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ORIGINAL PAPER

Tree growth response of *Fokienia hodginsii* to recent climate warming and drought in southwest China

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Abstract To date, few attempts have been made to assess the influence of climate change on forest ecosystems and on the relationship between tree growth and climate in humid areas of low latitudes. In this paper, we studied the response of tree growth and forest ecosystem to climate change by using *Fokienia hodginsii* tree-ring cores from the northern Yunnan-Guizhou Plateau, southwest of China. Tree growth correlates the highest ($r = -0.64$, $p < 0.01$) with mean temperature (July–September), but the coefficients were changing with time as revealed by a moving correlation analysis. Tree growth is significantly ($p < 0.05$) and positively correlated with January–April mean temperature from AD 1961–1987, while correlations with precipitation are insignificant. In contrast, from 1988 to 2014, tree growth correlated negatively with mean temperature of previous summer and positively with precipitation of previous August–September. This indicated that the limiting factors for tree growth have changed under different climate conditions. The meteorological data suggested that from 1961 to 1987 it was cold and wet in the study area and radial growth is limited by winter and spring temperatures. This restriction is weaker if the climate is appropriate in general. However, from 1988 to 2014, the combined effects of recent warming and decreasing precipitation have led to an increasing response of tree-ring width to drought. In addition, a large proportion of mature *F. hodginsii* mortality occurred from 2007 to 2013, which corresponds with a drastic reduction of radial growth (narrowest in recent 100 years). The recent drought, induced by decreasing precipitation and increasing temperature, may have passed the threshold which *F. hodginsii* could tolerate, causing tree growth reduction, tree growth-climate relationship change, as well as catastrophic tree mortality. All these changes may lead to further responses of the local ecosystem to climate change which should be highly regarded.

Keywords Northern Yunnan-Guizhou plateau · *Fokienia hodginsii* · Drought stress · Divergence phenomenon · Tree mortality

Introduction

Global surface mean temperature has increased by 0.85 ± 0.20 °C in about the last 130 years (1880–2012) (IPCC 2013), and this trend is supposed to continue in the near future. Global warming has caused a large number of extreme weather and climate events (drought, flood, snow disaster) across the world (Alexander et al. 2006; Anderegg et al. 2015; Easterling et al. 2000; Min et al. 2015). In recent years, a severe drought struck the southwest of China, which has brought enormous socio-economical losses. The impact of extreme climate events on regional societies and

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environments has received widespread attention (Allen et al. 2010; Easterling et al. 2000; Walther et al. 2002).

Tree rings have been widely used in paleoclimatic studies as a high-resolution proxy around the world. However, tree-ring research in China is focused on northwest China, Tibetan Plateau, and the surrounding area (Fang et al. 2010b; Gao et al. 2015; Gou et al. 2014; Liang et al. 2008, 2009; Yang et al. 2014; Zhang et al. 2015), but it is still scarce in the low latitudes and humid southern China. There are many difficulties for tree-ring research in humid regions, cause by vegetation deterioration, richness in tree species, and an only weak climate limitation of tree growth. Tree growth may also reflect information about microclimate, competition between individuals and species, as well as human and other biotic activities. To date, there are some tree-ring-width and isotope studies in southern China (An et al. 2012; Duan et al. 2013; Li et al. 2016; Qian et al. 2002; Shi et al. 2013, 2015). However, still few attempts have been made to assess the influence of climate change (especially the recent drought in southwest China) on forest ecosystem and the relationship between tree growth and climate.

A stable relationship between tree-ring width and climate is a basic principle of dendroclimatology. However, a "divergence phenomenon," expressing a remarkable instability in the climate sensitivity of tree growth, was found in recent decades. For example, D'Arrigo et al. (2008) reported that the temperature signal in white spruce ring width and maximum latewood-density chronologies from altitudinal and latitudinal tree-line sites in interior and northern Alaska has weakened in recent decades. Schneider et al. (2014) found that the strong coherence between tree-ring data and instrumental climate data in northern Fennoscandia is interrupted by a short, but significant correlation decrease in the early twentieth century; they ascribed this phenomenon to a substantial reduction in interannual summer temperature variability during that time period. D'Arrigo et al. (2008) reviewed the literature on the "divergence problem" and concluded that a clear identification of a sole cause for the divergence is probably unlikely due to the combination of reasons, such as the varying locations, species, and other factors. The divergence problem has caused extensive concern and challenged the traditional tree-ring-based climate reconstructions. This problem may have potentially significant implications for large-scale patterns of forest growth, the paleoclimatic reconstructions based on tree-ring records, as well as the global carbon cycle. However, on a global scale, the divergence problem research is focusing on middle and high latitudes (Briffa et al. 1998; Carrer and Urbinati 2006; Esper and Frank 2009; Jacoby and D'Arrigo 1995; Schneider et al. 2014); In China, it focuses on arid areas in the northwest of the country, on the Tibetan Plateau, and in surrounding areas (Gao et al. 2011; Jiao et al. 2015; Yu et al. 2013; Zhang et al. 2009), but it is very scarce in humid low latitudes (Fang et al. 2010a; Li et al. 2016). Therefore, it is meaningful to carry out such research in these areas.

Drought-related tree mortality has also given wide attention. Increasing tree mortality rates have been reported for boreal forests, temperate forests, tropical forests, and savannas (Peng et al. 2011; Phillips et al. 2010; van Mantgem et al. 2009). Suresh et al. (2010) analyzed the mean annual mortality rate over a 19-year period (1988–2007) of all trees with stems thicker than 1 cm dbh, and found that tree mortality can be categorized into several major causes. Fire, elephant-herbivory and climate change were the main agents for the mortality of trees with a stem of 1–5 cm, 5–10 cm, and thicker than 10 cm of dbh. Additionally, tropical dry forests growing in regions of a high rainfall variability may have developed greater resistance to rainfall deficit in comparison with tropical moist or temperate forests. Drought may tend to impact some tree species, as Fensham and Holman (1999) found in northeast Australia. Species with a shallow root system will have a high-risk to suffer severe water stress in semi-arid environments, while competition for soil moisture of different species resulted in a patchiness of drought-induced tree death. Moreover, Slik (2004) proposed that severe drought can regulate the structure of a plant community and affect the recruitment and growth conditions of small and immature trees. Tree death, as a fundamental process in ecosystems, has a substantial leverage in forest ecosystem responses to global environment change (Allen et al. 2010; Franklin et al. 1987). Recently, a severe drought impacted southwestern China, but to date, no attempt has been made to assess the influence of this extreme climate event on forest ecosystems.

