

Mountain forest growth response to climate change in the Northern Limestone Alps

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Abstract

Key message Growth response to climate differs between species and elevation. Fir is the most drought-tolerant species. The mountain forests are robust to the climatic changes until now.

Abstract Alpine mountain forests provide a wide range of ecological and socio-economic services. Climate change is predicted to challenge these forests, but there are still considerable uncertainties how these ecosystems will be affected. Here, we present a multispecies tree-ring network of 500 trees from the Berchtesgaden Alps (Northern Limestone Alps, Southeast Germany) in order to assess the performance of native mountain forest species under climate change conditions. The dataset comprises 180 spruce, 90 fir, 110 larch and 120 beech

trees from different elevations and slope exposures. We analyse the species with respect to: (1) the general growth/climate response; (2) the growth reaction (GR) during the hot summer in 2003 and (3) the growth change (GC) resulting from increasing temperatures since the 1990s. Spruce is identified as the most drought-sensitive species at the lower elevations. Fir shows a high drought tolerance and is well suited with regard to climate change. Larch shows no clear pattern, and beech remains unaffected at lower elevations. The unprecedented temperature increase of the last decades did not induce any distinct GC. The mountain forests of the Berchtesgaden Alps appear to be robust within the climatic changes until now.

Keywords Tree-rings · Climate signal · Radial growth · Elevational belts · Dendroecology · Berchtesgaden Alps

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Introduction

Forests cover 1.02 billion Ha of Europe's total land area (FOREST EUROPE UaF 2011) and 41 % of Europe's mountain area (Mc Morran and Price 2011). Mountain forests offer a wide range of socio-economic and ecological services, e.g. by providing timber, serving as a hotspot of biodiversity and fulfilling protective functions (Björnsen et al. 2005; Bugmann et al. 2005; Lindner et al. 2010; Mc Morran and Price 2011; Schumacher and Bugmann 2006). Global change is likely to impact these ecosystems and their functions (Hofer 2005; Lindner et al. 2010). However, there is still a high degree of uncertainty and the effects will depend both on the sensitivity of the ecological and biological system itself and on species-specific tolerances (Elkin et al. 2013).

The IPCC (2013) reports an unequivocal warming of the climate system in the last decades and a further warming is likely. Additionally, likeliness and duration of heat waves have increased in Europe over the last century and are projected to increase even more in the future (EEA 2012). The extraordinary summer in 2003 for example was very likely the hottest summer with respect to the past 500 years (Luterbacher et al. 2004). And the frequency of events such as the heat wave of 2003 has been projected to increase substantially in the near future (Schär et al. 2004).

An unprecedented warming of 1.2 °C was observed in the Alps in the twentieth century (Auer et al. 2007), which even doubles the global temperature shift (Lindner et al. 2010). This temperature rise occurred especially within the past 30 years (Auer et al. 2007), and in general, the late twentieth and early twenty-first century decades were the warmest periods since 1500 or even longer (Luterbacher et al. 2004). A continuing warming in combination with a possible precipitation decrease may play an important role in the future development of mountain vegetation (Engler et al. 2011) and may have substantial impacts on forest ecosystems and the services they provide (Elkin et al. 2013). But the consequences of drought events on tree vitality might be more severe than changes in average conditions (Fuhrer et al. 2006). Due to their long lifespans, trees and forests are considered to possess only limited adaptability and therefore to be particularly vulnerable to climate change (Lindner et al. 2010).

For trees, an elevation-dependent growth response to climate change is expected; e.g. the heat wave in 2003 caused growth suppression in montane forests but growth enhancement at high elevation sites in the Swiss Alps (Jolly et al. 2005). At high altitudes global warming is assumed to increase radial growth (Körner 2012), as observed in the European Alps (Paulsen et al. 2000; Rolland et al. 1998) or in North America (Salzer et al. 2009). A study from the Tatra Mountains reveals a positive growth effect of Norway spruce to increasing temperatures at higher elevations, but a negative influence at lower sites due to drought stress (Savva et al. 2006). At the colline and submontane belt Norway spruce is expected to be more sensitive to climate change than other native tree species (Bolte et al. 2009; Zang et al. 2011; Zang 2012), but current knowledge is insufficient for a clear assessment of the behaviour of different tree species at higher elevations. Dendroecological studies offer a high potential to analyse the possible effects of climate change on trees since the tree-ring width (TRW) is assumed to reflect a tree's vitality (Dobbertin 2005). Several TRW networks in the Greater Alpine Region have been analysed with a dendroclimatological approach aiming at the reconstruction

of temperature, precipitation or drought events (e.g. Affolter et al. 2010 and citations herein). However, only few Alpine studies deal with the ecological interpretation of the response to changing climate conditions (e.g. Lévesque et al. 2013; Schuster and Oberhuber 2013; Weber et al. 2007 for inner-Alpine dry valleys), and especially in the Northern Limestone Alps dendroecological information is scarce.

