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Global warming-related tree growth decline and mortality on the north-eastern Tibetan plateau

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Abstract Semi-arid forests at the limit of their existence close to the Gobi Desert in Inner Asia might be vulnerable to warming-induced drought stress. Yet, not much is known about the impact of global-change-type droughts on these forests. Here, we show that warming-related tree mortality is recently taking place in high-elevation semi-arid Qinghai spruce (*Picea crassifolia* Kom.) forests of the north-eastern margin of the Tibetan Plateau (Qilian Mountains). Tree-ring samples were collected from 24 Qinghai spruce forest plots (20 m × 20 m) at three elevations (2600, 2700, 2800 m) along eight elevation transects on north-facing slopes. Three lines of evidence suggest that these forests are increasingly at risk of increased tree mortality as a consequence of global warming, (i) a strong precipitation and air humidity dependence of radial growth, (ii) increasing frequency of missing tree rings, and (iii) a rising tree mortality rate in recent decades. The recent drought episode on the north-eastern Tibetan Plateau may represent a precursor of future global-change-type drought events in large parts of Inner Asia. Warming-related tree mortality of the semi-arid forests may be interpreted as early-warning signs for the densely populated artificial oases surrounding the Gobi Desert, which largely depend on river run-off from the mountain forests on the edge of the Tibetan Plateau.

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1 Introduction

A growing body of evidence shows that a combination of drought and heat, resulting from anthropogenic greenhouse gas emissions and hereafter referred to as 'global-change-type drought', is recently altering the composition and structure of forests worldwide (Breshears et al. 2005; Allen et al. 2010; Anderegg et al. 2012). In many forests worldwide, drought and warming have caused reductions in annual stem increment and productivity (Barber et al. 2000; Ciais et al. 2005; Wilmking et al. 2004; Sarris et al. 2010; Piao et al. 2008; Vila et al. 2008; Phillips et al. 2009; Zhao and Running 2010; Peñuelas et al. 2011; Büntgen et al. 2013). Reports of increased rates of tree mortality also are on the rise globally (Adams et al. 2009; Van Mantgem et al. 2009; Allen et al. 2010; Carnicer et al. 2011; Peng et al. 2011; Williams et al. 2013; Niu et al. 2014; Zhang et al. 2014). Resistance against drought events and resilience after drought impact are important elements that determine the drought vulnerability of trees (Vicente-Serrano et al. 2012). We need accurate assessments of forest responses to current and future climatic conditions at regional scales to understand species-level adaptation, resilience, and vulnerability to mortality in the face of climate change (Law 2014).

Semi-arid forests are considered to be particularly vulnerable to climate change because the trees exist close to their drought limit (Allen et al. 2010; Rotenberg and Yakir 2010; Poulter et al. 2013). The Gobi Desert and the surrounding fringe of semi-arid forests and steppes in Inner Asia constitute one of the largest drylands of the globe (Liu and Piao 2013). However, it is not well studied whether and to what extent global-change-type drought is already causing tree mortality in the semi-arid forests of Inner Asia (Dulamsuren et al. 2010; Liu et al. 2013; Wu et al. 2013).

The widespread semi-arid forests at the north-eastern margin of the Tibetan Plateau are part of the vast Inner Asian drylands. The transition zone between the Tibetan Plateau and the Gobi Desert in northern China (known as the Hexi Corridor) (Fig. S1 in the Supplementary Information) was part of the Silk Road during the Han and Tang dynasties with human settlements depending largely on river run-off from the adjacent Qilian Mountains. The semi-arid mountain forests at the fringe of the desert fulfill important functions as a source area of water for the artificial oases of human settlement. Increasing drought will not only affect the forests but these settlements as well. The recent decade was the warmest period in the past one thousand years in Inner Asia (Esper et al. 2002; Liu et al. 2005; Zhu et al. 2008). Large areas of Inner Asia, including the Tibetan Plateau, experienced extended and severe droughts in recent decades (Li et al. 2009; Ji et al. 2014; Pederson et al. 2014). Yet, it is not known whether these forests in the Qilian Mountains are suffering from drought-induced mortality due to global warming. Moreover, the sensitivity and resilience of semi-arid high-elevation forests to climate change is generally not well understood.

The objectives of this study were to examine long-term tree growth dynamics along altitudinal transects in high-elevation forests of Qinghai spruce (*Picea crassifolia* Kom.) and to present the first detailed analysis of tree mortality at the north-eastern margin of the Tibetan Plateau. We tested the hypothesis that recent warming has decreased the trees' productivity and led to increased tree mortality. It was reported that extreme drought stress can result in abundant locally missing annual rings in semi-arid forests (Liang et al. 2006). We thus expected that global-change-type drought in the north-eastern Tibetan Plateau has increased the frequency of missing rings and has caused increased rates of tree mortality.

