Fig. 4b). In some cases this led to an earlier timing of bud burst at higher rather than at lower altitude sites. The data show, however, that leaf unfolding climbed up,

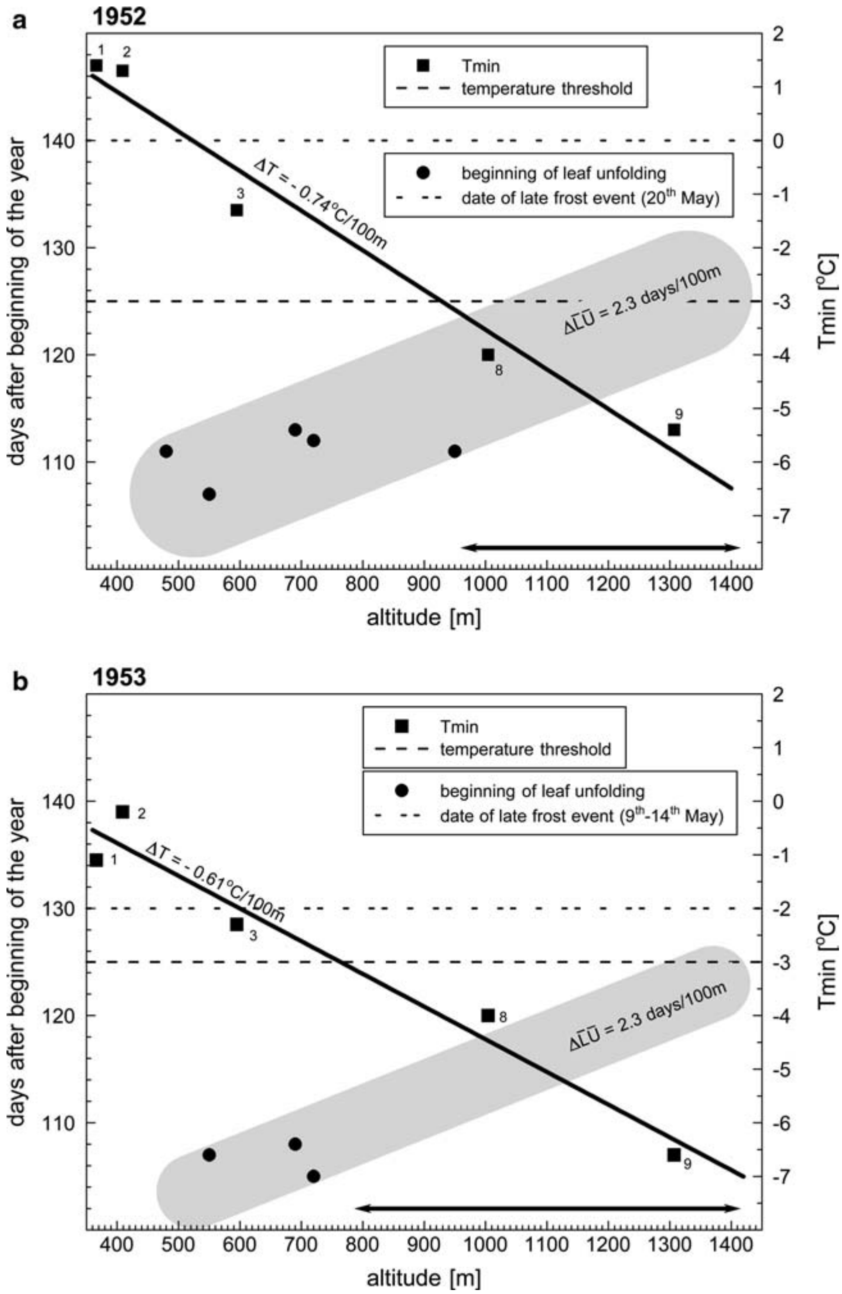


Fig. 2 Minimum temperatures (T_{min}, plotted as filled square, *right axis*) during late frost events in the years 1952 (**a**) and 1953 (**b**) at different climate stations (see Table 1) and beginning of leaf unfolding (*LU*, plotted as filled circle, *left axis*) in these years at different phenological stations in the Bavarian Forest. *Grey* areas indicate the dispersion of LU data and the long-term average of the vertical gradient of LU ($\Delta\bar{L}\bar{U}$) in this region according to Dittmar and Elling (2006). The decrease of T_{min} with altitude during the days of late frosts is plotted as a regression line. Altitudinal belts potentially affected by late frost impacts are highlighted by an *arrow*