Here, we present the first tree-ring-width chronology from a long-lived conifer, *Fokienia hodginsii* in the Xishui National Nature Reserve of the northern Yunnan-Guizhou Plateau. This paper explores the temporal stability of the relationship between tree growth and climate, the possible reason of drastic tree growth reduction and catastrophic tree mortality. This study is an expansion of tree-ring research in humid areas, and it will provide important information for policy decisions, rare species protection, and forest management.

Materials and methods

Research area

Our study was conducted in the Xishui National Nature Reserve, in the northwestern Guizhou province, China (105° 50′~106° 29′ E, 28° 07′~28° 34′ N, 420–1756 m asl) (Li et al. 2015) (Fig. 1). With an undulating topography with steep hills, this national wildlife refuge is trackless. This area features a subtropical monsoon climate, and the 56-year-long records of monthly mean temperature and monthly total precipitation at the Xishui weather station (Fig. 2) represent the

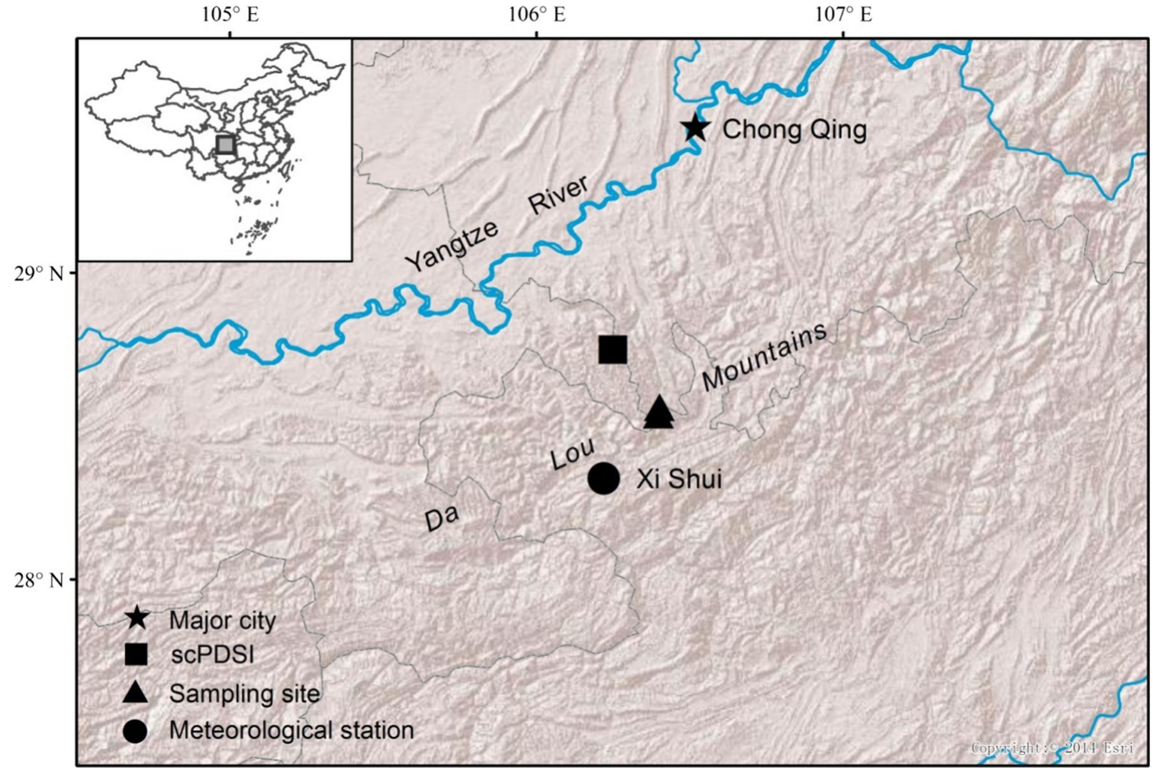
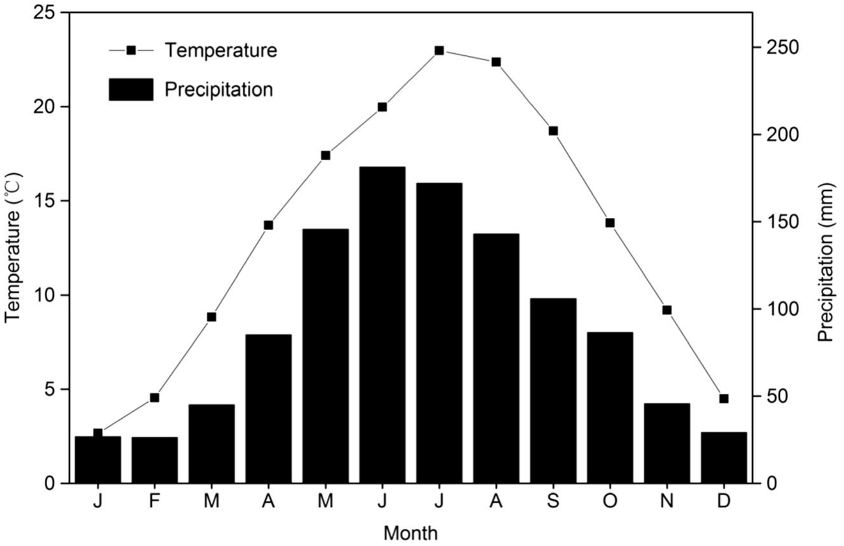