In this study, we compile a multispecies TRW network in the Northern Limestone Alps (Berchtesgaden, Southeast Germany) in order to assess the aptness of native mountain forest species, i.e. Norway spruce [*Picea abies* (L.) Karst.], silver fir (*Abies alba* Mill.), European larch (*Larix decidua* Mill.) and common beech (*Fagus sylvatica* L.) under conditions of climate change. Using a dendroecological approach we analyse the vulnerability of the different species to climate change through: (1) the long-term growth/climate response; (2) the GR to the unprecedented heat wave in 2003 and (3) the potential GC due to the exceptional twentieth century warming. The results contribute to the assessment of tree species suitability in mountain forests under changing climate.

Materials and methods

Study area and sampling design

Five hundred trees (180 Norway spruce, 90 silver fir, 110 European larch, 120 common beech) were sampled at 18 sites in the Berchtesgaden National Park and the surrounding forest districts (Northern Limestone Alps/Southeast Germany) (Fig. 1; Table 1). Sampling was performed in closed, mixed stands (without any visible natural and human disturbances or recent harvesting) resembling the natural forest types as far as possible. The whole investigation area was influenced by humans since the early medieval age due to salt mining, and tree species composition was strongly altered in favour of spruce (current proportion 50 %) and larch (28 %). The originally dominating species beech and fir nowadays cover only 8, 1 % of the area, respectively (Konnert and Siegrist 2000).

Sampling sites cover an altitudinal gradient of 680–1,670 m a.s.l. and comprise sunny and shady slopes. The dataset was categorised into four elevational belts: lower montane (<950 m), montane (950–1,200 m), altimontane (1,200–1,400 m) and subalpine (>1,400 m) belt. At each site, ten healthy dominant trees per species (termed collective further on) were sampled by taking two increment cores per tree at breast height parallel to the contour. On the whole a TRW network of 50 collectives and 1,000 individual series was compiled.

Table 1 Site description and chronologies

#	Site code	Lat.	Lon.	m a.s.l.	Slope exposure	Onset of chronologies ^a			
						S	F	L	B
1	NGML	N47°35.0'	E12°59.7'	680	su	1901			1897
2	SAGB	N47°31.9'	E12°44.3'	700	su	1874			1902
3	BGOB	N47°38.9'	E13°01.2'	770	su	1880	1869		
4	TSSW	N47°35.3'	E12°59.7'	690	sh	1934	1869		1915
5	BGBS	N47°40.0'	E13°01.3'	760	sh	1857	1878	1850	1855
6	BGOA	N47°39.4'	E13°01.3'	1,020	su	1882	1868		1848
7	SAMA	N47°30.6'	E12°46.7'	1,080	su	1879	1871	1889	1818
8	NGEW	N47°34.4'	E12°48.2'	960	sh	1870	1860		1864
9	BGGP	N47°37.9'	E12°51.1'	1,040	sh	1885	1830	1838	1811
10	NGLS	N47°30.7'	E13°01.0'	1,220	su	1820			1817
11	SAMG	N47°30.6'	E12°47.0'	1,250	su	1871	1837	1803	1817
12	NGMW	N47°33.4'	E12°48.2'	1,310	sh	1794	1850	1832	1840
13	NGMK	N47°35.0'	E12°53.3'	1,330	sh	1849		1806	1825
14	SAKK	N47°32.3'	E12°49.4'	1,530	su	1851		1782	
15	NGHS	N47°33.7'	E12°48.9'	1,620	su	1848		1747	
16	NGKS	N47°31.3'	E13°00.9'	1,670	su	1836		1781	
17	NGMA	N47°33.1'	E12°48.3'	1,560	sh	1879		1780	
18	NGSB	N47°34.1'	E12°49.5'	1,600	sh	1684		1706	

su sunny, *sh* shady, *S* spruce,
F fir, *L* larch, *B* beech

^a End of chronologies = 2008

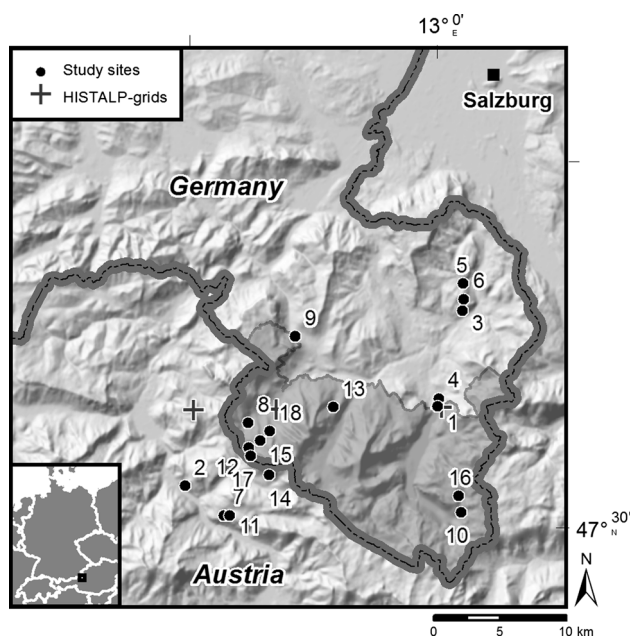


Fig. 1 Study area and sampling sites in Southeast Germany. The National Park Berchtesgaden is shaded (base map: SRTM X-band data, DLR/ASI)

Climate data

Monthly climate data (temperature, precipitation) representative for different elevation belts (grid mode 2, 5 in. × 5 in. grid) (Table S1; Fig. 1) and monthly

sunshine duration data as deviation of long-term means (CRMS data, Region NE and summits) were obtained from the HISTALP database (Auer et al. 2007). Climatic conditions of the study area are characterised by high precipitation sums, and most of the precipitation falls during summer months (June, July, August) (Table S1; Fig. S1). Average temperatures decrease with altitude and maximum temperatures are reached in July (Table S1; Fig. S1). The yearly temperature amplitude is 18.6 °C in the lower montane and 17.7 °C in the sub-alpine elevation belt.

