

Climate-growth pattern of *Pinus tabulaeformis* plantations and their resilience to drought events in the Loess Plateau

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ABSTRACT

Large-scale plantations were established under the Grain for Green project to improve the ecological environment of the Loess Plateau (LP) of China. However, there are increasing concerns regarding the sustainability of plantation ecosystems under climate change. In this study, we developed tree-ring width chronologies of *Pinus tabulaeformis* at seven sites along a precipitation gradient from south to north in the LP. Correlation analysis was performed to investigate the climate (temperature, precipitation, self-calibrating Palmer Drought Severity Index)-growth relationship. Moreover, the tree resilience components were computed to study the adaptability of trees to extreme drought during the growth periods. The results showed that the differences in radial growth to climate change along the precipitation gradient and the cluster analysis of the tree ring width index (RWI)-scPDSI correlation coefficient illustrated that the climate-growth response pattern along the LP was divided into southern and northern regions. Tree growth in the southern region is limited by humid environment conditions, while tree growth in the early and middle growing seasons of the northern region is limited by warming-induced drought. As the temperature rising over the past fifty years, the growth was found to be negatively correlated with temperature, especially in the spring and autumn seasons of the northern region. In contrast, the effect of precipitation on tree growth became more negative in the southern region, but more positive in the middle and late growing seasons of the northern region. Moreover, tree resilience analysis showed that the high resistance of *Pinus tabulaeformis* in the southern region, whereas high recovery in the northern region. It was difficult for the growth of *Pinus tabulaeformis* to recover from drought in the southern region, but stronger adaptability to extreme drought events in the northern region. Our study illustrated that there are different climate response patterns and limiting factors of *Pinus tabulaeformis* along the precipitation gradient in the LP; thus, different ecological restoration and regional forestry management strategies should be initiated in the LP.

1. Introduction

Forest ecosystems cover approximately 30% of the total land surface of the world, accounting for 75% of terrestrial gross primary production and 80% of total plant biomass on Earth (FAO, 2020). They play a particularly significant role in soil erosion, runoff regulation, and perform many ecological services to mitigate climate change worldwide (King et al., 2013; Pan et al., 2013). However, climate change and its impacts on forest ecosystems are a major force in the twenty-first century (IPCC 2013; Jiao et al., 2016). In particular, precipitation and temperature-induced drought is a crucial factor affecting plant growth

and distribution globally (Engelbrecht 2012; Walck et al., 2011). Intergovernmental Panel on Climate Change (IPCC) reports illustrate that the past two decades have included 18 of the 20 warmest years since record-keeping began in 1850. It also predicted that the global temperature will rise by 1.5 °C from the pre-industrial level between 2030 and 2052 if the climate warming continues at the current rate (IPCC, 2018). Widespread decline in tree growth triggered by warming-induced drought has been consistently reported due to the sensitivity of plants to climate change (Gentilesca et al., 2017; Gessner et al., 2013; Wang et al., 2019). Therefore, the succession process of forest ecosystems is likely to change under the temperature rises (Bolte et al., 2009; Piao et al., 2010),

Abbreviations: LP, Loess Plateau; T, temperature; P, precipitation; scPDSI, self-calibrating Palmer Drought Severity Index; RWI, ring-width index; XY, Xunyi; HL, Huangling; FX, Fuxian; YC, Yichuan; MZ, Mizhi; ZD, Zhidan; SM, Shenmu; Rt, resistance; Rc, recovery; STD, Standard chronology; BAI, basal area increment.

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the relationship between tree growth and climate change should be studied in ecological vulnerability areas.

The Loess Plateau (LP; $6.4 \times 10^5 \text{ km}^2$) is a fragile ecological area that situated in the arid and semi-arid zone of northwest China with serious soil erosion (Zhang et al., 2008). The Grain for Green project implemented in 1999 significantly reduced soil erosion, increased vegetation cover (from 31.6% in 1999 to 59.6% in 2013), and played a significant role in improving ecosystem carbon sinks and environment conditions (Chen et al., 2015; Fan et al., 2012; Lu et al., 2018). However, the extreme temperature events have become more severe in the LP (Zhi et al., 2010). Rainfall is unevenly distributed throughout the year and is far exceeded by evaporation in the LP. Combined with the increasing transpiration of soil water by planted vegetation, the surface soil of the LP became arid because of the imbalance between soil water availability and water utilization (Chen et al., 2015). Furthermore, the annual temperature showed a significant increasing trend of $0.097 \text{ }^\circ\text{C}/10$ years between 1901 and 2014, and it was predicted to increase to $0.558 \text{ }^\circ\text{C}/10$ years between 2015 and 2100 (Peng et al., 2018). Therefore, plantations are increasingly strongly affected by temperature rising in the LP, it is necessary to study the climate-growth relationship of plantation in the LP under warming.

Satellite data have always been used to study vegetation growth and climate response in the LP under climate change at large scale, but they lack data on tree growth measurements (Bai et al., 2019; Qiu et al., 2021; Yang et al., 2021; Zhang et al., 2021). Tree rings can be observed to study the impact of environmental factors on vegetation as they provide a climate-sensitive record of the relationship between tree growth and climate conditions (Fritts 1976; Fritts and Swetnam 1989; Kienast et al., 1987). Therefore, the tree ring method is widely used to study how climate-growth relationships change across species distribution ranges (Dorado-Liñán et al., 2019; Gazol et al., 2015; Jiang et al., 2014; Liang et al., 2016; Xu et al., 2012b). In addition, a narrow ring width can be observed when a tree suffered from drought and recovered thereafter, which is referred to as resilience. Resilience is broadly defined as the capacity of an ecosystem, community, or individual to recover after a disturbance and regain its pre-disturbance structure and function (Folke et al., 2004). Tree resilience has been applied in a large number of studies to analyze and quantify the generic and specific responses of species to extreme events such as drought (Merlin et al., 2014; Vanhellemont et al., 2018). Studies have shown that frequent drought events can reduce the resilience of trees (Cole et al., 2014; Gazol et al., 2017). Gazol et al. (2018) have illustrated that temperate trees have a low ability to recover from drought events under warming.