2 Material and methods

2.1 Study area and climate

The study was conducted in monospecific mountain forests of Qinghai spruce at elevations of 2600–2800 m a.s.l. in the central Qilian Mountains (38°34′ N, 100°10′ E) c. 50 km SW of Zhangye (Gansu Province, PR China; 38°56′ N, 100°26′ E) on the north-eastern slope of the Tibetan Plateau to the Gobi Desert (Fig. S1). The area is located in the transition zone between the reaches of the East Asian Monsoon and the zone influenced by the Westerlies. Annual precipitation is c. 130 mm yr^{-1} in Zhangye (1483 m a.s.l.; mean of 1950–2012) and c. 370 mm yr^{-1} (range: 290–468 mm $yr.^{-1}$) in the forest belt at 2800 m (mean of 1994–2004; station Xishui, 38°24′ N, 100°17 E; Niu et al. 2006). While precipitation remained constant since the 1950s at the Zhangye station, annual mean air temperature significantly increased since the 1970s by c. 1.5 °C; the increase accelerated after 1990 (Fig. 1). Annual pan evaporation is c. 1050 mm in the forest belt (Niu et al. 2006).

About 85 % of the annual precipitation is received from May to September within the growing season. Based on observations from 22 May to 12 September 2008, precipitation shows a significant linear increasing trend with increasing altitude from 1000 m to 3500 m in the Qilian Mountains (Wang et al. 2009); the increase is by 11.5 mm/100 m altitude. Considering that a calibration for climate-tree growth correlation focuses on the variability rather than on absolute values of precipitation and temperature, we have a high degree of confidence that the variability in the monthly precipitation records at Zhangye reliably represent the variations of precipitation in the forest areas at 2600–2800 m. In another example, based on 3-year climatic records at the upper timberline (4400 m a.s.l.) on the south-eastern Tibetan Plateau, we found that the variations of the valley bottom precipitation records (3000 m) were reliable indicators of the conditions at the upper timberline (4400 m) on the south-eastern Tibetan Plateau (the distance of the two weather stations was 53 km; Liang et al. 2011) and hence could be used for the calibration in the dendroclimatic reconstructions at timberlines.

From December to May, there is little snowfall, but no significant snow pack in most years at the elevation of our sample plots between 2600 and 2800 m. The equilibrium line (snowline)

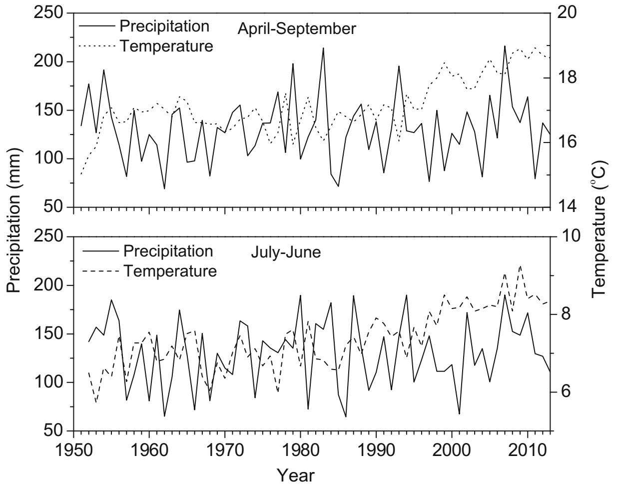

Fig. 1 Variation in mean temperature and sum of precipitation from April to September or from July of the previous year to June of the current year for the period 1950–2011 at the station Zhangye

for the Qiyi Glacier in the Qilian Mountain was around 5131 m a.s.l. in 2006 (Wang et al. 2010), suggesting that above this elevation, there is significant snow pack throughout the year.

2.2 Sampling design and tree-ring analysis

Tree-ring samples were collected in 24 spruce forest plots (20 m × 20 m) at three elevations (2600 m: lower forest, 2700 m: middle forest, 2800 m: upper forest close to the alpine tree line). These three plot types of different elevation were replicated three times on eight north-facing slopes. While the upper forest on steep slopes (20–25°) shows no signs of major human disturbance, the lower forest was affected by wood pasture and local logging before 1986, when the area was declared a nature reserve and human intervention ceased. Based on our dating, one spruce tree snag stood upright in the upper forest for more than 140 years after its death around AD 1870, giving evidence of low human impact at this elevation. The dendrochronological analysis is based on cores taken from all live trees (diameter > 5 cm) present in the 400 km^2 plots (932 trees in total with one or two cores sampled per tree). In six plots from two transects, all dead trees were also sampled to date the year of death of downed or standing spruce trunks. In order to avoid misinterpretations due to local cambial mortality occurring in different years along the stems, two cores from breast height and one core from the stem basis close to the ground were sampled from a total of 210 dead trees.