at least partly, to high altitudes until the late frost of 11–12 May occurred. According to the minimum temperatures reached at different climate stations, late frost damage above an altitudinal belt of 1,050–1,100 m a.s.l. was possible. All climate stations below 1,050 m a.s.l. recorded minimum temperatures above −3°C. At the northern slope below the Herzogstand mountain, the year 1978 was repeatedly found as a negative pointer and event year in tree-ring series of beech stands above 900 m a.s.l. (Fig. 5a, b). Not only there, but also at other high altitude sites of Central Europe, the year 1978 appears as part of a repeatedly documented growth depression during the late 1970s (Dittmar et al. 2003a; Elling and Dittmar 2003). At the northern fringe of the Alps, according to the situation presented in Fig. 4b, late frost impact could only have been effective as an additional and accelerating, but not as a primary and triggering, factor (see below).

All years between 1900 and 2000 were accordingly analysed and late frost events compared with signals in the tree-ring series of the investigated 24 beech stands. In the Bavarian Forest and especially in the Northern Alps, the number of pointer years which could be explained by advective frost events during or after leaf unfolding increases markedly with altitude (Fig. 5). This is in line with earlier findings that the intensity and frequency of late frost events strongly influence the vitality and reproduction of beech at higher altitudes (Schwerdtfeger

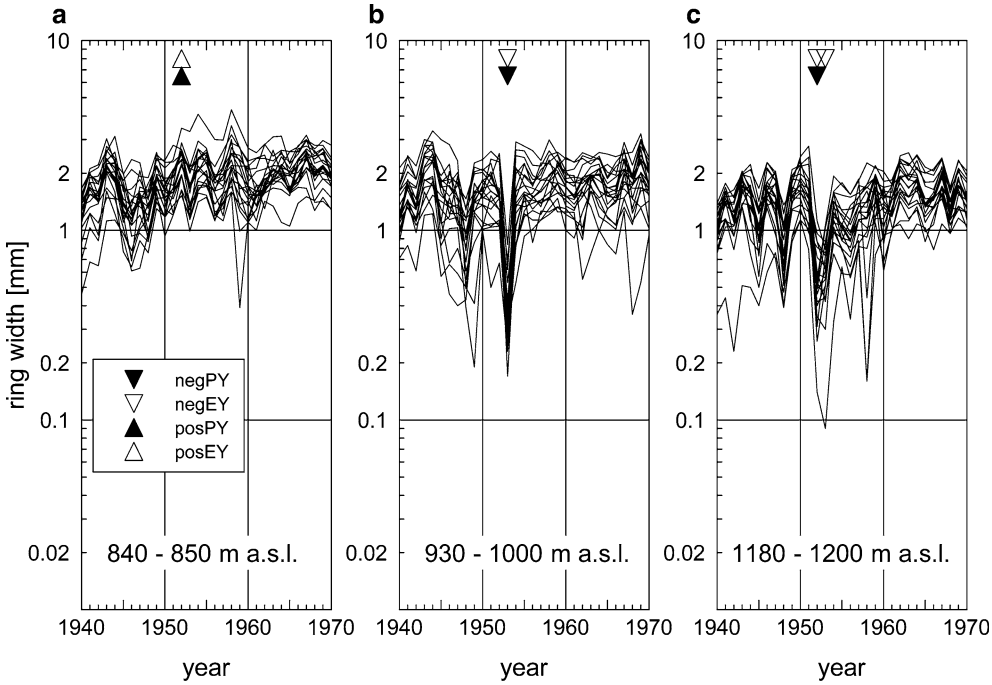


Fig. 3 Radial growth (tree curves of 20 trees per stand, log scaled) of beech at different altitudes in the Bavarian Forest between 1940 and 1970. Signals in tree-ring widths during the two late frost events in the years 1952 and 1953 are signed as pointer (*pos*/*negPY*) and event years (*pos*/*negEY*). Site **a** (Guglöder Riegel) and site **c** (Gfeichtet) are located in the Bavarian Forest National Park (tree-ring data according to Koch and Landgraf 2003), site **b** is located at the mountain Brotjacklriegel (Jägerriegel, tree-ring data according to Reischl 2002)