Tree-ring data and statistical analyses

TRW was measured to the nearest 0.01 mm with a LINTAB 6 system (RINNTECH, Heidelberg, Germany) and TSAP-Win Scientific software (Rinn 2003). Cross-dating was confirmed both visually and statistically using the program COFECHA (Holmes 1983). Standard parameters such as average growth rate (AGR), mean sensitivity (MS) and first-order autocorrelation (lag-1) were calculated for the 50-year period 1959–2008.

Detrended chronologies were used for long-term growth/climate response. For reducing non-climatic trends related to age and size, or internal and external disturbances from the raw ring widths (Fritts 1976), negative exponential curves were applied to the individual series. The ring width index (RWI)-chronologies

were obtained by averaging the detrended single series collective-wise based on a robust mean (Mosteller and Tukey 1977). Chronologies were corrected for lag-1 autocorrelation, i.e. resulting in residual chronologies, and truncated at a minimum sample replication of five series. For signal strength estimation, inter-series correlation (R_{bar}) and expressed population signal (EPS) were calculated based on the residual chronologies for the 50-year period 1959–2008. To assess the common climatic control along the elevational gradient, bootstrapped correlation coefficients were computed for the individual residual chronologies and the corresponding mean temperatures, precipitation and sunshine duration sums of six different current year seasons (May/June = MJ, June/July = JJ, July/August = JA, May/June/July = MJJ, June/July/August = JJA and May/June/July/August = MJJA) within the common period 1934–2003. The climate response of two previous years' late summer seasons (July/August = pJA and August/September = pAS) is shown in Fig. S3 and Table S2.

For further analyses, TRW series from one tree were averaged and transformed to basal area increment (BAI) according to the formula:

$$\text{BAI} = \pi(R_t^2 - R_{t-1}^2)$$

where R is the radius of the tree inside the bark and t the year of tree-ring formation. The radius of a tree was derived through measured diameter at breast height and bark thickness. Converting TRW to BAI removes age-related trends but maintains other growth trends (Speer 2010). Using this standardisation method preserves low- and mid-frequency growth variance—e.g. caused by climate change what is of special interest here—which might be removed through conservative detrending techniques.

To study the percentage GR of each tree to the heat wave in 2003, BAI of this year was compared to the mean BAI of the five previous years (1998–2002). For assessing the tree response to twentieth century temperature trends, the percentage GC since 1990, compared to the 30-year reference period 1961–1990, was calculated for each tree. A Student's t test was performed for testing the significance of mean growth deviation on collective level for GR and GC. To estimate the differences in GR and GC between elevation belts and/or slope exposures, analyses of variance (ANOVA) followed by a Tukey-HSD post hoc test was applied. Elevation and species-specific GC was finally averaged based on a robust mean (Mosteller and Tukey 1977).

All statistical procedures were performed using R 3.0.1 (R Development Core Team 2013) and the packages dplR (Bunn et al. 2012) and bootRes (Zang and Biondi 2013).

Results

Climate change and the extreme event 2003

The study area is characterised by mild temperatures and high precipitation during the growing season (Fig. S1). Since 1990 temperature increased by 1.43 °C and precipitation decreased by 30 mm at all altitudinal belts (Fig. 2). The sunshine duration (data not shown) increased by 37 h in the montane elevations and by 55 h in the high mountains during growing season. In summary, climate change induces warmer and drier growing seasons with increased radiation.

The temperature of the growing season in the exceptional hot summer in 2003 was ~3.8 °C higher compared to the 1961–1990 reference period throughout all the elevations (Fig. S1). Furthermore, a precipitation reduction of 150 mm at the lower montane belt (montane/altimontane 120 mm, subalpine 165 mm), equal to a reduction of ~20 % (montane/altimontane 16 %, subalpine 21 %) was observed (Fig. S1).

Chronology characteristics

AGR decreases with elevation for all species. The maximum ring width (3.1 mm) was found for spruce at the lower montane belt (site 4) (Fig. 3). The minimum radial growth rates (0.4 mm) were observed for larch at the subalpine belt (site 15 and 18). MS is low for spruce and fir (0.15–0.24) and decreases with elevation. In contrast, MS for larch and beech is higher (0.19–0.38) and increases with altitude (Fig. S2a). Lag-1 is generally high and fluctuates between 0.34 and 0.78 (Fig. S2b). R_{bar} values range from 0.16 to 0.69 and the EPS statistics indicate sufficient internal signal strength for nearly all sites, since EPS is above the widely accepted quality threshold of 0.85 (Wigley et al. 1984) (Fig. S2c).