Fig. 1 Location of the study region in China (*inset*); the location of the sampling site, the nearby meteorological station, and scPDSI grid point are shown in the detailed map

general climate of the study region. The mean annual precipitation is 1096 mm, 58.8% of which fall in the monsoon months from May to August. The average annual temperature is 13.1 °C, and the hottest season is July to August. Though not found in pure stands, *F. hodginsii* is one of several canopy species such as *Masson pine*, *Pinus fenzeliana*, and *Gordonia acuminata*, which are scattered throughout dense and tall mixed forest stands with multiple canopy layers consisting of both evergreen and deciduous tree species. Our *F. hodginsii* community in this study area is known as one of the highest latitude natural community for this species. This species is mainly distributed in Vietnam and south-southwest China (110°~118° E, 24° 30′~26° 30′ N) (Wang et al. 1984).

Fig. 2 Monthly total precipitation and monthly mean temperature of Xishui from 1959 to 2014



Climate data

The Xishui station (28° 19′ 48″ N, 106° 13′ 12″ E, 1180.2 m asl) (Fig.1) is the closest meteorological station to the sampling site (~30 km). Climate variables for climate-growth analyses include monthly mean temperature and total precipitation from 1959 to 2014. In addition, the nearest grid point (28.75° N, 106.25° E) of the monthly self-calibrating Palmer Drought Severity Index (scPDSI) dataset was downloaded from http://climexp.knmi.nl. This drought index was first proposed by Wells et al. (2004) to quantitatively measure the accumulated deficit of local mean moisture conditions, allowing comparisons of drought severities across regions and time.

We use the linear regression method to analyze the variations of climate recorded at the Xishui station (Fig. 3) since 1961. Precipitation has decreased by 31.2 mm/10a ($p < 0.01$), while the mean temperature has increased by 0.16 °C/10a ($p < 0.01$). The temperature change is not evident from 1961 to 1987 but rapid from 1988 to 2014 (0.38 °C/10a, $p < 0.01$). The precipitation decreased, but not highly significantly in all four seasons, whereby the maximum decrease occurred in autumn by a rate of 19.3 mm/10a ($p < 0.01$). The mean temperature has increased in all four seasons, with a maximum increase by 0.23 °C/10a ($p < 0.01$) in autumn. Those characteristics of climate change in the Xishui are similar to other places in southwestern China (Wang et al. 2015; Zhang et al. 2013a, b), which means that the Xishui station represents large-scale climate patterns. With the precipitation decreasing and temperature rising, this area is getting drier. The scPDSI values showed evidence of a significant trend of moisture decreasing after 2004, when the mean annual scPDSI value is −4.8, which is far below its long-term average (−0.83) (Table 1).

Tree-ring data

The tree-ring samples were collected from old-growth *F. hodginsii* trees, at an altitude range from 1200 to 1270 m in the Sancha River scenic area (SCH), Dalou Mountains,

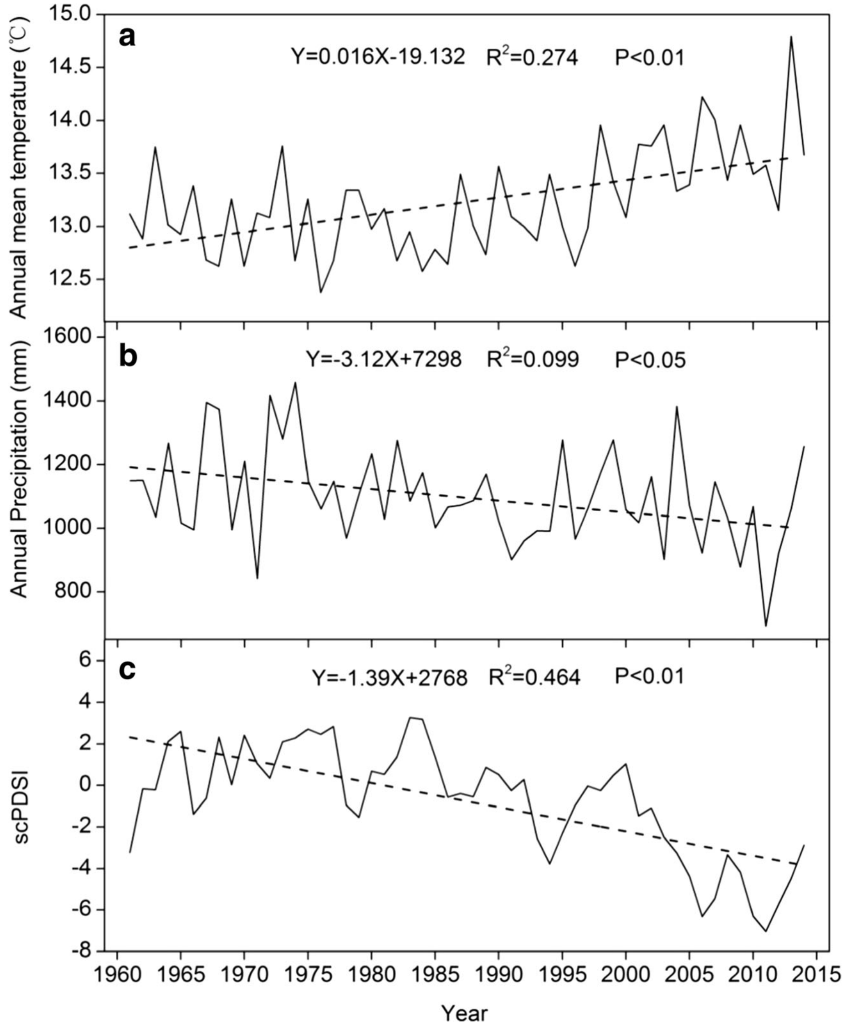


Fig. 3 Variations of **a** annual mean temperature, **b** annual total precipitation, and **c** annual mean scPDSI over the period from 1961 to 2014. The *dashed straight lines* represent the temporal trends