Some scholars have studied the dendrochronology in the LP. However, most of them are focus on historical drought indices and temperature reconstructions (Fang et al., 2010; Fang et al., 2011; Li et al., 2010; Liu et al., 2012; Song and Liu 2011; Song et al., 2014). Only a few studies have recently focused on the climate-growth relationship of plantations in the LP. For example, a new study proved the different climate-growth relationship of *Robinia pseudoacacia* Linn. in the southern semi-humid and northern semi-arid regions of the Chinese LP under warming (Keyimu et al., 2021). However, the study of forest vulnerability to climate change, particularly drought events, is complicated by macro-climatic, structural, and compositional differences of forest sites at continental scales (Vicente-Serrano et al., 2014). Studies in Mediterranean showed that the climate-growth relationship of *Juniperus thurifera* L. was different in dry and wet stands (Desoto et al., 2014). Over the last five decades of warming, divergent tree growth trends and the contrasting effects of climate change on tree growth have been detected throughout the species' range in the Tibetan Plateau (Gao et al., 2018; Guo et al., 2019; Song et al., 2020). Climate change has rendered forest development highly uncertain as it depends on species and environmental heterogeneity (He et al., 2013). Therefore, a comprehensive understanding of the radial growth responses of different planted tree species to local climate conditions in different regions of the LP is needed to provide information for afforestation management.

Pinus tabulaeformis is one of the main afforestation species in the LP that plays an important role in soil erosion and alleviation of climate change. However, the growth of plantations was stressed by drought in the semi-arid region due to the increasing temperature. To improve the management of plantations, promote ecological reconstruction, and set references for optimizing afforestation practices, we selected seven sample sites of *Pinus tabulaeformis* plantations from south to north along the precipitation gradient in the LP to study the climate-growth relationship and drought response using the tree-ring method. Our study aimed to clarify the climate response patterns and warming impacts on *Pinus tabulaeformis* plantations as well as their spatiotemporal resilience patterns to extreme drought events in the LP.

2. Material and methods

2.1. Study areas

Seven sampling sites, including Xunyi (XY), Huangling (HL), Fuxian (FX), Yichuan (YC), Mizhi (MZ), Zhidan (ZD), and Shenmu (SM) counties, along the precipitation gradient from south to north in the LP of northwest China were selected (Table 1). According to previous studies on precipitation isolines for different climatic regions in the LP, XY, HL, FX, and YC are located in the semi-humid region of the LP ($500 \text{ mm} < \text{precipitation} < 800 \text{ mm}$), with a mean annual temperature of $8.43 \text{ }^\circ\text{C}$ and mean annual precipitation of 556 mm (Chen et al., 2008; Wang et al., 2011), and ZD, MZ, and SM are in the semi-arid region of the LP ($250 \text{ mm} < \text{precipitation} < 500 \text{ mm}$), with a mean temperature of $8.32 \text{ }^\circ\text{C}$ and annual precipitation of 437 mm . All climate data were averaged over the past 50 years in the semi-humid and semi-arid regions (1968–2018) (Fig. 1).

2.2. Meteorological data

Temperature and precipitation are the main factors linked to water balance. The self-calibrating Palmer Drought Severity Index (scPDSI) is an improved index that represents soil moisture conditions with consideration of atmospheric input and soil evaporation, which can reflect the degree of drought (Wells et al., 2004). Thus, temperature, precipitation, and scPDSI were used to analyze the relationship between tree radial growth and climate. All temperature and precipitation data at each site were derived from a high spatial resolution monthly dataset over China (Peng et al., 2019). The gridded scPDSI dataset nearest to the seven sampling sites was downloaded from the KNMI Explorer (<http://climexp.knmi.nl>).

2.3. Tree-ring core sampling and chronology development

All tree-ring cores were extracted from the pure *Pinus tabulaeformis* plantations in the seven counties in the summer of 2019. At each sampling site, we selected 30 healthy trees and took one core at breast height (1.3 m) to build the chronology. All tree cores were air-dried and mounted on supports, and sanded with 240-, 400-, and 600-gritted sandpaper until the tree rings could be clearly identified. Tree-ring width was measured using a LINTAB 6 (Rinntech Inc., Germany) measurement station with a resolution of 0.001 mm , while TASP software 4.6x (Rinntech Inc., Germany) was used for cross-dating the tree-ring chronology. The biological growth trend in the raw tree-ring width measurements was detrended first by a negative exponential curve and then by linear regression using the ARSTAN program (chronologies of sites) and dprl package of R (regional chronology). Standard chronology (STD) was used for relationship analysis (Tables S1, S2, and Fig. 2).

2.4. Data analysis

The mean monthly temperature (T), precipitation (P), and scPDSI were used for the climate-growth relationship analysis. The correlation

Table 1
Information of sampling sites.

Sample site	XY	HL	YC	FX	ZD	MZ	SM
Latitude(°N)	35.33	35.78	35.98	36.08	36.60	37.86	38.80
Longitude(°E)	108.80	108.99	110.96	109.63	108.88	110.19	110.63
Altitude(m)	1486	1265	1159	1157	1463	1096	1220
Slop (°)	NE48	NE45	NE33	N48	NW46	N20	NE34
Mean height (m)	20.56	20.40	21.72	19.38	21.88	5.74	17.13
Mean DBH (cm)	23.83	23.60	18.37	23.31	18.29	10.66	9.20
Time period	1975–2018	1968–2018	1966–2018	1968–2018	1975–2018	1984–2018	1983–2018