Ring width was measured to an accuracy of 0.01 mm using a LINTAB measuring system (Rinntech, Heidelberg, Germany). Missing rings were dated and recorded as well. The quality of cross-dating and measurement accuracy was checked using COFECHA software (Holmes 1983). Tree-ring width data were standardized using the program ARSTAN (Cook 1985) to remove growth trends related to age and stand dynamics. Most tree-ring width series were detrended with a smoothing spline of 67 % of the series length. In addition, a data-adaptive power transformation was applied to stabilize the variance and mitigate non-normality in the series prior to detrending. Then, indices were calculated as the difference between the power-transformed ring-width measurements and the values of the fitted curves. This procedure effectively prevents the introduction of bias into the final series, which can occur in the traditional ratio-method standardization as a result of the division process. Basal area increment (BAI) was deduced from tree-ring width assuming a cylindrical shape of the stem at 1.3 m above the ground.

2.3 Climate-response analysis and statistical analysis

For analyzing climate-growth relationships, bootstrapping correlations (Biondi and Waikul 2004) were calculated between three standard chronologies at lower, middle and upper elevations and monthly climate data of the meteorological station in Zhangye for the 1950–2013 period. Climatic variables included in the analysis were the monthly maximum, mean and minimum temperatures, monthly precipitation totals, and monthly mean relative air humidity. Correlation analysis was performed for a 15-month period from July of the year prior to ring formation to September of the year of ring formation.

The chi-square test was used to test whether the age structure of those trees with a missing ring was associated with the age structure of all investigated trees. This analysis was conducted year-wise and was restricted to the period from 1995 to 2005. If there is a significant ($P \leq 0.05$) association, it suggests that the occurrence of missing rings is not age-related. Superposed epoch analysis (SEA) was calculated to test the statistical significance of the temporal relationships between tree mortality events and the occurrence of missing rings since 1950 using the dplR package of R 3.1.3 software. This analysis employs a conventional bootstrapped resampling with replacement (Haurwitz and Brier 1981), where confidence intervals are calculated by repeating the SEA using repeated ($N = 10,000$) random draws of pseudo-'event' years from the available time span. Significance is evaluated by comparing percentiles from the random draw to the composite mean of the real data.

Z-transformed data were used to analyze for temporal trends in the BAI; z-transformation was achieved using the formula $z_i = (x_i\text{-}\mu)/\sigma$, with x_i being the BAI of the actual year, μ being the mean of the time series, and σ being the standard deviation of the time series. Two-way analysis of variance (ANOVA) was calculated with R 3.1.3 to test the influence of tree vitality and altitude on tree-ring width.

3 Results

3.1 Tree growth and its response to climate

Annual stem increment showed a relatively consistent year-to-year variation within the same elevation and across the three elevations as displayed by the ring width standard chronologies (Fig. S2). Mean inter-correlation between the individual living tree-ring series was 0.82 in the upper forest (277 trees with a mean series length of 99 yr), 0.81 in the middle forest (320 trees, 89 yr), and 0.79 (235 trees, 64 yr) in the lower forest (Table S1 in the Supplementary Information). Stem increment variation showed a high synchronicity across the three elevations with a series inter-correlation of 0.80 among all investigated living trees; for the 1900–2013 period, the relevant correlation coefficients even ranged from 0.92 to 0.98 ($P < 0.0001$). Z-transformed series of basal area increment (BAI) showed linear trends for decline since the 1950s across the three elevations (Fig. S3).