Table 1 Trends in annual and seasonal temperature and precipitation

	Temperature (°C/10a)	Precipitation (mm/10a)
1961–2014	0.16	−31.2 (−2.8%)
1961–1987	−0.08	−25.5 (−2.2%)
1988–2014	0.38	−17.9 (−1.7%)
Spring	0.11	−6.04 (−2.2%)
Summer	0.12	−4.36 (−0.1%)
Autumn	0.23	−19.3 (−8.1%)
Winter	0.20	−2.97 (−3.6%)

northern Guizhou province (Fig. 1). The samples were collected from two sites, including both dead trees and living trees (Table 2). Dead trees (25 cores/12 trees) were obtained from a scenic spot locally known as Wangxiantai (SCH01), in which almost all mature *F. hodginsii* were dead (Li et al. 2013, 2015); a similar situation was observed in Tiantanggou (Li et al. 2015; Wang et al. 1984), another scenic site in this Nature Reserve. Only 10 trees out of 17 dead trees were precisely cross-dated by attributing calendar years to the outermost annual rings because of the rapid decay of dead trees in this warm and humid environment. The living trees (30 cores/17 trees) were obtained from SCH02 of a similar elevation and slope direction as SCH01, and no standing dead trees were found in this site. The two places are about 3 km apart. Two or three cores per tree were obtained by an increment borer at breast height (~1.3 m).

The tree-ring samples were processed following standard dendrochronological practices (Fritts 1976). All cores were air dried and glued onto wooden mounts with the transverse surface exposed and polished with progressively fining sandpapers until the cellular structure became clearly visible. All cores were visually cross-dated using the skeleton plot methodology (Fritts 1976) to assign an exact calendar year to each growth ring. Then, the ring widths were subsequently measured to a precision of 0.001 mm using a Velmex measuring system. The quality of the cross-dating was checked using the COFECHA program (Holmes 1983). Cores that were too short, profoundly corrupt, or not suitable for cross-dating due to uneven radial growth and frequent “wedging” of rings and “false rings” (Buckley et al. 2007; Sano et al. 2007, 2008) were excluded from further analysis. Because the samples from the two sites cross-dated well, we merged them into one chronology.

This chronology was developed from 40 cores from 21 trees. The ring-width series were standardized using ARSTAN (Cook 1985). Thirty-five series were de-trended with a negative exponential curve or a straight line (negative slope or horizontal), and the other remaining five series were fitted by a cubic smoothing spline of 67% of the series length (Cook and Kairiukstis 1990). The de-trended individual series were finally combined into a standard chronology (Fig. 4a) using a bi-weight robust mean methodology.

Summary statistics for the STD chronology

Mean sensitivity (MS) is a measure for the change of ring width from 1 year to the next and thus of the high-frequency variance in a given tree-ring series (Speer 2010). A tree-ring series with a high MS is believed to contain more climate information than a tree-ring series with lower MS; the mean sensitivity in this site is 0.27 (Table 3). The chronology has a low percentage of absent ring (0.12%), which are mainly associated with extremely narrow ring in other trees. In general, tree-ring series in arid and other harsh environments have higher percentages of absent rings than series in humid and habitable environments. The first-order autocorrelation quantifies the dependence of the tree-ring widths from their directly preceding tree-ring width hence reflecting the influence of previous climate factors on the current ring growth. This tree-ring series has a fairly high first-order autocorrelation (0.74), which indicates that tree growth was influenced by the climate of the previous year and lag effects may exist in the time series (Wu 1990). The subsample signal strength (SSS) was used to determine the most reliable period within a chronology, with SSS above 0.85 as a desirable level (Wigley et al. 1984). This chronology has a high correlation within trees and a low correlation between trees, suggesting that tree growth may be influenced by a multiple of climate factors, different habitats, as well as other interferences.

Assessment of the relationship between tree growth and climate

Correlations between tree-ring chronology and the climatic variables (monthly temperature, total monthly

Table 2 Survey of the sampling site

Sites	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Cores/trees	Canopy density	Slope (°)	Slope aspect	Mean length of series/a
SCH01	28° 33′ 44″	106° 24′ 05″	1200–1270	30/17	0.4	40	SW	125.3
SCH02	28° 32′ 14″	106° 23′ 54″	1200–1240	25/12	0.4	40	SW	86