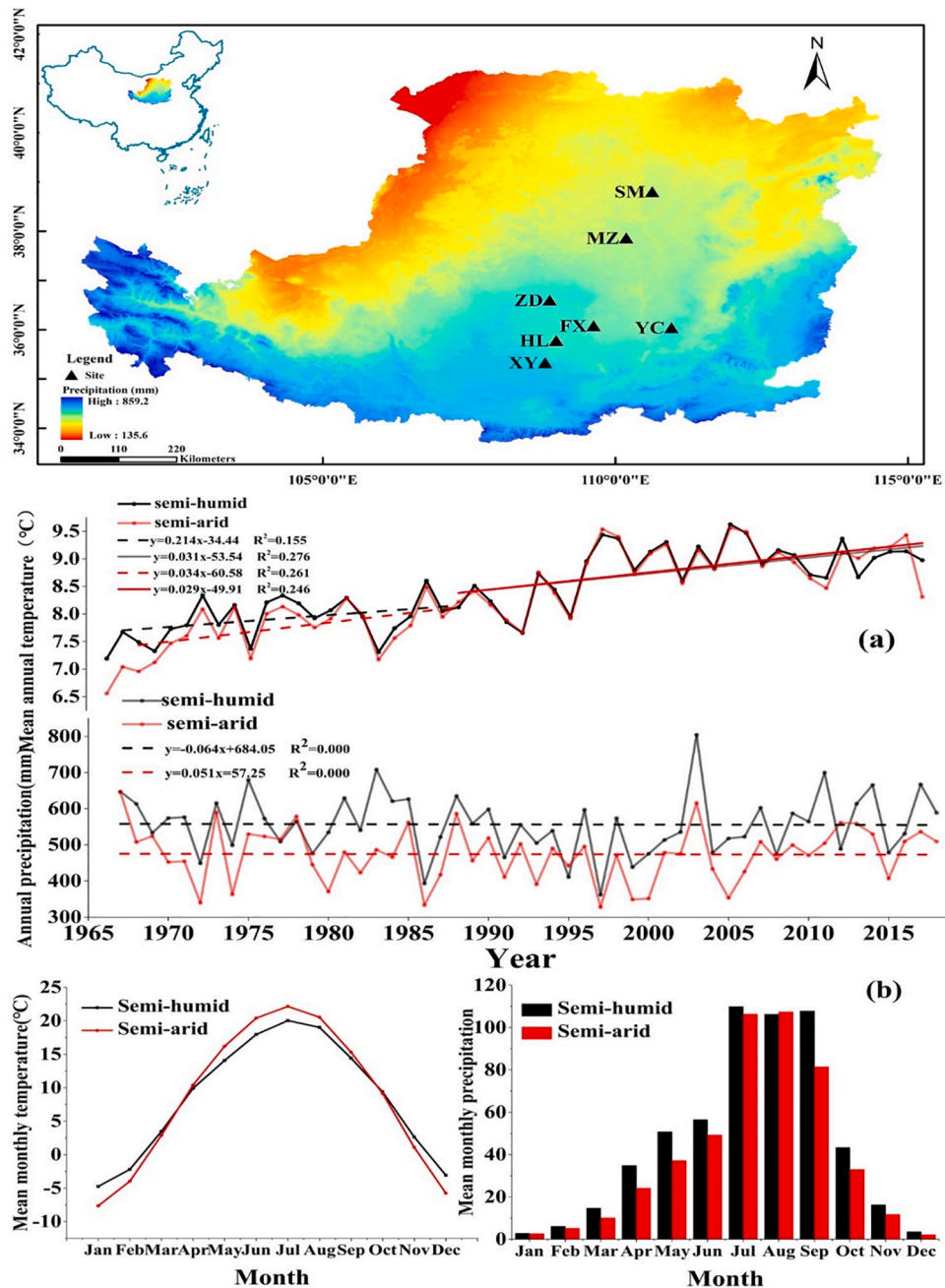


Fig. 1. Location of sampling sites in the Loess plateau along a precipitation gradient and the mean annual/monthly temperature and precipitation from sites in semi-humid and semi-arid regions, respectively (a) Mean annual temperature and annual precipitation; (b) mean monthly precipitation and mean monthly temperature averaged from 1967 to 2018 using Origin 2017.

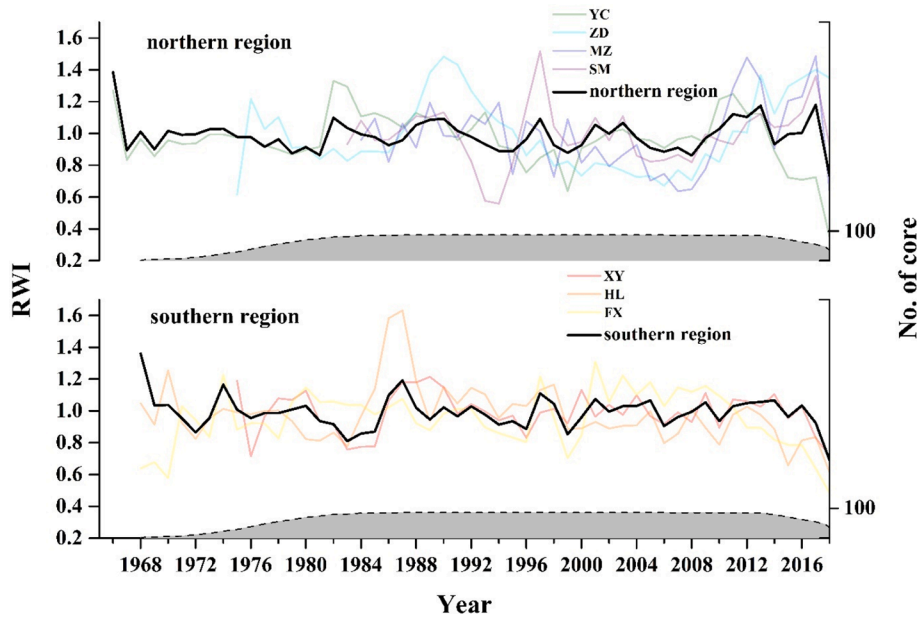


Fig. 2. Standard ring-width chronologies of *Pinus tabulaeformis* in the southern and northern regions of the Loess plateau, northwest China. The black line represents the regional chronologies of southern and northern regions. The dotted line represents the number of cores per year used for chronology built.

analysis between climate factors and the tree ring width index (RWI) was performed from April of previous year to October of current year during 1968–2018 by DENDROCLIM2002 (Biondi and Waikul, 2004). Meanwhile, the spatial pattern of drought response was analyzed by cluster analysis using the RWI-scPDSI correlation coefficient to determine the different drought response patterns among the sampling sites. In addition, the mutation points of temperature and precipitation over the LP were identified by the Mann-Kendall test using MATLAB 2016 (Math Works Inc., Natick, MA, USA). Then, Pearson correlation were performed to analyze the change in the climate-growth relationship before and after the mutation points. Moving correlation were further performed to observe the relationship change over the past fifty years.