Dendroclimatological analysis revealed a uniform climate response of stem radial growth across the three elevations with a dominant influence of factors related to water availability and drought stress. Precipitation and relative air humidity in May and June of the current year and in August and September of the previous year were principal factors correlating closely ($P \leq 0.05$) with radial increment in Qinghai spruce (Fig. 2a and b), suggesting a strong control of moisture availability on cambial activity. The strongest moisture response existed at the highest elevation (2800 m a.s.l.), where the correlation between ring width and precipitation in the 12 months prior to ring formation (July to June) was stronger ($r = 0.64$) than at middle and lower elevation (2600–2700 m; $r = 0.61$ and 0.59, respectively). Despite the high altitude (2600–2800 m), increment did not respond positively to the recent temperature increase of more than 1.5 °C (Fig. 1), unlike the temperature-sensitive radial growth observed in trees from alpine timberlines of the Tibetan Plateau. The only significant correlation ($P \leq 0.05$) of temperature with tree-ring width was found for the previous year's late summer (August) mean maximum air temperature (Fig. 2c and d). Summer mean maximum temperature (June to August) of the present year showed a trend for negative correlation with ring width which was only marginally significant ($P \leq 0.10$).

3.2 Missing rings and their indication of drought stress

The occurrence of missing rings provides important information on the severity of the drought stress effect on tree growth in the past 200 years. In the 24 spruce stands of the Qilian

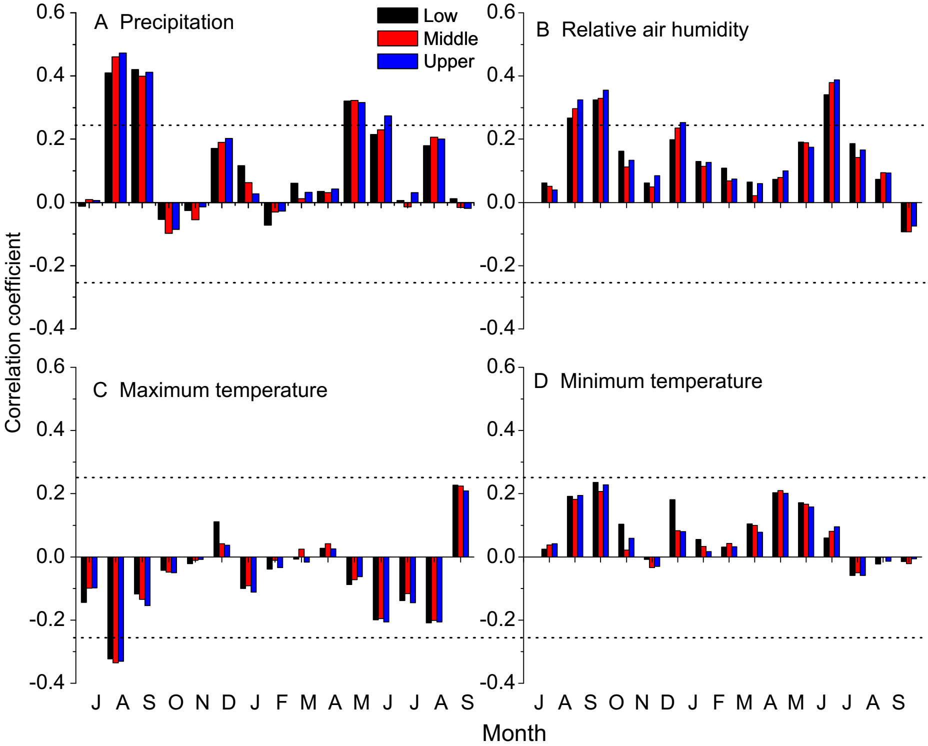

Fig. 2 Correlation coefficients for the relation between tree-ring width standard chronologies from living trees at lower, middle and upper elevations and four climatic variables from the previous year's July to current year's September in Zhangye

Mountains, missing rings occurred in consistent temporal patterns at all three elevations, but with different frequencies (Fig. 3). This phenomenon was most frequent in the 1920s and between 1995 and 2005; the frequency exceeded 10 % in 1928, 1995, 2000, 2001, 2003 and 2005. Thus, the number of missing rings was abnormally high between 1995 and 2005. According to this criterion, the trees were exposed to more severe drought stress during the global-change-type drought from 1995 to 2005 than during the sub-continental drought of the 1920s. Missing ring frequency was associated with increased maximum summer (June − July) temperatures (Fig. S4). Linear regression analysis showed that missing ring frequency was significantly correlated to higher temperature and lower relative air humidity. Among the climatic variables, we found that the occurrence of missing rings showed the strongest (negative) correlation with monthly mean air relative humidity in June − July ($r = -0.32$, -0.41 and -0.38, $P \leq 0.01$, at lower, middle and higher elevations, respectively), and positive correlation with the monthly mean maximum temperature in June and July ($r = 0.32$, 0.40 and 0.34, $P \leq 0.01$).