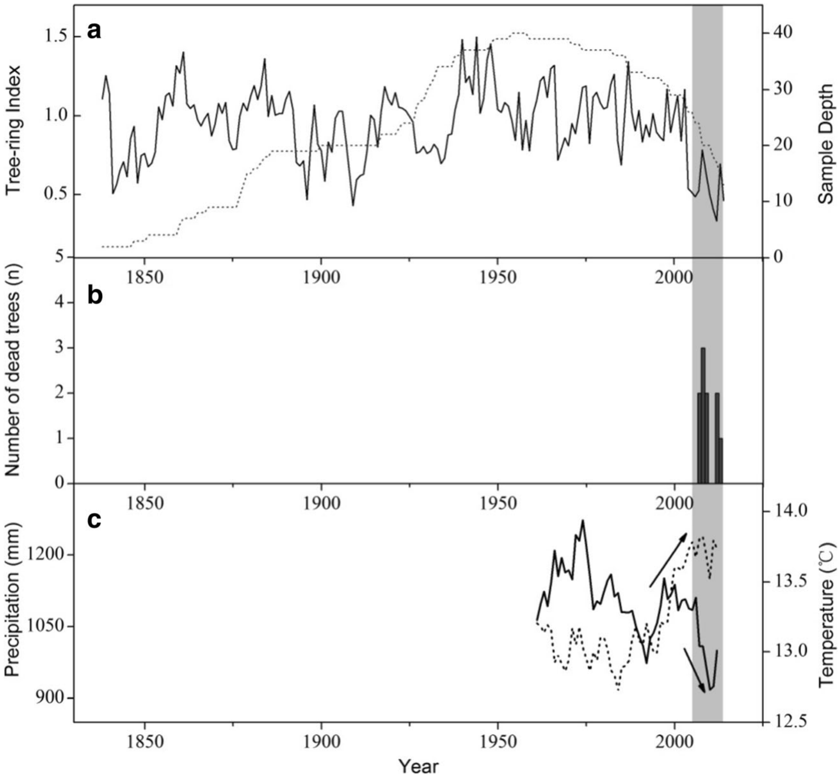


Fig. 4 **a** Tree-ring-width standard chronology (*solid line*) and the corresponding sample size (*dotted line*); **b** the number of dead trees (*black columns*) with the years of death; the *white star* shows the number of missing rings with the exact timing; **c** 5-year moving average of annual precipitation (*solid line*) and annual mean temperature (*dotted line*)

precipitation and monthly scPDSI)—extending over a 20-month window from March of the previous year to October of the current year were examined via Pearson correlation (Briffa and Jones 1990). Given that the relationship between tree-ring chronology and climate factors may be influenced by the remarkable change of hydroclimate condition of study area in recent decades, a moving correlation analysis was applied to the chronology and the meteorological data to explore the possible temporal instability of the relationship. In addition, as the correlation coefficient was influenced by the linear tendency as discovered in another section below, we therefore used the first difference of the meteorological data and the tree-ring data.

Table 3 Statistical characteristics of the tree-ring chronology

Statistical item	STD
Subsample signal strength (SSS) >0.85	Since 1865 (8 cores)
Mean sensitivity (MS)	0.27
Mean correlations within trees	0.74
Mean correlations between trees	0.21
First order autocorrelation	0.74
Common period	1887–1996
Absent rings (%)	0.12

Results

Correlation between the tree-ring chronology and climate variation

Figure 5a shows the Pearson correlations between the SCH chronology and monthly precipitation and temperature in Xishui station and the scPDSI grid point nearest to the study area. There were significant negative correlations ($p < 0.05$) with the mean temperatures in previous June–September and November, with previous September (−0.47, $p < 0.01$) being the strongest (Fig. 5a). In contrast, for monthly precipitation, no significant correlations existed with the tree-ring chronology. All monthly scPDSI from previous March to current October are positively correlated with the ring-width chronology, with the highest in previous October (0.6, $p < 0.01$).

Despite evidence for strong correlations, the correlation coefficient may be influenced by the tendency of the linear variation of climate and chronology. This is why the correlation coefficient distinctly declined with scPDSI after applying the first-difference methodology. Accordingly, the chronology is significantly correlated with scPDSI only from previous July to current January (Fig. 5b). However, the correlation coefficients between tree-ring data and mean temperature do not change significantly and neither did the relationship with precipitation.

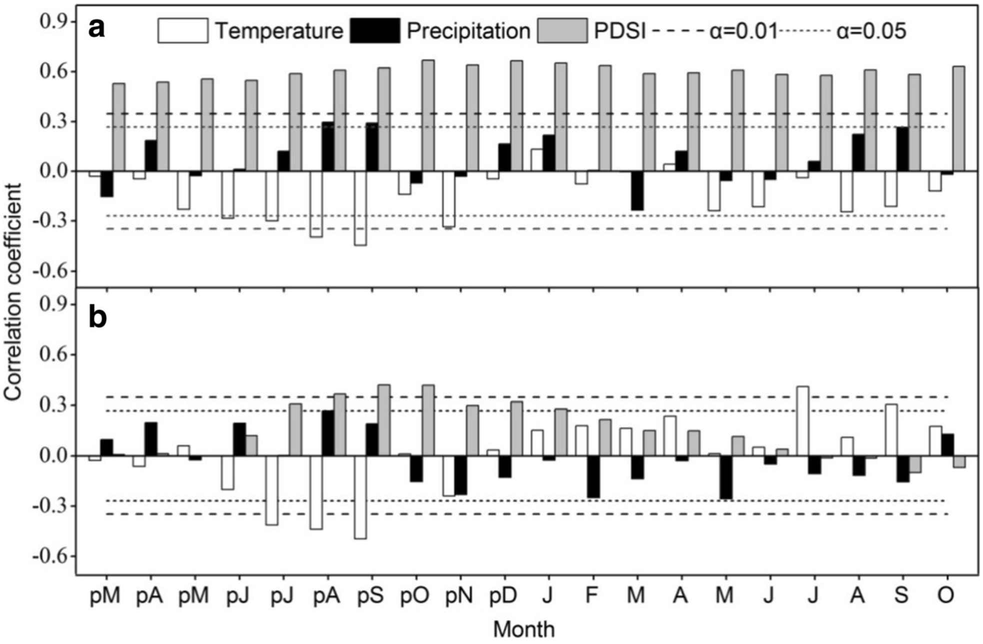


Fig. 5 **a** Correlation between the tree-ring chronology and monthly mean temperature, precipitation, and scPDSI (1961–2014) from March of the previous year to October of the current year. **b** The same as (**a**) but using first-difference records. *Dotted and dashed horizontal lines* indicate $p = 0.05$ and $p = 0.01$ significance levels, respectively

The “response divergence”

Before early 1990s, the 21-year running correlation calculated between chronology and climate facts (except temperature) were most of the time not significant and decreasing (Fig. 6). However, a different situation was found in the early 1990s that the correlation coefficients of the chronology with precipitation and scPDSI increased quickly and gradually reached the significance level, and the correlation coefficients of the chronology with temperature was consistently highly negative and suddenly increased. This huge change was coincidence with a tremendous difference in the variation of climate patterns that the temperature showed a decreasing trend while precipitation and scPDSI maintained higher than mean before the early 1990s, but a rapid increase while precipitation and scPDSI showed a decreasing trend in the early 1990s (Fig. 6).