1981; König and Mayer 1988; Reif and Papp-Vary 1995; Piovesan et al. 2003). Especially strong signals in tree rings were found if late frosts occurred in two subsequent years (1927/1928, 1941/1942, 1952/1953, and 1968/1969).

Three late frost events (1928, 1953, and 1991) with damage potential and documented signals in tree rings of beech stands at around 1,000 m a.s.l. from the northern fringe of the Alps were used to quantify the growth reduction in years with late frost events (Table 3). The mean increment reduction in all eight stands (mean of 6–20 trees) ranges between 31 and 52% in comparison to the previous year and between 17 and 52% in comparison to the average of the ten previous years. Especially strong was the reduction in 1953 with a mean decrease of ring widths in individual stands up to 71 and 90%, respectively. In some individuals, missing rings, due to the failure of cambial activity at breast height, occurred in 1953 (Fig. 5a).

Discussion

The results above demonstrate that retrospective analyses of late frost impacts on common beech are possible if a temporally and regionally coherent network of different data records is available. Phenological, temperature, and tree-ring data of beech stands at different altitudes in Southern Germany enabled the differentiation of late frosts and their damage potential in single years for particular altitudes.

At Hohenpeißenberg, in the Bavarian Forest and Southern Bavaria, a considerable number of growth minima can be related to late frost during or after leaf

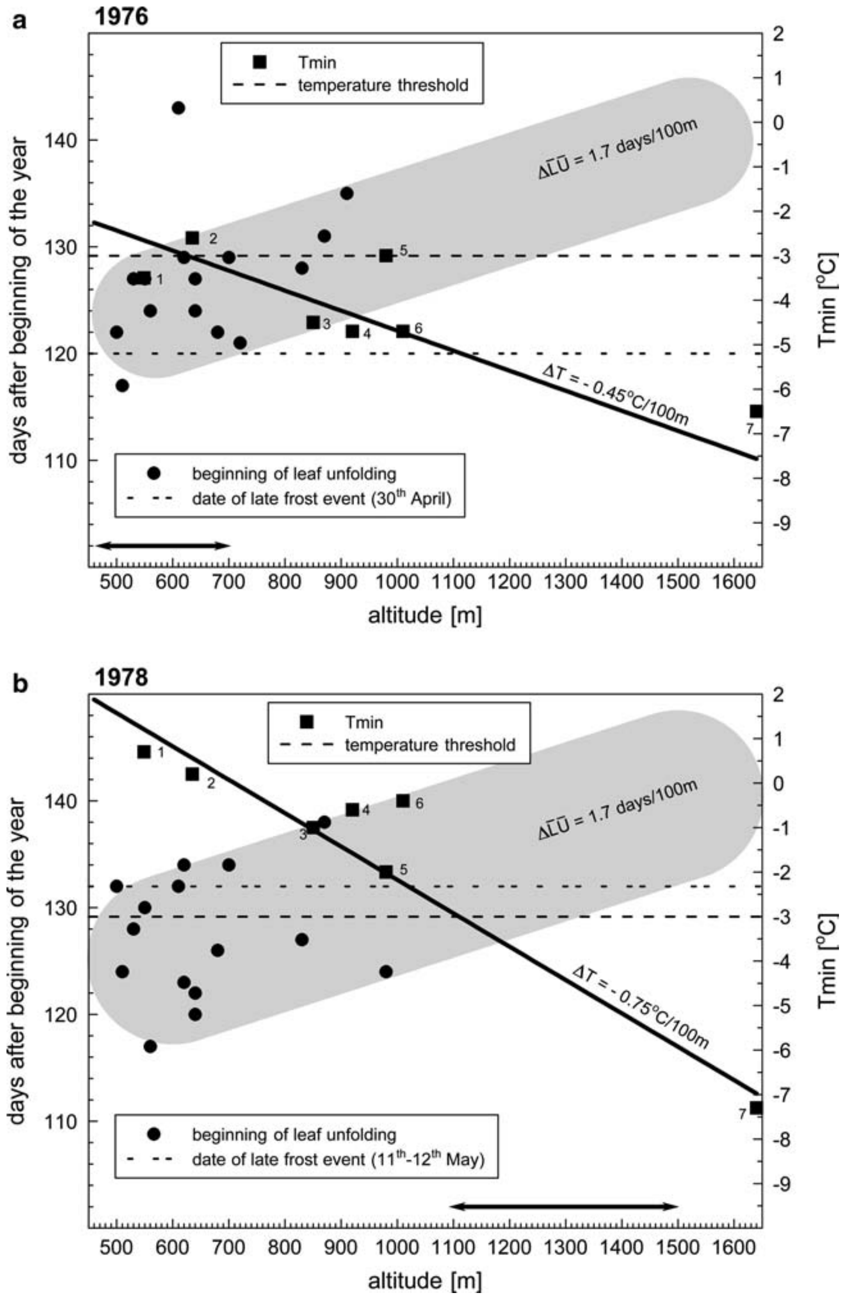
Table 3 Reduction of radial growth in years with late frost impacts at the 1,000 m altitudinal belt at the northern fringe of the Alps