The percentage of missing rings was higher at upper (2800 m: 1.67 %) and middle (2700 m: 1.55 %) elevations than at lower elevation (2600 m: 0.79 %) matching the observed higher mean sensitivity and mean correlation between ring series at upper-middle elevations (Table S1). The occurrence of missing rings did not depend on tree age. The chi-square test showed evidence for highly significant association ($P \leq 0.001$) between the age structure of trees with missing rings and the total of all investigated trees in each year in the period from

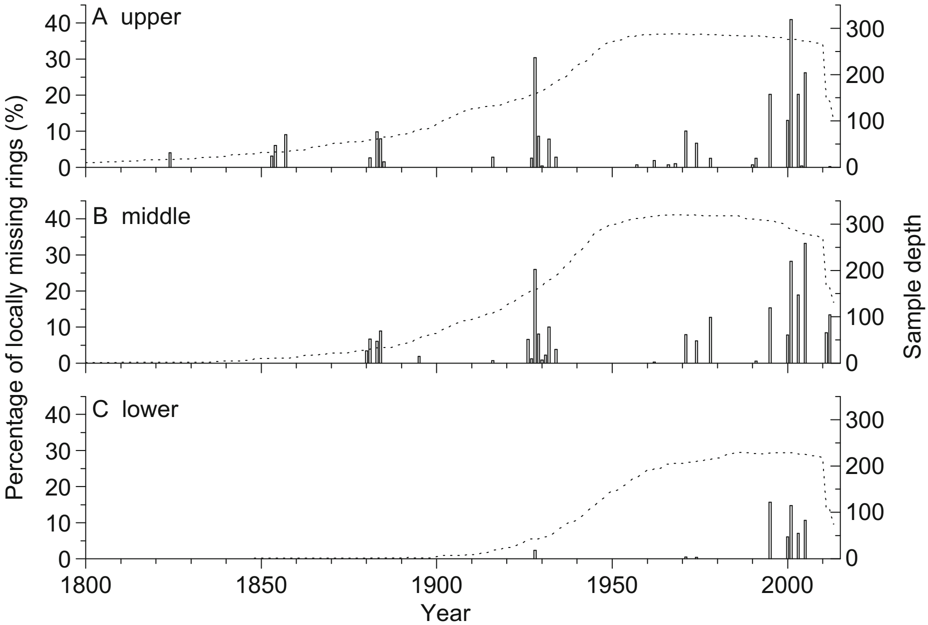

Fig. 3 Percentage of missing rings since 1800 in all the investigated living spruce tree populations at lower, middle and upper elevation. The fieldwork was performed in May 2011, September 2012 and October 2013. The dash line shows the sample depth

1995 to 2005, suggesting that occurrence of missing rings was not age-related (Fig. S5). There is no occurrence of missing rings for trees less than 20 years old. However, trees less than 20 years old only accounted for 2 % of the whole population and thus cannot have great influence on the main conclusion.

3.3 Tree mortality

Tree mortality mainly occurred after the 1940s and more events of increased rates of tree mortality were registered at upper than lower elevation (Fig. 4). We found that tree mortality often occurred in extremely dry years with frequent missing rings, or one to four years after a very dry May and June. Maximum tree mortality occurs in the fourth year (95 % confidence) after the year with missing rings, as suggested by SEA analyzing the occurrence of missing rings and tree mortality since 1950 at the upper elevation (Fig. S6). Thus, a dry early summer not only reduces stem increment in the following year but also triggers mortality in Qinghai spruce. Tree mortality events coincided with extreme drought in May in the years 1968, 1971, 1981, 1984, 1995, 2000, 2001, 2008, 2011, and 2013. The recently increased tree mortality is associated with increased growing season temperatures (Fig. 4). In linear regression analysis, tree mortality frequency in the upper forest showed the highest correlation with monthly mean maximum temperature ($r = 0.34$, $P \leq 0.01$) and growing season mean temperature ($r = 0.38$, $P \leq 0.01$) from March to August, suggesting that the occurrence of tree mortality is related to high temperature. However, we did not find significant association between tree mortality and climatic variables at middle and low elevations.