High tree resilience is composed of low resistance and high recovery (Lloret et al., 2011). Therefore, tree resistance (R_t) and recovery (R_c), were calculated for all individual trees at each site using the following formulas (Fang and Zhang 2019).

$$R_t = \frac{Dr}{Pre\ Dr} \quad (1)$$

$$R_c = \frac{Post\ Dr}{Dr} \quad (2)$$

Dr represents the RWI in the year of drought; Pre and $Post\ Dr$ indicate the mean RWIs during the four years before and after the drought, respectively.

The first-order differences of scPDSI (mean value averaged from April to September of current year) were calculated from 1967 to 2018, and the values that are 1.5 times the standard deviation below the mean value were considered as extreme drought years. The R_t and R_c of each tree core in the drought years were calculated. Furthermore, we considered that a tree with an $R_t > 1$ (the ratio of drought year RWI and that of four years before) can resist the disturbance, while a tree with an $R_c > 1$ (the ratio of four years after drought RWI and that of drought year) can recover from the event. Meanwhile, the proportion of $R_t > 1$ and $R_c > 1$ of individual trees at each site was computed. All significant differences were determined using nonparametric tests.

3. Results

3.1. Relationships between tree-ring width chronology and climate factors

Site-by-site correlations between RWI and T or P showed different

patterns (Fig. S1). In general, significant negative correlations with temperature were sporadically observed in the HL, YC, and ZD sites, while positive relationships with precipitation were detected in the ZD, MZ, and SM sites.

The relationships with scPDSI presented a clear spatial pattern. The seven sampling sites were statistically clustered into the southern (XY, HL, and FX) and northern (YC, ZD, MZ, and SM) regions according to the strength of the correlation coefficients between RWI and scPDSI (Fig. 3). In the southern region, RWI was negatively correlated with scPDSI, especially in April and May of the current and previous year in FX. In contrast, tree growth was significantly positive with scPDSI in the northern region (except from March to June of the current year in the MZ and April to July of the previous year in YC). Hence, in the following

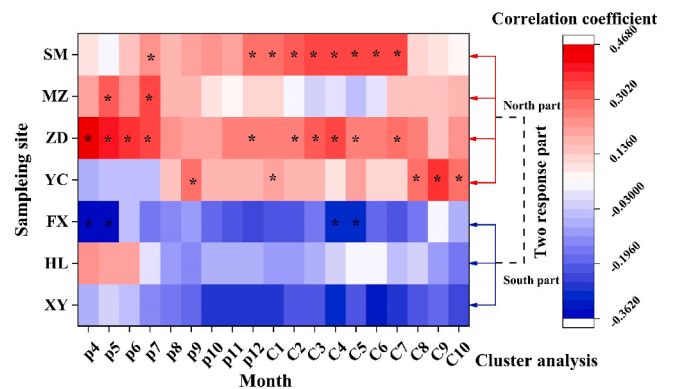


Fig. 3. Correlations between RWI and scPDSI in seven sites. “*” represents the level of significance at $P < 0.05$ level, p: previous year, C: current year. 19 months (P4-C10) were used for analysis. The cluster analysis of correlation coefficients between PDSI and RWI was carried. The “red” and “blue” arrows indicate that drought response is divided into two different patterns. The p4-p5 (the early growing season of the previous year), p6-p7 (the middle growing season of the previous year), p8-p10 (the late growing season of the previous year), p11-C3 (non-growing season), C4-C5 (the early growing season of the current year), C6-C7 (the middle growing season of the current year), C8-C10 (the late growing season of the current year). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis, we mainly focused on the characteristics of the combined southern and northern regions, ignoring the specific values for each sampling site.

3.2. The climate-growth relationship over the past fifty years in the LP

According to the Mann-Kendall test, two statistics intersect above the significance level of 0.05 in 1989, and it was identified that 1989 was the year where a mutation point of temperature occurred (Fig. S2). However, no significant mutation points for precipitation were observed over the past fifty years. After temperature mutation, the correlation coefficients between temperature and RWI decreased in both southern and northern regions. However, these changes were not significant (Fig. 4). Moving correlation analysis showed that the relationship between tree growth and temperature in autumn and winter changed from positive to negative in the southern region over the past fifty years (Fig. 5). Moreover, more negative correlations with precipitation were observed (October of the previous year; January and June of the current year) (Fig. 4), indicating that precipitation had a stress effect on tree growth after the mutation. In the northern region, tree growth was negatively correlated with temperature in spring and autumn, but positively correlated with precipitation in summer and autumn as warming over

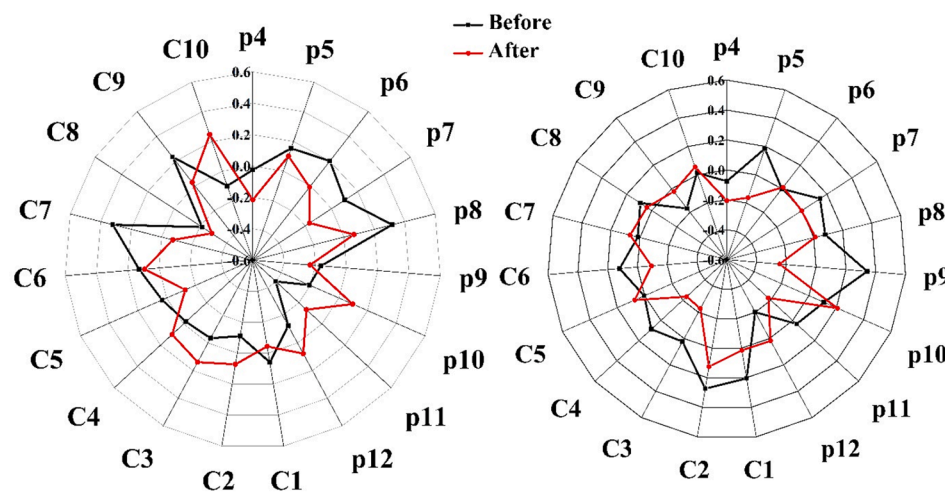
past fifty years (Fig. 5). This shows that the growth of trees in the northern region was promoted by precipitation but was stressed by temperature after warming.