In order to quantify the temporal variation of tree-ring response to climate, we divided the meteorological data into two periods (1961–1987 and 1988–2014) (Fig. 7), taking the time of correlation coefficient change and the length of the two periods into consideration. In the 1961–1987 period, the chronology is positively correlated with mean temperature from January to April ($r = 0.52$; $p = 0.05$), while no persuasive relationship exists with monthly precipitation and scPDSI. This confirmed that the radial growth is limited by winter and spring temperature in this warm and humid climate, but their restriction on tree-ring growth is weak, therefore, the ring widths are wide and above average in this time period. In the 1988–2014 period, however, there is a highly negative correlation ($p < 0.01$) between tree-ring indices and previous July, August, and September temperature. The correlation between the chronology and precipitation is also noticeable in the late growing season of the previous year. The correlation between tree-ring chronology and previous August–September precipitation is 0.52 ($p < 0.05$), which is higher than the correlation ($r = 0.45$, $p < 0.05$) with current August–September monthly precipitation. These results suggest that moisture is the main limiting-factor for tree growth in the period from 1988 to 2014.

The above results suggest a clear “response divergence” phenomenon that shows up as limiting factor for tree growth is changing with time. From 1961 to 1987, the chronology is positively correlated with mean temperature in winter–spring, while no persuasive relationship existed with monthly precipitation. During this same time, the annual mean temperature decreased, with a modest decreasing rate in January–April (−0.13 °C/10a, $p < 0.05$). For annual precipitation, no obvious trend was observed during these year periods. Consequently, a relatively cold winter–spring restricted tree growth under the circumstance of plentiful precipitation, but this restriction is weaker if the climate is appropriate in general. The situation was notably different from 1988 to 2014, during which the chronology is negatively correlated with temperature and positively with precipitation. The correlation between the chronology and winter–spring temperature suddenly decreased with temperature rising after the early 1990s (Fig. 8). That is to say that the rapid increase of temperature by 0.43 °C/10a ($p < 0.01$) combined with a gradual decrease of precipitation may be the reason for the limiting factor shifting in the early 1990s and enhancing after the early 1990s.

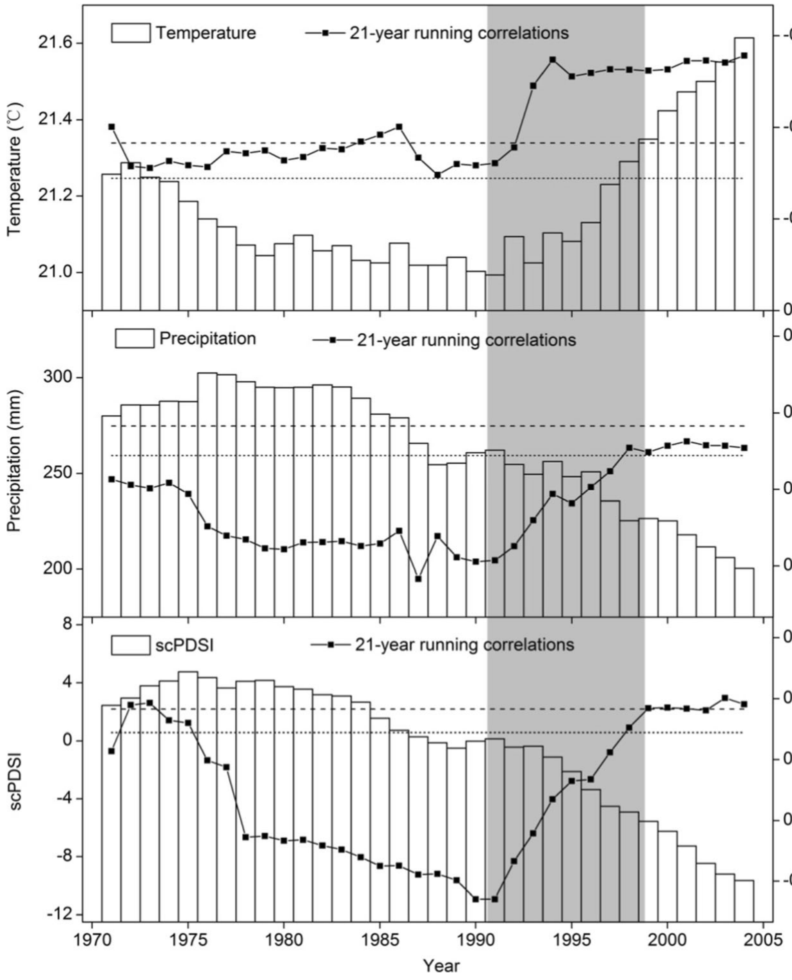


Fig. 6 Twenty-one-year running correlations between the chronology and the mean temperature (July–September of the previous year), precipitation (August–September of the previous year), and scPDSI (August–October of the previous year). For comparison, a 21-year running mean of the climate data (*columns*) was added. *Dotted and dashed horizontal lines* indicate the $p = 0.05$ and $p = 0.01$ significance levels, respectively

The mortality of *F. hodginsii*

Meteorological data record that 2005, 2006, 2009, and 2011 were extreme drought years. We found a rapid reduction of radial growth from 2004 (narrowest in more than 100 years) coincided with recent drought and rapid warming (Fig. 4b) and tree mortality which concentrated from 2007 to 2013 occurred in extremely dry years or 1 to 3 years after a very dry