Reconstruction of the fate of selected tree individuals may help to understand the interdependence of growth decline and tree death. As an example, two neighboring spruce trees in the

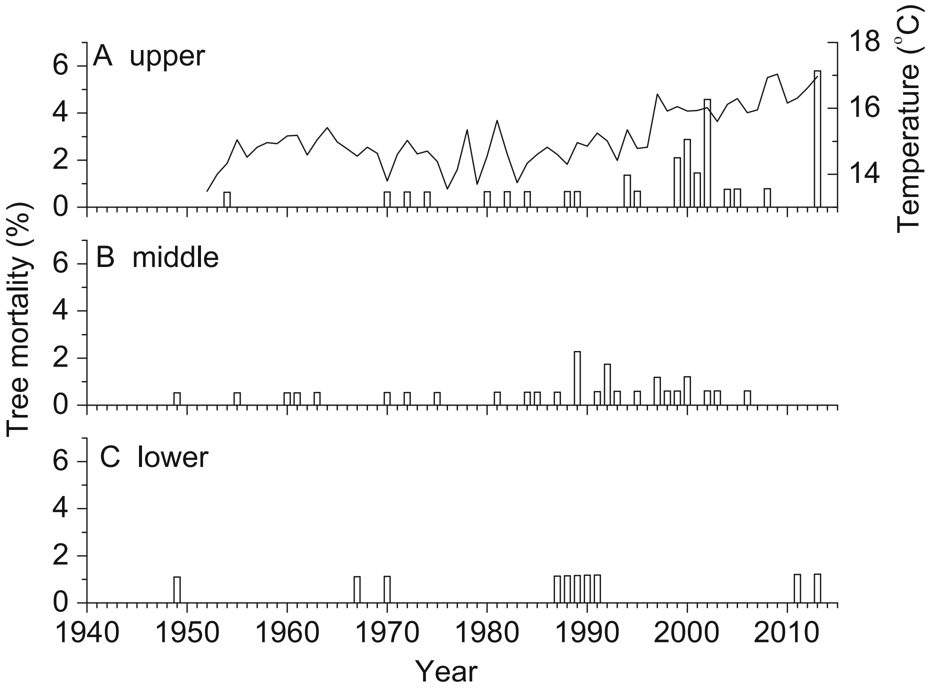

Fig. 4 Percentage of tree mortality events (shown as the years with last tree-ring formation) since 1940 in the plots at lower, middle and upper elevations according to cores analyzed in dead trees from 6 plots (20 m × 20 m) along two altitudinal transects. The line in A shows the mean growing season temperature (March to August)

upper forest, one live and one dead, showed similar interannual growth variations over decades until the extremely dry and warm summer 1995 (Fig. 5), when the dead tree had a missing ring and exhibited a sharp growth decline in 1996 with continued drought in May; the last narrow ring was formed in 1999. This tree died either in the dry June 1999 or in very dry May 2000 after four years of very low increment. The growth of the more vital tree was also substantially reduced in 1995, but recovered afterwards and this tree still survives. In general, mean ring width was higher in live than in dead trees in the lower and middle forest, but not in the upper forest, where the highest rates of tree mortality occurred and tree-ring width was consistently low (Table S2).

4 Discussion

The extremely high increment synchronicity across all plots suggests a strong macroclimatic control of spruce growth, with moisture availability likely playing a key role in this semi-arid region. The combined results of the climate-response analyses for annual stem increment, missing ring frequency and tree mortality are strongly supportive of our hypothesis that the recent climate warming has reduced the productivity and has increased tree mortality rates in Qinghai spruce.

The strong negative effect of mean maximum air temperature of previous year's August on ring width suggests that the growth of Qinghai spruce is hampered, and not supported, by elevated summer temperatures. The trend for a negative relationship between current years'

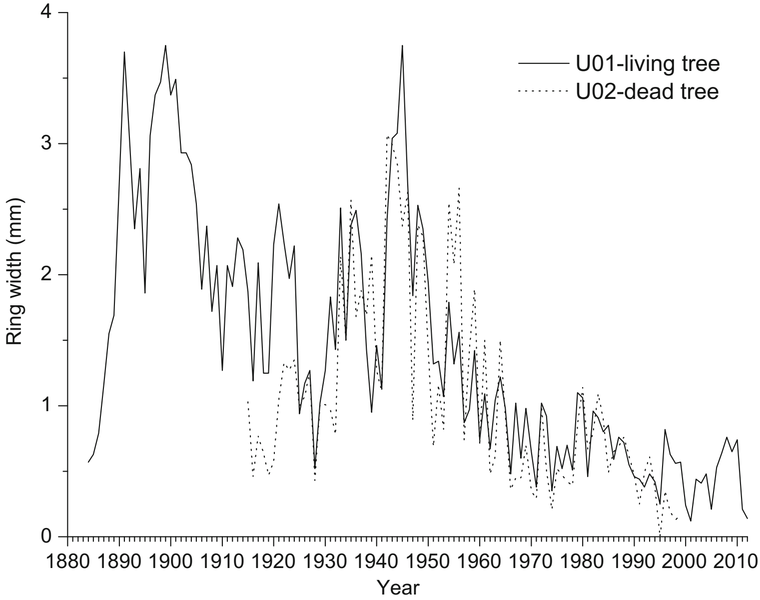

Fig. 5 Ring-width chronology of a living spruce tree and a tree that died in 1999 growing in close vicinity at the upper elevation (2800 m a.s.l.). The samples were taken in September 2012