Site	1928		1953		1991		Number of trees
	pry	10 pry	pry	10 pry	pry	10 pry	
Rosenheim/Schwarzenberg (960 m a.s.l)[a]	81 ± 30	76 ± 28	41 ± 17	40 ± 18	n.d.	n.d.	20
Schliersee/Seeberg (1,020 m a.s.l.)[b]	69 ± 28	67 ± 32	88 ± 31	75 ± 29	68 ± 22	81 ± 33	10
Füssen/Northern Schwarzenberg (1,010 m a.s.l.)[c]	31 ± 9	30 ± 8	29 ± 28	10 ± 12	70 ± 14	94 ± 21	20
Bad Tölz/Grenzgraben (1,020 m a.s.l.)	64 ± 26	73 ± 30	45 ± 19	53 ± 29	72 ± 16	88 ± 19	20
Oberammergau/Mühlweg (1,060 m a.s.l)	68 ± 24	77 ± 31	47 ± 14	49 ± 14	56 ± 17	82 ± 33	20
Rosenheim/Kranzhorn (940 m a.s.l.)	91 ± 13	84 ± 22	54 ± 26	61 ± 33	79 ± 16	84 ± 21	20
Hohenpeißenberg (977 m a.s.l.)	47 ± 27	39 ± 23	37 ± 24	40 ± 20	74 ± 17	80 ± 20	6
Garm.Partenkirchen/Höhenberg (960 m a.s.l.)[d]	78 ± 15	114 ± 43	39 ± 13	38 ± 12	64 ± 21	73 ± 25	20
Mean	66 ± 22	70 ± 27	48 ± 22	48 ± 21	69 ± 18	83 ± 25	136

Values mean of radial increment ± standard deviation in percent of the previous year (*pry*) and the ten previous years (10 *pry*), respectively

[a,b,c,d]Tree-ring data according to Gabriel et al. (1985), Mühlbacher and Haider (1996), Mühle (2000), and Ganserer (personal communication)

Fig. 4 Minimum temperatures (T_{min}, plotted as filled square, *right axis*) during late frost events in the years 1976 (**a**) and 1978 (**b**) at different climate stations (see Table 1) and beginning of leaf unfolding (*LU*, plotted as filled circle, *left axis*) in these years at different phenological stations at the northern fringe of the Alps. *Grey* areas indicate the dispersion of LU data and the long-term average of the vertical gradient of LU ($\Delta\bar{L}\bar{U}$) in this region according to Dittmar and Elling (2006). The decrease of T_{min} with altitude during the days of late frosts is plotted as a regression line. Altitudinal belts potentially affected by late frost impacts are highlighted by an *arrow*