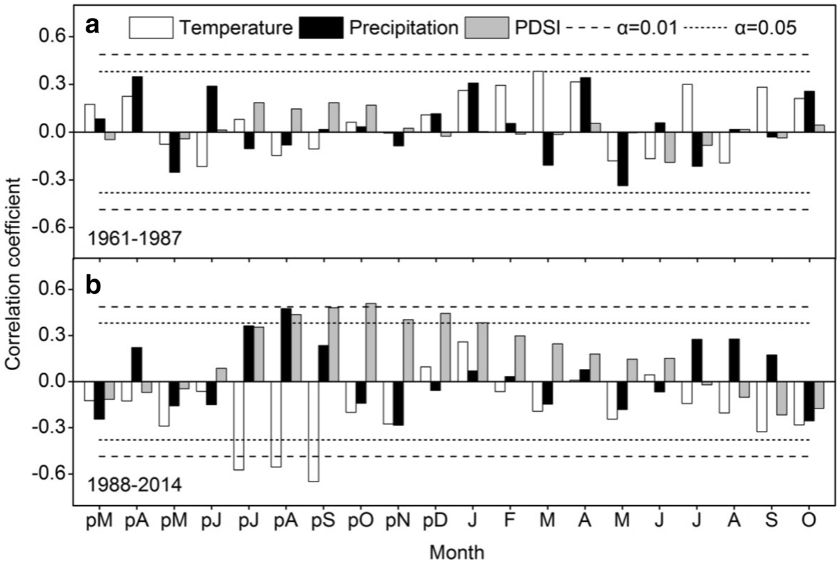


Fig. 7 Correlation between tree-ring index and monthly mean temperature, precipitation, and scPDSI from March of the previous year to October of the current year. **a** Correlation over the 1961–1987 period. **b** Correlation over the 1988–2014 period. *Dotted and dashed horizontal lines* indicate the $p = 0.05$ and $p = 0.01$ significance levels, respectively

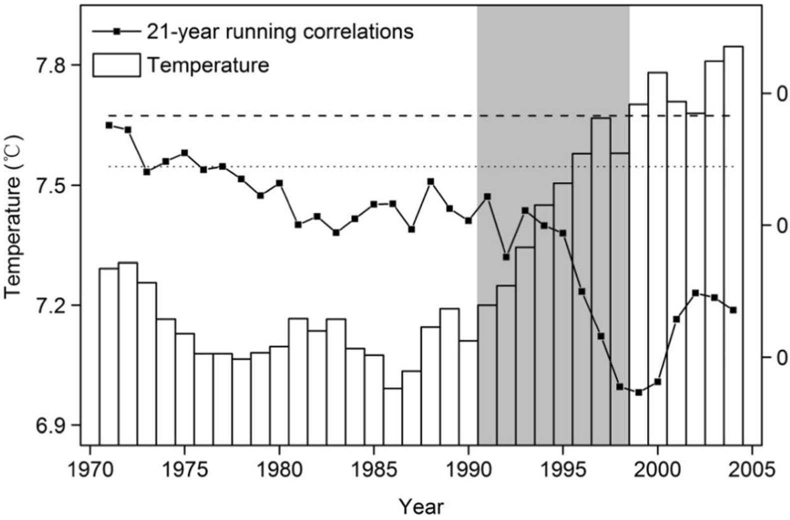


Fig. 8 Twenty-one-year running correlation between the chronology and the mean temperature (January–April of the current year). For comparison, a 21-year running mean of the climate data (*columns*) was added. *Dotted and dashed horizontal lines* indicate the $p = 0.05$ and $p = 0.01$ significance levels, respectively

summer or autumn. Following with sustained extreme drought during 2005 and 2006, most of the missing rings recorded by living younger trees in SCH02 occurred in 2007. Moreover, running correlation analysis (Fig. 5) shows high correlation coefficients of chronology with temperature, precipitation, and scPDSI, suggesting that the recent warming and decreasing precipitation may cause stress for *F. hodginsii* and thus may relate to the mortality and reduce growth of this species in this region (Fig. 5).

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 *F. hodginsii* trees in the sampling site, one alive (young tree) and one dead (old tree), showed similar interannual growth variations over decades until the extremely dry and warm summer and autumn in 2007 (Fig. 9) when the young living tree had a missing ring and exhibited a sharp growth decline. The old tree died in 2007 after 10 years of very drastic reduction of radial growth from 1998 and the growth of the living tree also substantially reduced after 1998, but recovered afterwards, and this young tree still survives.

Discussion

It is generally acknowledged that the climate limitation on tree growth is weak in humid areas and low latitudes. But in this research, we found the response divergence and the response of tree growth to climate change is enhancing as climate is getting drought and warm. During 1961 to early 1990s, a relatively cold winter–spring restricted the tree growth under the circumstance of plentiful precipitation, since a warm winter–spring can protect trees from frost damaging and triggering the cambium to activate earlier, which may enhance growth (Shi et al. 2010, 2013; Yang 2012), but this restriction is relatively weaker as the climate is appropriate in general. However, after the early 1990s, the excessively high

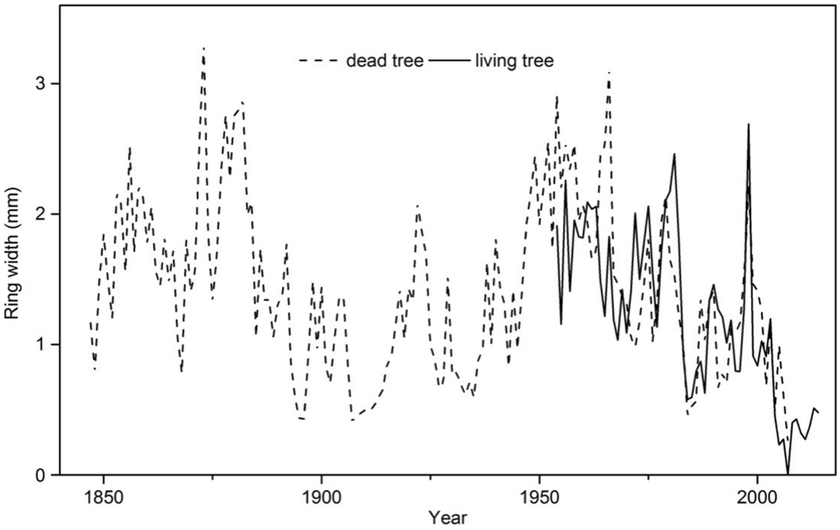


Fig. 9 Ring-width chronology of a living *Fokienia hodginsii* tree and a tree that died in 2007. The samples were taken in November 2014

temperatures in late summer and early autumn during the previous year would reduce the water reserve in the soil, which may have enhanced the transpiration and respiration of trees, and therefore can constraint tree growth in the following year by reducing the carbohydrate storages that trees use for growth during the next year. This phenomenon was also found in some other tree-ring studies (Chen et al. 2012; Rolland 1993; Shang et al. 2011).