summer temperature and tree-ring width, which was only marginally significant ($P \leq 0.10$), points into the same direction. The negative relationship of high summer temperatures with radial stem increment contrasts with the situation in many boreal conifer forests (Briffa et al. 2013). A probable explanation for the negative temperature effect is the rising atmospheric evaporative demand in warmer summers, which has the potential to deteriorate the water status of the trees in the core growing season, independently from precipitation that remained stable in the region since the 1950s (Fig. 1). Stronger correlation of tree-ring width with relative air humidity and precipitation than with temperature supports the conclusion that temperature-driven changes in the water budget are more crucial for stem increment in Qinghai spruce than temperature effects on physiology itself.

The occurrence of missing rings indicates that the environmental conditions are close to the survival limit of the trees. Missing rings, i.e. the failure to produce stem wood in a particular year, represent an adaptive mechanism that may increase tree survival under extreme drought stress, when the tree has to reduce the respiratory demand and to decrease the risk of hydraulic failure. A line of compelling evidence shows for semi-arid northern China that the frequent occurrence of missing tree rings was coupled with a large decline in river run-off, the drying of various streams and rivers, a massive reduction in lake areas and even complete desiccation of inland waters, and in local forest dieback, repeated crop failures, severe famine and the death of several million humans in the 1920s (Liang et al. 2006). Based on 2359 publicly available tree-ring width records across the northern hemisphere, St. George et al. (2013) presented evidence that locally missing rings are most common in trees at drought-prone sites but very rare (or absent) in trees whose growth is not primarily limited by moisture. Thus, the percentage of missing rings may serve as an excellent indicator of the severity of drought stress effects on tree growth in semi-arid regions.

The frequency of missing rings provides compelling evidence for a strong sensitivity of the semi-arid Qinghai spruce forests to global-change-type drought. Even though the 1995–2005 drought was not as extreme as the extended drought in the 1920s, which was the most severe drought episode in the past 200 years in China (Liang et al. 2006), missing rings occurred much more frequently in the 1995–2005 period. We suggest that this is caused by higher summer temperatures in recent time than 80 years ago (PAGES 2k Consortium 2013). Such a hypothesis can be tested by comparing two event years during the instrumental period. The amount of precipitation was almost the same in 1962 and 2001, characterized by low precipitation of 2.9 mm in May-June in both years, and of 67.5 and 65 mm from July of the previous year to June of the current year, respectively. However, the occurrence of locally missing rings was 40.9 % in 2001 in contrast with 1.1 % in 1962 at the upper elevation (2800 m). Such a difference may largely be attributed to 1.3 °C warmer temperatures in 2001 than in 1962 in both May-June and from July of the previous year to June of the current year. The effects of low precipitation on forest growth have doubtlessly been exacerbated by high temperatures and increased evapotranspiration during the recent drought. If extended summer drought combines with elevated temperatures and atmospheric saturation deficits, the drought stress exposure may well have been higher during 1995–2005 in these semi-arid forests than in the 200 years before.

With increasing temperature, plants usually increase their maintenance respiration (Schulze et al. 1973; Atkin and Tjoelker 2003; Adams et al. 2009), which may result in a decline of net photosynthesis in tree species without a high temperature optimum of photosynthesis. In a whole-tree chamber experiment, Zhao et al. (2013) could demonstrate that high temperatures in combination with mild drought may result in a negative carbon balance of the plant due to increased respirative carbon losses and earlier stomatal closure (Zhao et al. 2013). Thus, elevated temperatures in conjunction with drought could well explain the occurrence of missing rings in recent time in our forests.

A similar climatic extreme hit many European forests through the extraordinary heat and drought in summer 2003 reducing growth substantially and increasing mortality (Ciais et al. 2005). In central Mongolia, the early 21st century-drought was the hottest drought in the last 1112 years (Pederson et al. 2014). In that area, the years 2000–2009 were warmer by 1.9 °C than the period of 1959–1999 (Pederson et al. 2014). In the central Himalayas, where birch forms a drought-induced alpine timberline, global-change-type droughts have increased the frequency of missing rings during recent decades (Liang et al. 2014). As an excellent ecological indicator of extreme drought stresses, the frequency of missing rings offers additional evidence for increasing drought stress under the recent warming on the north-eastern Tibetan Plateau. Further research may use missing rings as a key parameter for characterizing tree health in a stage of reduced vitality and for analyzing the mechanisms leading to death.