Long-term growth/climate response

Distinct differences were observed in the long-term growth/climate response between tree species and elevation belt (Fig. 4, Fig. S4). The assessment of shorter (and variable) seasons generally does not change the response pattern along the elevational gradient (Fig. S4; Table S3). The growth/climate response for the whole growing season (MJJA) results in most frequent significant relationships (Table S3).

Spruce growth at the lower montane and montane belt is rather negatively correlated with temperature during the growing season. At the altimontane belt a switch to positive correlation coefficients occurs and at

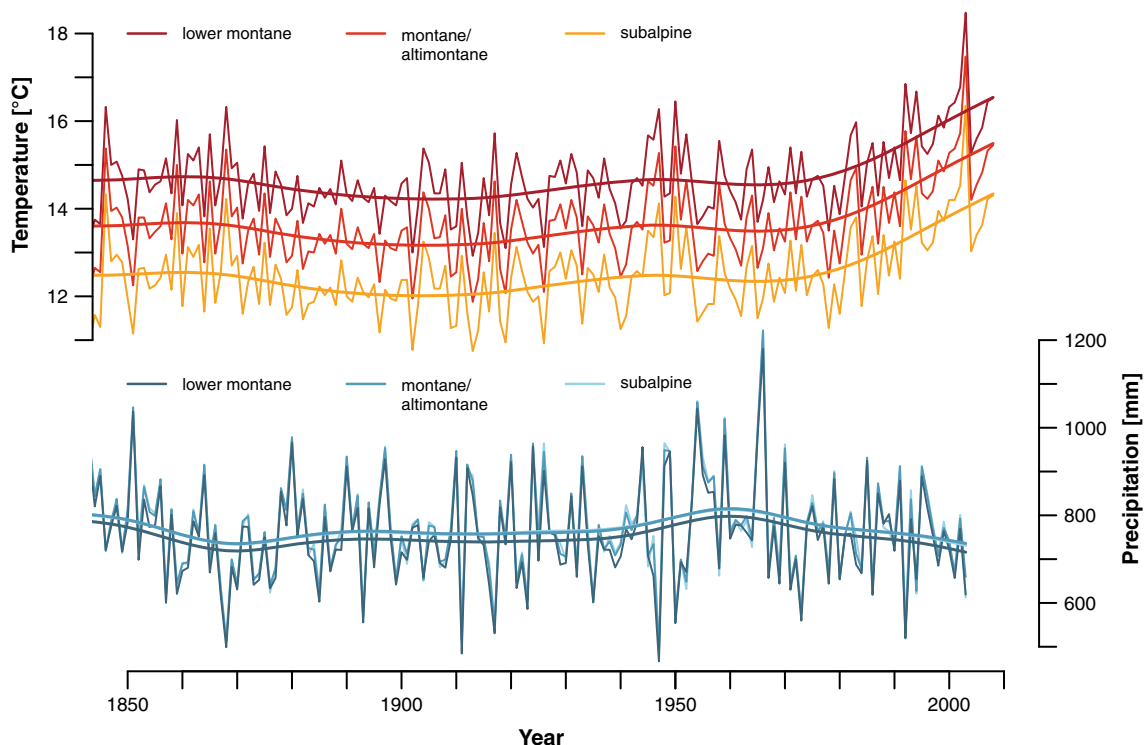


Fig. 2 Long-term temperature (mean) and precipitation (sum) records of the growing season (May–August) in different elevational belts. The smooth curves are 10-year low-pass filters (data basis HISTALP)

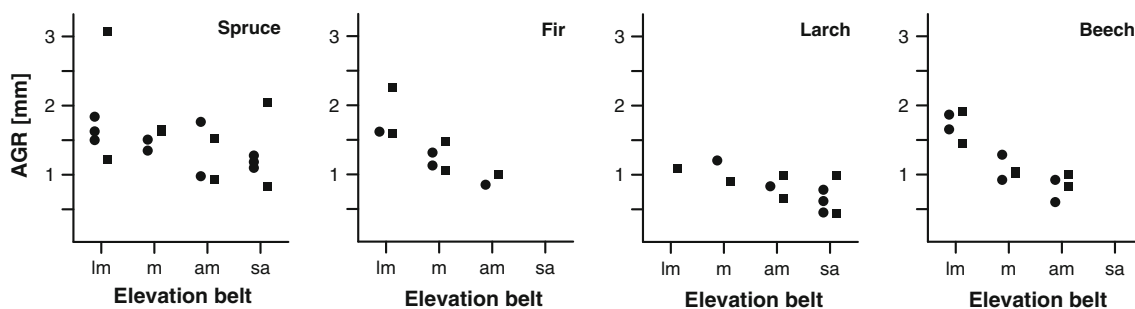


Fig. 3 Average growth rate (AGR) of spruce, fir, larch and beech at different elevation belts in the 1959–2008 period. Circles denote sunny and squares shady slopes (lm lower montane, m montane, am altimontane, sa subalpine belt)

the subalpine belt spruce growth is significantly positively correlated with temperature (Fig. 4a; Fig. S4a; Table S3). Fir growth correlates positively with temperature, especially from June to August (Table S3). For larch, the response is positive at almost all belts and seasons. The coefficients increase with altitude and become significant at the subalpine belt. Only at one site beech growth is negatively correlated with temperature during the growing season. Even at the montane belt significant positive correlations were observed (Fig. 4a; Table S3).