3.3. The spatial resilience of *Pinus tabulaeformis* on the LP

According to the scPDSI, extreme drought events were identified in 1986, 1998, 2004, and 2014 (Fig. S3). Tree resilience showed a significantly different pattern between the southern and northern regions (Fig. 6). R_t in the northern region was significantly lower than that in the southern region in each drought year, and was more sensitive to the drought effect; there was more serious growth decline when drought occurred in the northern region. However, the mean value of R_c and the proportion of $R_c > 1$ in the northern region was significantly higher than those in the southern region (except in 1998 and 2004), indicating that the recovery of trees in the northern region was strong than that in southern region after drought.

In addition, according to the proportion variation analysis of $R_t > 1$ and $R_c > 1$ in the temporal dimension of the southern and northern regions, we found that the proportion variation trend of $R_t > 1$ and $R_c > 1$ of *Pinus tabulaeformis* in the southern and northern regions are completely opposite, and converse variation trend of $R_t > 1$ and $R_c > 1$

Temperature



Precipitation

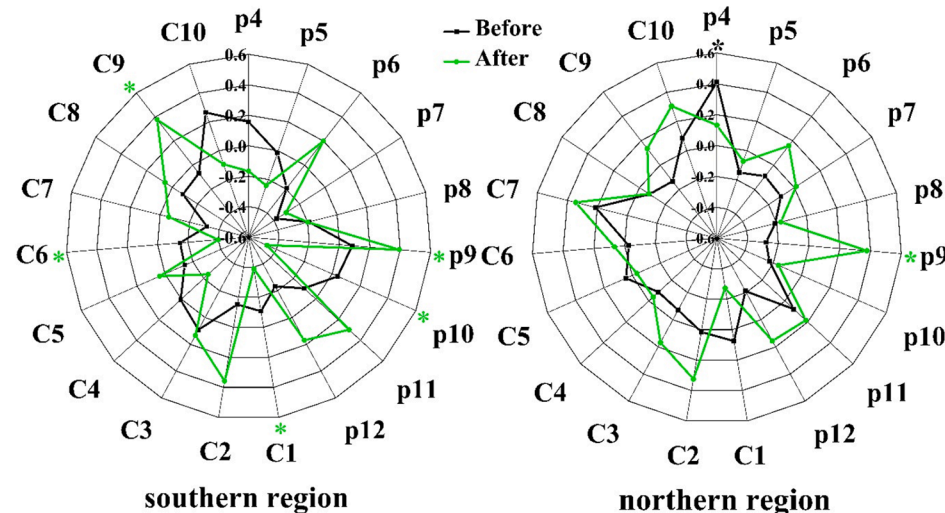


Fig. 4. Response patterns before and after temperature mutation in the northern and southern regions of the Loess plateau, northwest China. The red/green line represent the correlation between RWI and temperature/precipitation after the mutation, while the black line represents the correlation between RWI and temperature/precipitation before the mutation; “*” represents significance at the $P < 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