Our results indicate that drought-induced tree mortality of Qinghai spruce was highly temperature-sensitive, raising concern about future forest health, when temperatures may have risen by 2 or 3 °C at the end of the century. Mixed forests could then face shifts in community composition toward more drought-tolerant species, as it is recently demonstrated in a long-term rainfall manipulation experiment in Spain (Barbeta et al. 2013). In a forest dominated by a single species as in the Qilian Mountains, a thinning of the stands and local or regional deforestation are the likely responses.

In our stands, tree mortality occurred one to four years after a very dry May and June, highlighting the key role of stress in the early growing season for mortality (Fig. 5). Recent research in other forest ecosystems has also documented lags of several years between a drought event and subsequent tree mortality (Bigler et al. 2004; Hogg et al. 2008). The causes of tree mortality are complex and still a matter of debate, potentially involving several biotic factors predisposing, inciting or contributing to drought-induced mortality (McDowell et al. 2011; Choat et al. 2012). Insect outbreaks, which are often involved in conifer mortality, were apparently not effective in our case, as suggested by own field observations and unpublished records of the local forest authorities. Human disturbance at lower elevations before the establishment of a strictly protected conservation area in the study area in 1988 is surely a source of uncertainty in our analysis, since wood likely was selectively cut and deadwood might have been collected from the forest. However, the clear response of missing ring frequency and tree mortality to high summer temperatures support our conclusion that a significant negative impact of climate warming has been exerted on the trees' productivity and vitality.

Our results indicate both a strong sensitivity of drought-related mortality to temperature as well as to intraspecific competition for soil moisture in these semi-arid forests. The higher frequency of mortality events at upper than lower elevation matches the pattern observed for missing rings. This pattern is likely caused by stand structural factors rather than by a climatic gradient, because canopy cover (60–80 vs. 30–50 %) and stem density (1792–1829 vs. 1167 tress ha^{-1}; Wagner et al. 2015) were higher at upper and middle than lower elevation suggesting that competition for soil moisture and thus water shortage is more severe in the denser upper forests. The putative density effect on spruce mortality is in line with reports that climate effects on tree mortality and growth decline are stronger when intraspecific competition is high (Linares et al. 2009; Dulamsuren et al. 2010).

Spruce plants younger than 20 years are very rare in the Qilian Mountain forests nowadays, resembling the situation in other semi-arid forests in Inner Asia (Dulamsuren et al. 2010, 2013; Liu et al. 2013). Thus, increasing mortality of adult trees is not accompanied by increasing recruitment rates which suggests that the recent global-change-type drought period is driving the Qinghai spruce forests beyond the point of ecosystem resilience and toward stand-level deforestation (Ponce Campos et al. 2013).

Rising temperatures since the late 1970s have increased aridity in many continental regions of the globe exposing especially semi-arid forests to additional stress (Dai 2013; Ji et al. 2014). A similar climate response as in our study was observed in semi-arid areas of the northern Tibetan Plateau (Bräuning 2001; Zhang et al. 2003; Gou et al. 2004; Shao et al. 2005; Liu et al. 2006; Yang et al. 2014). These dendroclimatic studies, however, did not focus on tree mortality. On the Tibetan Plateau, our study is the first to display regional-scale mortality patterns of a dominant tree species in response to extended drought events in combination with anomalously high temperatures.

Increasing aridity due to rising temperatures is the likely cause of significant decreases in stream flow from the north-eastern margin of the Tibetan Plateau in recent time (Wang et al. 2008). Continued warming should further increase water shortage. The recent drought episode on the north-eastern Tibetan Plateau at the turn of the millennium may represent a precursor of future global-change-type drought events in large parts of Inner Asia, in which high temperature acts in concert with prolonged drought. The likely prospect of increasing tree mortality predicts a grim future for many regions of semi-arid Inner Asia, because important forest-related ecosystem functions and services such as water supply, run-off regulation, carbon storage, and wood supply may be at risk. Warning signs are also visible from the adjacent arid lowlands, where shrinking oases, the decline of natural groundwater-fed vegetation and accelerating desertification have been reported from the Hexi Corridor (Kang et al. 2008). Here, an ancient oasis with a history of 2000 years is already disappearing (Kang et al. 2008). This may demonstrate the challenge which is posed upon man and nature in this region by future global-change-type drought.

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