The precipitation/growth response is inverted compared to the temperature/growth response (Fig. 4b; Fig. S4b).

High amounts of precipitation during the growing season affect spruce growth (significant) positively at the lower altitudes but (significant) negatively at the subalpine belt. Fir does not show a clear dependence on precipitation at any elevation belt. The negative effect of high precipitation on larch growth increases with altitude. Beech growth at shady slopes at the montane belt is (significantly) negatively affected by high precipitation, but beech trees at sunny slopes do not show clear correlations with precipitation (Fig. 4b).

Growth response to sunshine duration compares to the temperature response (Fig. 4c; Fig. S4c). For spruce, the correlation is significantly negative at the lower

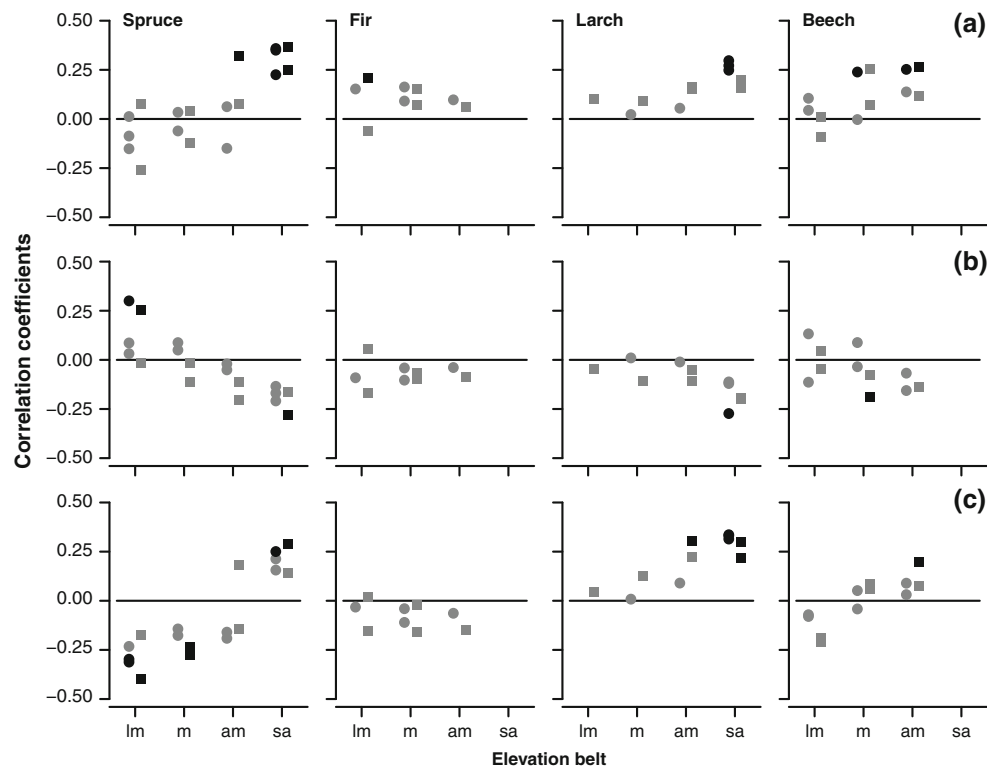


Fig. 4 Correlations between spruce, fir, larch and beech growth (residual chronologies) and seasonal (May–August) **a** temperature, **b** precipitation and **c** sunshine duration. Circles denote sunny and

squares shady aspects. Black symbols indicate $p \leq 0.05$ significant correlations (*lm* lower montane, *m* montane, *am* altimontane, *sa* subalpine belt)

elevations but significantly positive at the subalpine belt. Fir does not show any significant relationships. High sunshine duration has significantly positive effects on larch tree growth at the altimontane and subalpine belt and there is a clear effect of slope exposure at the montane belt. At the lower montane belt beech responds negatively to high sunshine duration, but the correlation coefficients get positive with increasing elevation (Fig. 4c; Fig. S4c).