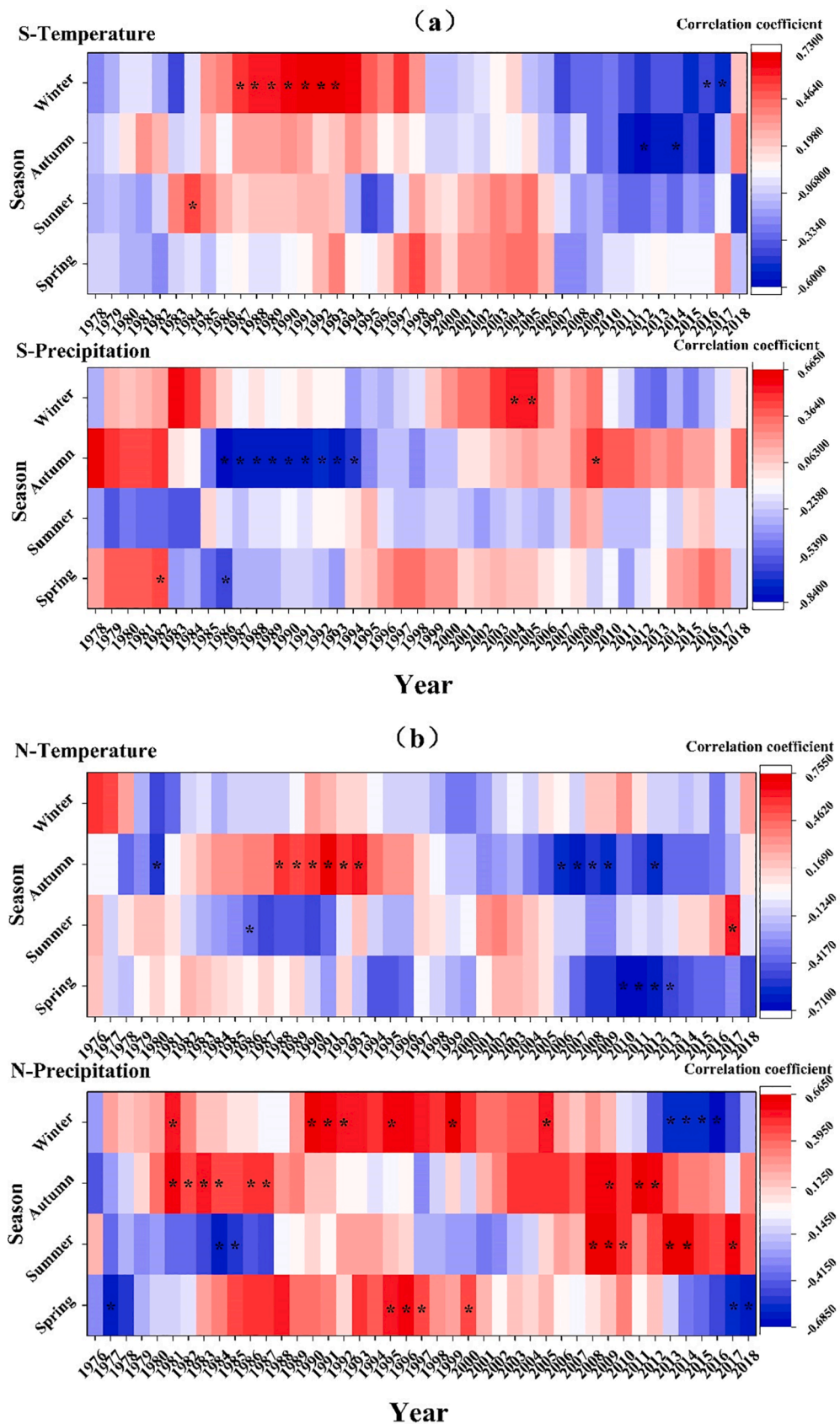


Fig. 5. Moving correlation results between RWI and seasonal climate factors (a) southern region; (b) northern region. Moving window: 11 years; “*” represents the level of significance at P < 0.05.

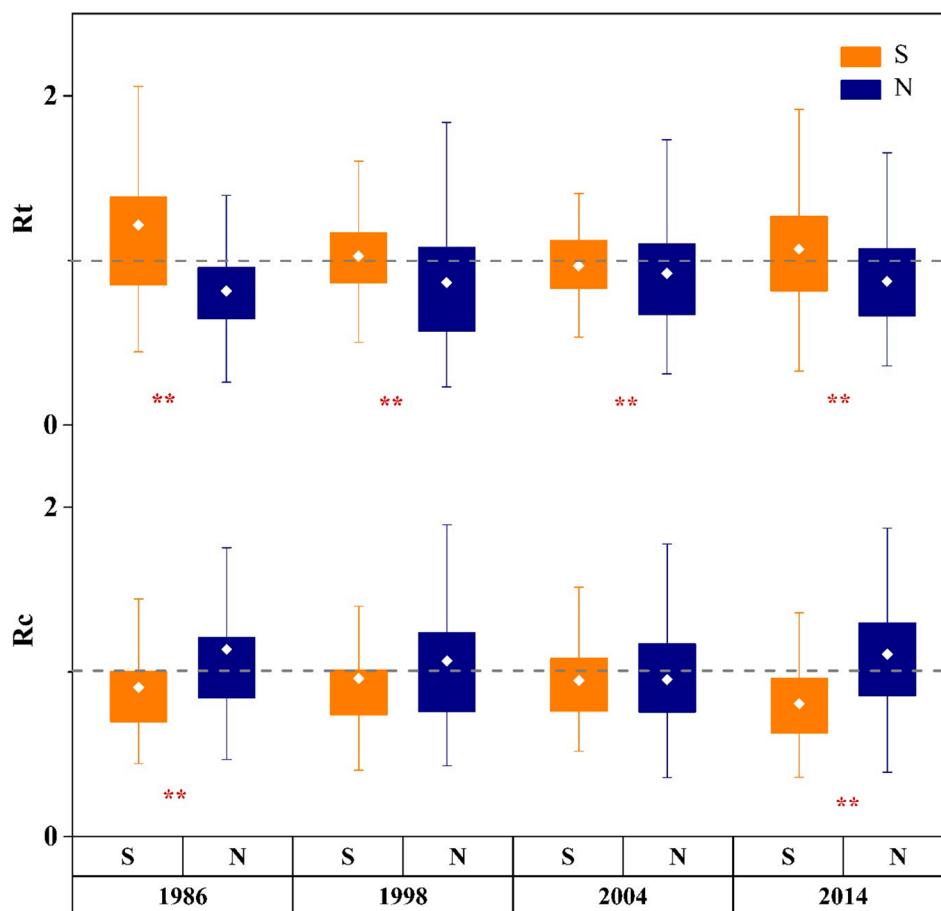


Fig. 6. Boxplots of resistance (R_t) and recovery (R_c) for individual trees in different drought events in the northern and southern regions of the Loess plateau, northwest China S: southern region; N: northern region; Dotted line represents R_t or $R_c = 1$; The boxes indicate 25th and 75th quartiles; the diamond in the middle of the box indicates the medium values; “**” represents the level of significance of $P < 0.01$.

also appeared within southern or northern region (Fig. 7). The proportion of trees with $R_t > 1$ in the southern region significantly decreased first and then increased (58.33%, 52.33%, 41.86%, 50.63%), but the proportion of $R_c > 1$ significantly increased first and then decreased (27.06%, 29.07%, 36.05%, and 20.83%) in the four extreme drought years. In the northern region, the proportion of trees with $R_t > 1$ first increased and then decreased (20.51%, 31.58%, 35.96%, and 29.36%), and those with $R_c > 1$ decreased first and then increased to the maximum (56.25%, 46.49%, 37.72%, and 52.88%), and a larger proportion of trees had $R_c > 1$ than $R_t > 1$ in each drought year in the northern region.