The reduced sensitivity of recent tree growth to temperature at Northern high latitudes may be due to the reduced limitation of temperature on tree growth under the circumstances of global warming (Briffa et al. 1998). In middle latitudes, the combined effects of recent warming and increasing intensity of climate extremes are enhancing synchrony of tree growth in Spain (Shestakova et al. 2015). Intense droughts and warming have led to decreasing tree growth and increasing mortality in southwestern USA, and tree growth will experience a substantial decrease during the twenty-first century if temperature and aridity rise (Williams et al. 2010). In general, there is still lack of direct evidence that growth–climate relationship has been changed in mid-high latitudes. However, we found that the association between climate and tree growth is changing as climate is getting warmer and drought. As a case study of the relationship between tree growth and climate under climate change in south China, this research could be a message that a large scale of tree-ring-climate patterns may be changing in humid areas of low latitudes. Unfortunately, it is unknown whether this regional tree-ring chronology which estimates response divergence can correlate with potentially more representative forest growth, as well as it is not clear whether this tree growth and climate patterns existed before since the instrumental records were too short. Consequently, more research is needed to confirm our observations.

The second objective of this study is to determine if drought or global warming were related to the drastic reduction of radial growth and tree mortality. Among endogenous processes, perhaps the best-known cause of increasing tree mortality rates is increasing competition resulting from increasing forest density and basal area. However, consistent with our observations of catastrophic mortality without compensating increases in recruitment, radial growth declined quickly during the study period. Thus, tree mortality is consistent with a quick decline of radial growth rather than an increase in potential for competition, which suggests that the catastrophic tree mortality cannot be attributed to forest dynamics. Furthermore, competition will be responsible for the gradual increase in tree mortality in general; however, consistent with recent drought and rapid warming, radial growth declined quickly since 2004 (narrowest in more than 100 years) and the mature dead *F. hodginsii* concentrated in a few years, and we did not find any missing rings and tree mortality before this time period. Thus, tree mortality is consistent with climate change rather than an increase in potential for competition.

Though not all samples from dead trees were collected since there are less *F. hodginsii* in this area, and is difficult to collect all of the outermost rings because of the rapid decay of dead trees in this warm and humid environment, it should generally represent the phase of recent tree death in this area. We observed that the trunks of mature *F. hodginsii* exposed to catastrophic tree mortality were tall and straight, and no dead young trees were found. It could be that big trees were more vulnerable to climate change, carbon starvation, as well as biotic diseases than smaller trees, as drought limits the plant leaf photosynthesis and carbon storage (McDowell et al. 2008; Phillips et al. 2010) and moisture determines the height of the tree (Niklas and Spatz 2004). Moreover, drought is more likely to hurt and kill mature *F. hodginsii* possibly (Fig. 9) because of its tall and straight trunk and less leaf features (Fensham and Fairfax 2007; McDowell et al. 2008). In addition, the occurence of missing rings provides compelling evidence for a strong sensitivity of the trees to global warming and local drought. Missing rings, i.e., the failure to produce stem wood in a particular year, represent an adaptive mechanism that may increase the survival rate of trees under extreme drought stress, when the trees have to reduce the respiratory demand and to decrease the risk of hydraulic failure (Liang et al. 2015). The occurrence of missing rings indicates that the environmental conditions are close to the survival limit of the trees. Thus, the crop up of missing rings may serve as an excellent indicator of the severity of drought stress effects on tree growth in this humid region of low latitudes. We suggest that the presence of recent drought and temperature stress thresholds beyond what *F. hodginsii* could suffer may operate as a trigger that caused the reduction of basal area increment and may ultimately result in catastrophic tree mortality. The implication is that if warming continues and effective moisture continue to increasingly become less available, populations of these species may become increasingly sensitive to drought and at risk for mortality. The above suggestions is supported by many studies. For example, Liang et al. (2015) suggested that recent climate warming has increased missing ring frequency and tree mortality rates of Qinghai spruce in north-eastern Tibetan plateau. Anderegg et al. (2012) provides insight into the physiological mechanisms of drought on tree death with modeling approaches. Van Mantgem et al. (2009) inferred that regional warming and consequent increases in water deficits may be the dominant contributor of the increases in tree mortality rates. Pedersen (1998) noted that the decreases in basal area growth and increases in tree mortality of red oak in America followed the drought event. However, the patterns and causes of tree mortality typically are complex, thus, it is hard to come to a conclusion at this point in time of whether climate change itself or other factors were responsible for tree mortality. More work should be done to test our hypotheses in the future.

Conclusion

We present the first *F. hodginsii* tree-ring-width chronology in the northern Yunnan-Guizhou Plateau. The response of tree-ring width to climate change and the impact of climate change on forest ecosystem were studied. This study is an important supplement to tree-ring research in the subtropical humid areas in China. We found a clear response divergence phenomenon that the limiting factors for tree growth changed under different hydroclimate conditions. The catastrophic tree mortality at the edge of *F. hodginsii's* natural distribution informs us that special attention should be paid to the ecological impact of global warming and extreme climate events, especially at the border area of tree species.

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