Growth reaction to the 2003-heat wave

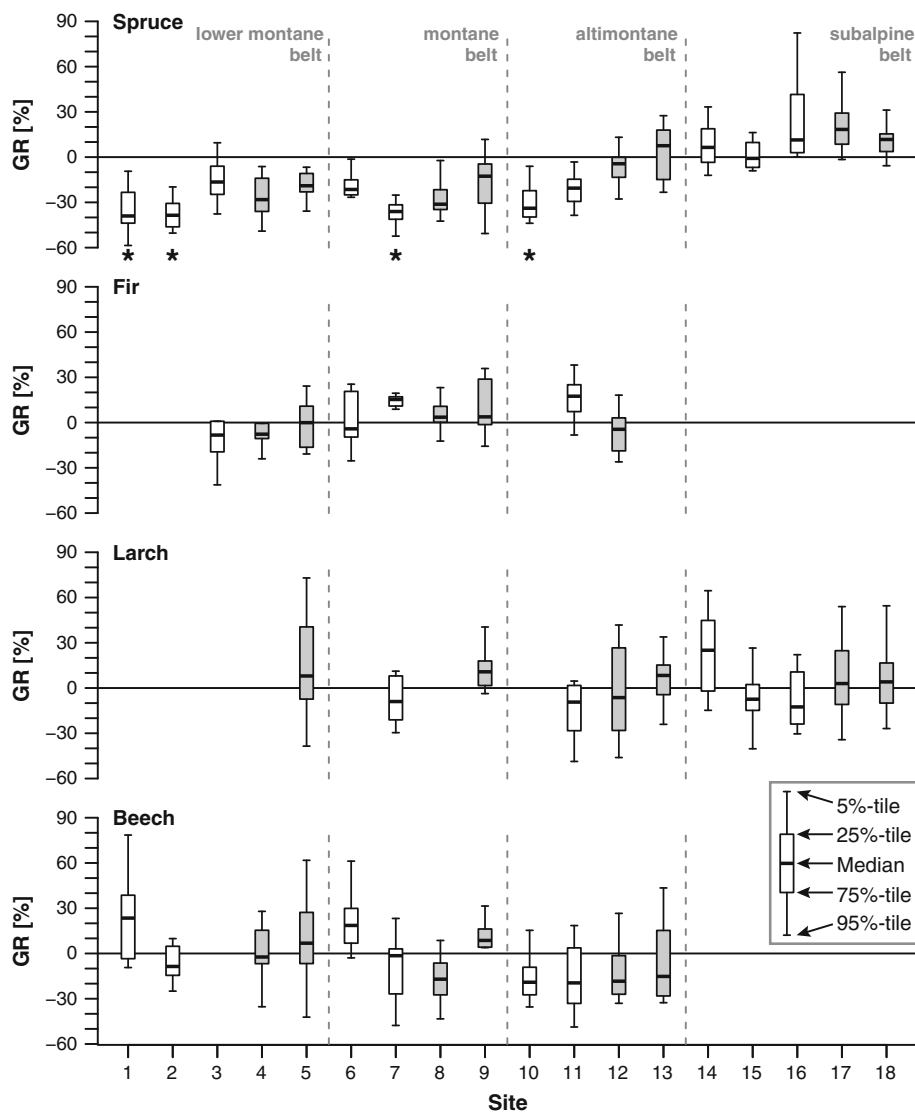
For spruce a negative GR was observed in the lower montane and montane elevations independent of the slope exposure (Fig. 5). Four sites (one even at the altimontane belt) showed significant ($p < 0.05$) growth reductions in 2003 (Fig. 5). At the altimontane belt trees at sunny slopes still show growth decline while growth increased at the subalpine belt (Fig. 5). The shady slopes at the altimontane belt and the subalpine sites differ significantly from the other sites (Table S4). Fir, larch and beech do not show a clear GR to this drought event, but a high tree-to-tree variability within one site. There are no clear effects in relation to altitude or slope exposure (Fig. 5; Table S4).

For beech, there is a tendency towards a growth reduction at the altimontane elevation belt (Fig. 5).

Growth change due to twentieth century warming

There was no clear growth trend induced by the temperature increase since 1990, except for one beech collective which showed significant growth increase (Fig. 6), and for neither species significant differences ($p < 0.01$) within the elevation belts were detected (Table S5). Tree-to-tree variability within one site is high for all species (Fig. 6). On average, among all sites there is a tendency towards increased growth rates for spruce, beech and fir (Table S6). For spruce, radial growth increased by $\sim 10\%$ compared to the reference period. This GC is highest in the lower montane belt (15%), about 10% in the altimontane and subalpine belt and lowest with about 7% in the montane belt (Table S6). Average growth increase was 22% for fir with the strongest effects at higher altitudes (Table S6). For beech, the positive growth effect at the different elevations ranged from 3 to 14%, with an average of 8% (Table S6). For larch, a slight growth decline in the lower montane and montane belt was balanced by a slight positive GC in the altimontane and subalpine belt (Table S6).

Fig. 5 Percentage growth reaction (GR) to the extreme event in 2003 for spruce, fir, larch and beech at the different sites. *White boxes* denote sunny, *grey boxes* shady slopes (*significant difference at $p < 0.05$)