unfolding. The frequency of this phenomenon increases with altitude. Especially strong growth reductions were found if the date of the late frost was close to the date of bud burst and when temperatures were distinctly below −3°C. This situation typically occurs more frequently at higher than at lower altitudes in connection with advective late frost events after the beginning of May. Hence, at high altitudes, unfolding or young leaves are more strongly and more frequently affected by late frost damage. Depending on the degree of damage, repairing or the production of new leaves demands assimilates and storage components. As a consequence, late frost impacts reduce radial increment in the current year (Schwerdtfeger 1981). After-effects (lag-effects) in subsequent years were not found in the investigated tree-ring data. Even after 1953, the strongest late frost event with the highest damage potential in the last century, a complete recovery of increment in most of the trees was noted for the following year. Especially small tree rings were found, however, if late frosts occurred in two subsequent years (1927/1928, 1941/1942, 1952/1953, 1968/1969). In these cases, late frost in the second year triggered a stronger reaction than expected.

Dendroecological analyses presented herein confirm the threshold value for significant late frost damage on young leaves of at least −3°C as presented in the literature and derived from experimental approaches (Till 1956; Holmsgaard 1962; Mayer et al. 1988; Tranquillini

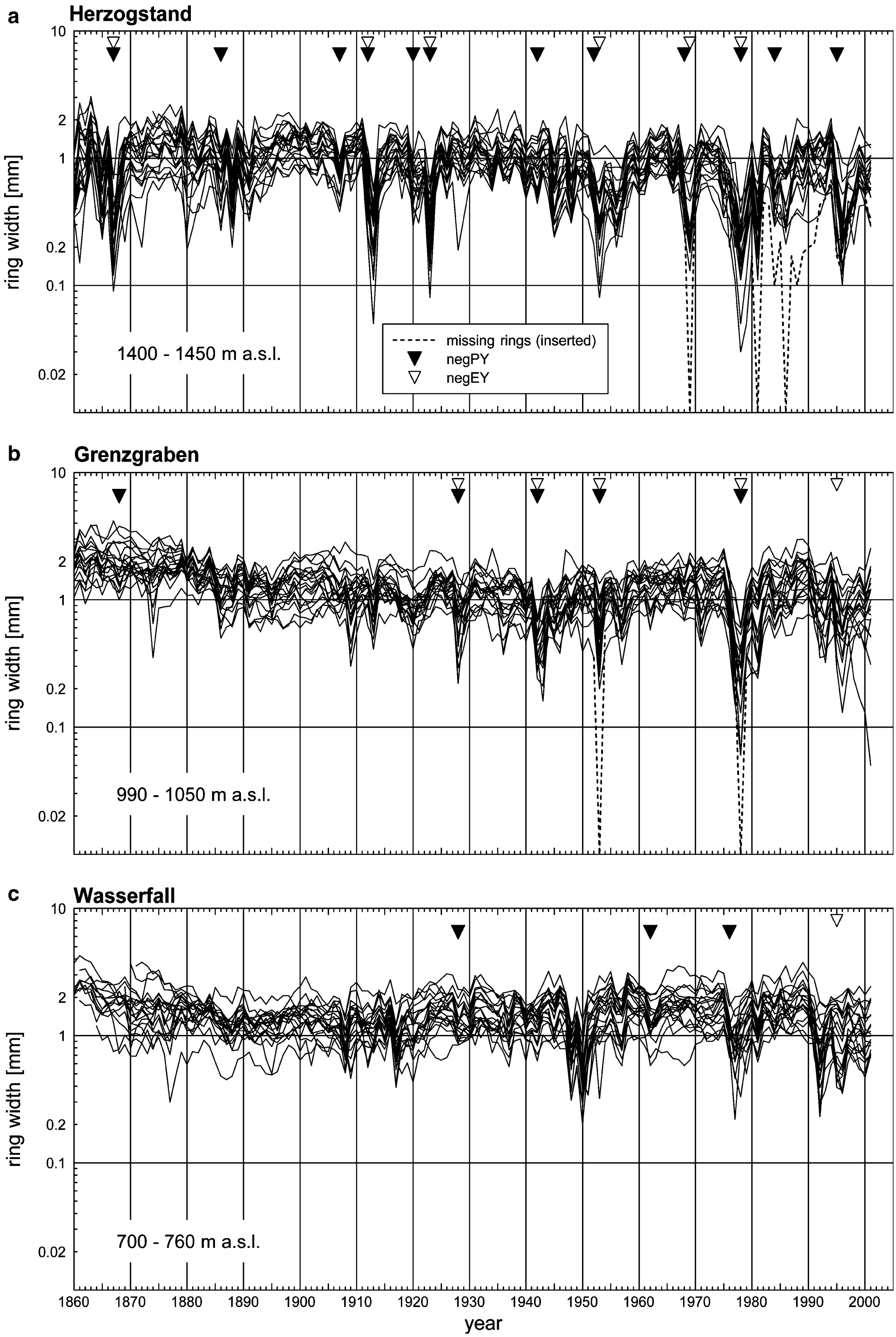


Fig. 5 Radial growth (tree curves of 20 trees per stand, log scaled) of three beech stands at different altitudes of the northern slope below the Herzogstand mountain (Bavarian Alps). Highlighted as *triangles* are negative pointer (*negPY*) and event years (*negEY*), which are related to late frost impacts in the same years (tree-ring data according Elling and Dittmar 2003). Series with dated and inserted missing rings are signed by *dotted lines*

and Plank 1989). Our results suggest that temperatures had to fall at least below this threshold in order to cause sensitive damage on unfolding and young leaves with consequences for radial increment in the current vegetation period (Mayer et al. 1988).

Only a few weak examples were found which may be related to late frost damage caused before leaf unfolding. An increased frost sensitivity up to 20 days before bud burst, during the phase of bud swelling (König and Mayer 1988), with consequences for radial growth, could not be confirmed by the analysed tree-ring data. It seems that damages before leaf unfolding require significantly lower temperatures and, therefore, are much more extraordinary; else they are easier to repair. We assume that especially late frost damages during bud burst and to young leaves are the important factors reducing beech vitality. At high altitudes, this situation is more frequent at the beginning of the vegetation period. Hence, late frost events are important ecological parameters for common beech in mountainous regions.