4. Discussion

4.1. Relationship between radial growth and climate factors

The climate-growth relationship in this study showed that trees in the semi-humid region of the LP were negatively correlated with temperature throughout the year. This is because the mean annual temperature in the semi-humid region (i.e. YC and HL sites) was higher than that in the semi-arid region (MZ, SM, and ZD sites) (Fig. 1). Therefore, increased soil evaporation and vegetation respiration, which deplete soil moisture, result in drought stress which possibly can lead to root growth inhibition and reduced water and nutrient uptake, and cambial activity (Xu et al., 2012a), thus, reducing the radial tree growth. However, tree radial growth tended to be positively correlation with precipitation in semi-arid region. Semi-arid regions have less precipitation and high temperatures in summer (Fig. 1), thus water deficiency and increased

evapotranspiration rate due to high temperatures in spring and summer reduce the storage level of carbohydrates and the growth of ring width (Delpierre et al., 2009), which can affect growth in the subsequent year (Gruber et al., 2012). In contrast, precipitation in the spring in the semi-arid region not only reduced the evaporation rate by adding to the cloud cover, but also provided available water for growth, which is conducive to cambium cell division and early wood formation during the growth season in arid regions (Liu et al., 2004). Meanwhile, high summer humidity reduces evaporative water losses in plants, thus indirectly contributing to carbohydrate storage and compensating for the loss of available water due to high temperatures in summer (Keyimu et al. 2021). Our results are consistent with those of *Robinia pseudoacacia* Linn. in the LP, which showed that the trees in semi-humid and semi-arid regions are strongly affected by thermal factors and hydroclimatic factors, respectively (Keyimu et al. 2021).

In addition, the cluster analysis of the correlation coefficient between scPDSI and RWI illustrates that the drought response of the seven sites can be divided into two patterns. A negative correlation was observed between growth and scPDSI in the southern region, whereas a positive correlation was observed in the northern region of the LP. All sample sites in the southern region are located in semi-humid region of the LP, where humid environment conditions had adverse effects on the growth of *Pinus tabulaeformis* (Fig. 3). This is consistent with a Mediterranean study, where a negative correlation appeared in the wettest stands of *J. thurifera* because of the effect of cloud cover or over-wetting on carbon storage depletion for growth (Desoto et al. 2014). First, the humid environment in the southern region of the LP can cause the tree root system to be anoxic and restrain its respiration due to the presence of

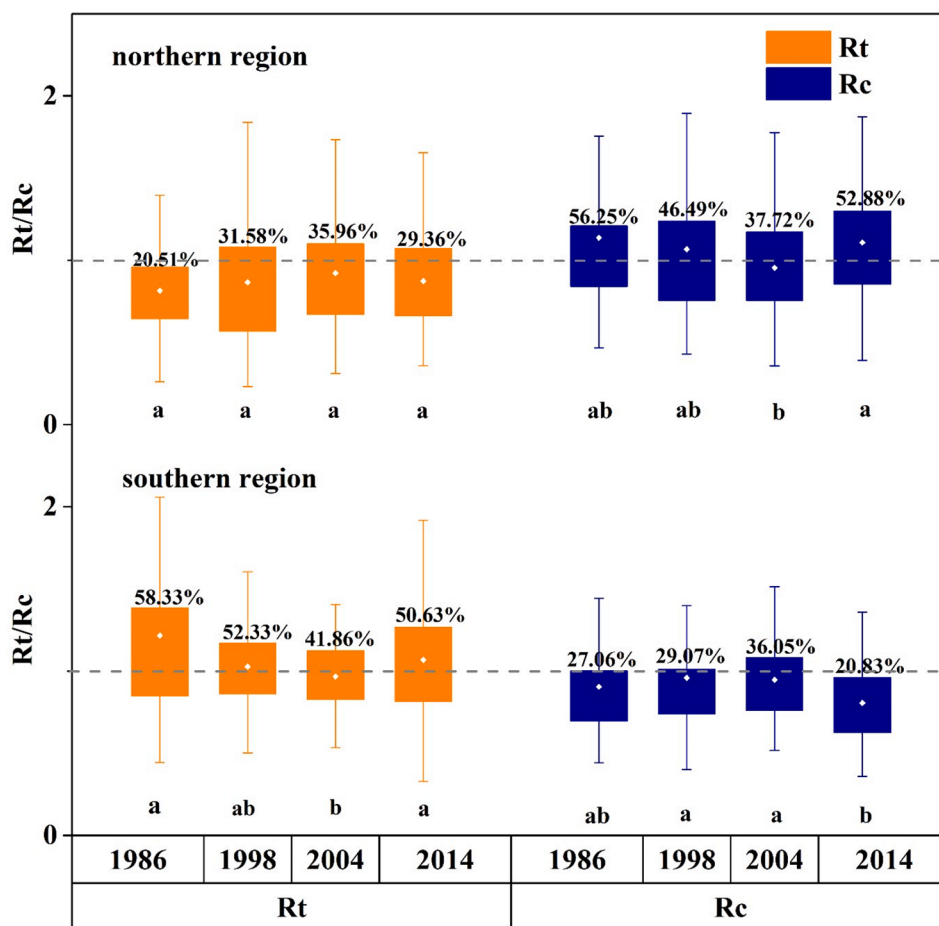


Fig. 7. Boxplots of resistance (Rt) and recovery (Rc) variation trend for individual trees in four drought events of northern and southern regions of the Loess plateau, northwest China. The dotted line represents R_t or $R_c = 1$; the boxes indicate 25th and 75th quartiles; the diamond in the middle of the box indicates the medium values; different lowercase letters represent the level of significance at $P < 0.05$.

supersaturated water (Kramer et al., 2008). As precipitation reduces the temperature, the time and duration of cambium activity would be delayed and shortened because resuming the activities of the cambium are determined by temperature to a great extent (Griar et al., 2006). Rossi et al. (2016) illustrated that the temperature from April to May in spring was a crucial climatic factor in inducing xylem growth of several coniferous trees in the northern hemisphere. Research on temperate tree species demonstrated that extremely low temperatures in late spring slow down the growth rate of most tree species (Vanoni et al., 2016). In the northern region, drought was the main factor affecting tree growth, especially during the early and middle growth seasons. Although some studies have shown that the initiation of cambium is mainly influenced by temperature (Oribe and Kubo 1997), drought inhibits cell division, thereby affecting the growth of trees and even delaying the growing season (Eilmann et al., 2011). In addition, soil moisture deficiency in spring and summer results in a decrease in available water and an earlier end time in cell division (Gruber et al., 2009; Pasho et al., 2012). Drought limits the development of twigs and buds in the early growth season of the previous year, causing a decrease in leaf area and auxin required for cambium cell division in the current year because auxin mainly comes from buds or twigs (Hansen and Beck 1994; Kagawa et al., 2006). On the other hand, water deficiency can restrict cell expansion due to the loss of cell turgor, preventing cell metabolism and inhibiting tree growth (Rossi et al., 2006), thus limited the growth of trees in the northern region in the LP.