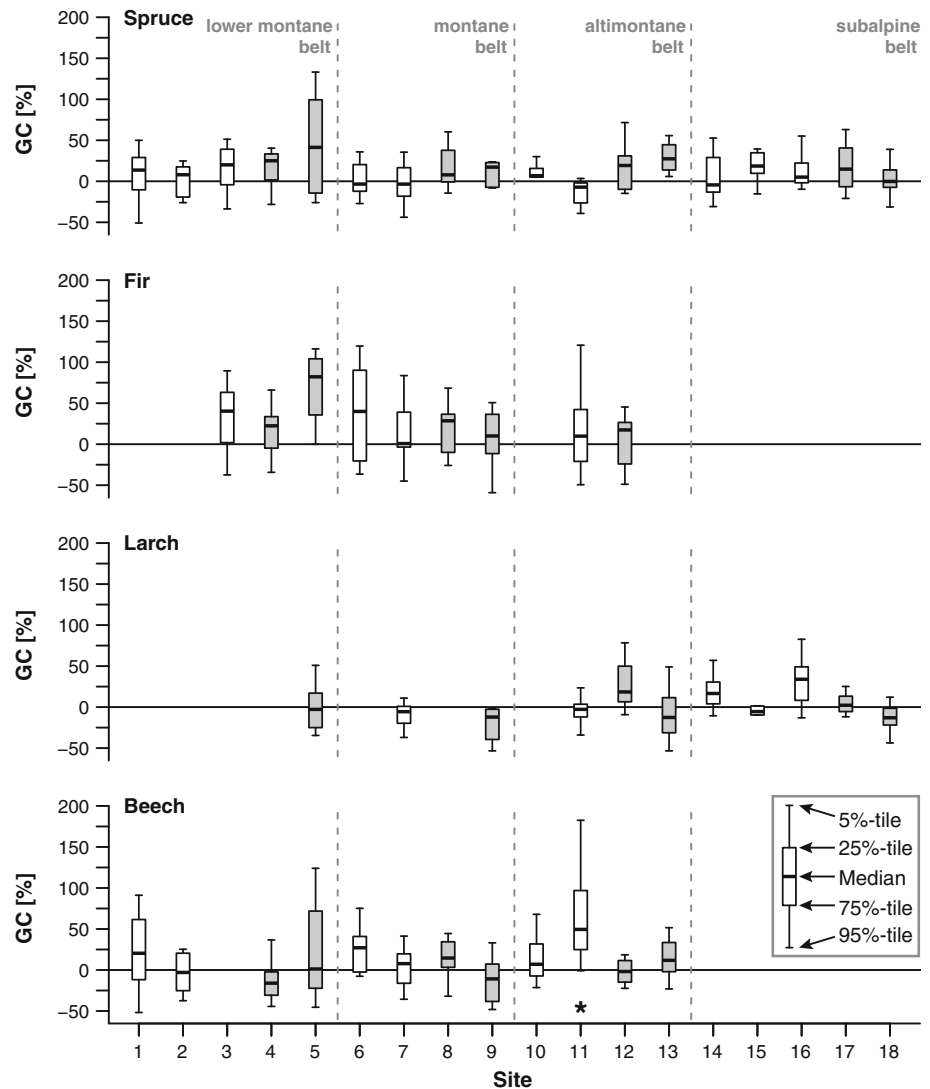
Discussion

Mountain forests are of critical ecological and economic importance in the European Alps, but there is still a high degree of uncertainty how these ecosystems will be affected by climate change (Elkin et al. 2013). In our investigation area a distinct temperature increase is unequivocal, but still there are high amounts of precipitation (Fig. 2). Based on these humid climatic conditions the notion of summer drought remains a relative term in this area. Nonetheless, even in the Berchtesgaden Alps the heat wave in 2003 was an exceptional extreme event and remarkably divergent from average conditions (Fig. 2; Fig. S1).

Our findings concerning the long-term growth/climate response of spruce confirm the ‘common knowledge’ that trees growing at higher elevations are sensitive to

temperature variations (Babst et al. 2013) and have distinct temperature signals, while trees growing at lower elevations are more sensitive to moisture (Luckman 2007). Spruce is drought sensitive at the lower montane and montane belt with a negative growth response to temperature/sunshine duration and a positive response for precipitation. We found inverse relationships at the altimontane and subalpine belt indicating that these sites will benefit from higher temperatures. Similar patterns for spruce were reported in several other studies (e.g. Dittmar and Elling 1999; Frank and Esper 2005; Leal et al. 2007; Mäkinen et al. 2002; Savva et al. 2006; Wilson and Hopfmüller 2001). For larch and beech, the growth/climate response also depended on altitude, but there was no clear drought sensitivity (in terms of negative/positive correlations to temperature/precipitation) at low elevation sites. At high altitudes, higher temperatures during growing season

Fig. 6 Percentage growth change (GC) since 1990 compared to the 1961–1990 reference period, for spruce, fir, larch and beech at the different sites. *White boxes* denote sunny, *grey boxes* shady slopes (*significant difference at $p < 0.05$)



favour growth of larch and beech. For beech, Dittmar and Elling (1999) found a distinct negative temperature response at low elevation sites but their sites were located at much lower elevations compared to our study. At the higher elevations in their study, Dittmar and Elling (1999) also found a positive temperature effect. Larch seems to benefit from higher temperatures or increased sunshine duration at the montane and altimontane belt especially at shady sites. The positive (negative) correlation between growth of fir and temperature (precipitation) of the growing season, and especially from June to August, in our study indicates that fir is less sensitive to drought. This is well in line with findings of, e.g. Elling et al. (2009), van der Maaten-Theunissen et al. (2013) or Zang et al. (2011) from regions north of the Alps. Studies which contradict the drought tolerance of fir are located in drier climates of Europe like Southern Italy (Battipaglia et al. 2009), the south-eastern Alps (Maxime and Hendrik 2011) or France

(Lebourgeois et al. 2010), where water consistently is a limiting factor. This is not the case in our humid investigation area and moreover, fir might originate from different provenances.