Frequency and intensity of late frosts have not increased in recent times. In accordance with the findings of Mayer et al. (1988), we found no strong late frost event since the beginning of the 1970s with a damage potential as high as in former decades (e.g. 1953). Hence, damage by late frosts cannot explain the repeatedly observed vitality loss of beech trees, especially at high altitude sites during recent decades (Elling and Dittmar 2003). The late frost in May 1978, however, may have acted as an accelerating factor during the wide-spread growth depression at the end of the 1970s. As this growth depression, however, often started before 1978 (at some sites already in 1975), it can be excluded as a trigger and primary cause of the observed suppressed growth. An appreciable contribution of late frost impacts on the observed vitality loss of beech during the last few decades, therefore, would only be conceivable if frost resistance of beech had strongly decreased in the recent past.

Quantification of the impacts of late frosts on radial increment suggests that tree-ring widths can be distinctly reduced in years with severe spring frost (e.g. 1953). It should be considered, however, that the degree of growth reduction is strongly influenced by growth conditions during the previous and current years. Hence, it is not possible to quantify an exclusively late frost-related growth impact.

Conclusions

- Late frost damage to common beech can be retrospectively analysed by phenological, temperature, and tree-ring data. Spring frost during or immediately after leaf unfolding and with associated temperatures below −3°C causes a strong negative response in radial growth.
- With increasing altitude, a greater number of growth minima can be related to late frost impacts. At high altitudes, vitality and competitiveness of beech are strongly influenced by the intensity and frequency of late frosts. There, advective late frost events are more frequent at the beginning of the vegetation period.
- As is already known for young leaves, radial growth is also affected and markedly reduced when the temperature is at least −3°C. Our results confirm this threshold value for late frost damage at the beginning of the vegetation period. No signals were found in tree rings if frost events occurred distinctly earlier than bud burst or when temperatures did not fall below −3°C.
- During recent decades, frequency and intensity of spring frost have not increased. Late frosts may have an additional influence on vitality loss and growth depressions of beech stands since the late 1970s, but they are excluded as primary triggering factors.

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