The drought sensitivity derived from the long-term growth/climate response can be verified by the reaction of the tree species during the 2003-heat wave. Spruce growth significantly decreased in 2003 at some lower elevation sites. At the altimontane belt there is a switch from a negative to a positive GR. Trees at sunny slopes show growth reduction, while trees at shady slopes benefit from high temperatures. At the subalpine belt the growth response is generally positive. Similar altitudinal effects in extreme years were found for spruce in other studies (e.g. Desplanque et al. 1999; Jolly et al. 2005; Neuwirth et al. 2004). Contrary to our findings, Desplanque et al. (1999) and Lebourgeois et al. (2010) observed an elevation-dependent growth decline caused by drought events for fir as well. In other studies (Elling et al. 2009; van der

Maaten-Theunissen et al. 2013; Zang et al. 2011) fir showed no significant reaction in drought years, which agrees well with our findings. Also larch and beech showed no consistent reaction during 2003 indicating a high resistance against such events. Only the growth decline of beech in 2003 at the altimontane belt contradicts the long-term growth/climate response at this belt and the findings from other studies (e.g. Dittmar et al. 2003). Since no growth decline was obvious for beech at lower elevations (even at sunny slopes), we assume that the growth reduction of beech at the altimontane belt results from other causes in this specific year. A possible explanation might be a late frost event, which could also explain the high MS values of beech at this belt. Dittmar et al. (2006) found a higher frequency of frost-related growth reductions with increasing altitude.

Due to their long lifespan, trees are considered to be particularly vulnerable to changing climate, since they are not able to adapt as rapidly (Lindner et al. 2010). Fuhrer et al. (2006) suggests that extreme events, such as drought may have more severe effects on tree vitality than changes in average conditions, but a long-term increase in temperatures may also have substantial consequences for forest ecosystems (Elkin et al. 2013). Average temperatures during the growing season were ~ 1.4 °C higher since 1990 compared to the 1961–1990 period in our investigation area. The strength and duration of this temperature signal was not enough to cause a significant growth response of the trees investigated. There were neither clear signals for growth reduction at the lower elevations (rather a slight growth increase) nor for growth increase in the altimontane or subalpine belt. At high elevation sites, positive growth trends of different tree species were found in the European Alps (Paulsen et al. 2000; Rolland et al. 1998) or North America (Salzer et al. 2009). These investigations were located at the respective timberline and in our study area, stronger growth signals might be present at the timberline as well. But the subjects of this study are mountain forests, i.e. closed canopy stands, since these forests fulfil important ecological, economic and protection functions in the region. Hasenauer et al. (1999) explained an increased growth of, e.g. Norway spruce since 1980 (including different elevations) with warmer climatic conditions and an associated prolonged vegetation period. In general, higher temperatures are expected to increase the growing season (Lindner et al. 2010) and we can approve the sensitivity of our examined species to the duration of the growing season since the AGR decreases with altitude. But a recent phenological study in our investigation area showed that trees are generally less sensitive to temperature changes than plants with shorter lifespans indicating that trees may react more slowly to climate change than perennial herbs (Cornelius et al. 2013). The missing growth effect—despite the temperature shift since 1990—was not

expected and somehow contradicts the findings of the long-term growth/climate response and the growth response during the 2003 event. However, in spite of the strong warming, all of our study sites and analysed species are still well within their bioclimatic envelopes (Kölling 2007). While Norway spruce and European larch were found to be at their dry distribution and physiological limits in inner-Alpine dry valleys (Lévesque et al. 2013; Schuster and Oberhuber 2013), the temperature signal may not have been strong and/or long enough in the Berchtesgaden Alps in order to cause significant growth effects.

Conclusion

Both the heat wave in 2003 and the temperature increase since 1990 had only minor effects on growth patterns of the main tree species in the Berchtesgaden area. The mountain forests seem to be vital and can tolerate a certain shift in climate. On the other hand, climate change is not restricted to rising temperatures or drought events. It is accompanied by other biotic or abiotic impacts (Bolte et al. 2009), e.g. a higher frequency and intensity of insect outbreaks (Seidl et al. 2008), and wind storms (Lindroth et al. 2009). Norway spruce is considered to be the most vulnerable tree species of the mountain forests to such disturbances and it was also the most drought-sensitive species in the lower elevations in our investigation. The ultimate ambition of silvicultural measure has to be the improvement of the stand stability against drought, storms and secondary factors (Bolte et al. 2009), especially in mountain forests, where the protection function is of critical importance. Therefore, we recommend the conversion of spruce monocultures at the montane belts into mixed mountain forests with beech and fir in the long term. Due to the higher drought tolerance of fir compared to spruce this will increase the climatic stability of mountain forests.

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