4.2. The relationship between radial growth and climate factors as temperature rising

Climate change has become an important driving force affecting the ecological and physiological processes of forest ecosystems in northwest China (Li et al., 2015). Some studies confirmed that tree growth changed the response to climate in recent decades, and the significance shifted over time (Briffa et al., 1998; Solberg et al., 2002). According to our study, the stress effect of precipitation on tree growth increased in the southern region of the LP. On the basis of the results of the drought response pattern, the humid environment conditions had a stress effect on trees in the southern region (Fig. 3). More precipitation increased soil moisture; however, root activity is restrained under the condition of supersaturated water, thus limiting the formation of wide rings and inhibiting growth (Kramer et al. 2008). Meanwhile, precipitation caused the lowering of temperature at the end of growing season (October of previous year), resulting in an adverse impact on the formation of latewood (Liu et al., 2016; Ping et al., 2015). Winter precipitation (January of current year) can cause freezing injury to plant tissue and subsequently affect its growth. In the northern region, the negative correlation between growth and temperature in spring and autumn was significantly increased, but the positive correlation with precipitation in summer and autumn was enhanced. Spring and autumn are the beginning and end of the growing season, and an increase in temperature leads to the evaporation of soil water in the arid northern region, resulting in the delayed resumption of cambium activity and advancing the end time, thus leading to the short growing season (Eilmann et al. 2011). Meanwhile, warming is predicted to enhance aridity,

exacerbating soil moisture deficit with the increase in vapor pressure deficit and causing a decline in growth (Giorgi and Lionello 2008; IPCC 2013), especially in the semi-arid region; thus, the correlation shifts to a stress effect on growth. The increased positive correlation with precipitation was because of more frequent water deficiency in summer and autumn, which was caused by the temperature rise, rendered tree growth more dependent on precipitation supplementation (Maaten-Theunissen et al., 2012). Water availability determined tree growth; thus, growth in the northern region has a stronger dependence on precipitation, and the correlation has changed.

In recent years, studies have shown that the extension of the growth season has promoted the growth of vegetation in the northern hemisphere under climate warming (Piao et al., 2007; White et al., 1999). However, the growth of vegetation on the LP is limited by drought due to rising temperature (Zhi et al., 2010). Drought was not alleviated after warming, and the main limiting factors did not change. Some studies have shown that drought stress caused by warming in the 20th century affected the growth of Pinaceae, considering that drought is an important factor stressing carbon absorption in the forests of northern America (Barber et al., 2000). In China, the basal area increment (BAI) of *Pinus koraiensis* decreased significantly with increasing temperature during the growing season (Wang et al. 2019). The growth of *Pinus massoniana* in the south and *Pinus tabulaeformis* in central China were negatively correlated with temperature (Duan et al., 2013; Liu et al., 2017). In our study, *Pinus tabulaeformis* growth on the LP was also limited by warming drought, indicating that the conifer species may show growth decline under climate warming.

In addition, climate records showed a significant increase in temperature and a slight decrease in precipitation across the LP of China, leading to a trend toward warmer and drier climates (Wen et al., 2018). Although precipitation is very important, soil moisture and plant transpiration increase because of rapid temperature rise (Adams et al., 2009). On the one hand, warming drought occurs when the temperature reaches a certain threshold, aggravating moisture deficiency, especially in the arid northern region. On the other hand, the rapid temperature rise masked the effect of precipitation, and rainfall was not equal to the growth rate of trees (Jiao et al. 2016). Warming drought caused by the inequality of precipitation and warming has been becoming the main stress factor in the LP under climate change, especially in the northern *Pinus tabulaeformis*, as the main coniferous tree species for afforestation in the LP, may decline in growth.

4.3. Resilience spatial pattern and change in *Pinus tabulaeformis* in the LP

In recent years, dieback and forest mortality have been attributed to warming-induced drought (Allen et al., 2010; Mantgem et al., 2009). Moreover, drought intensity is usually considered the main driver causing a reduction in growth. Trees can adapt to the environment. They are not sensitive to long drought conditions but they respond to sudden extreme drought (Anderegg et al., 2015). Therefore, using the research on the proportion of $R_t > 1$ and $R_c > 1$ of individual trees during the extreme drought years, we found that the trees resistance of the northern region to drought was lower than that of the southern region. A study confirmed that communities have experienced a long history of low precipitation in an arid ecosystem, consequently leading to low drought resistance (O'Brien et al., 2017). In addition, trees face growth decline when drought stress exceeds a certain threshold, as severe drought-depleted individual reserves result in canopy defoliation and growth ring reduction (Mori et al., 2013). Trees in the northern region with low precipitation and aggravated drought stress may show substantially inhibited growth, limiting its resistance (Zhang and Quan, 2019). However, the number of $R_c > 1$ in the northern region was significantly higher than that in the southern region, indicating that the northern *Pinus tabulaeformis* has a strong recovery after drought. Trees growing in arid areas originally have strong drought adaptability and established mechanisms to accelerate the recovery of growth when drought ends

(McNulty et al., 2014). This difference in resilience between the southern and northern regions is consistent with a study in the northern hemisphere that stated that conifers in arid regions have stronger recovery, and resilience of regional forests in drought events is a trade-off between R_t and R_c . Some trees have stronger R_t , while others have higher R_c to recover from drought (Li et al., 2020). Moreover, different mechanisms exist within widely distributed tree species such as conifers to deal with water deficit (Brodrribb et al., 2012).

Indeed, post-drought recovery is often inversely correlated with drought resistance (Hoover et al., 2016). Strong resilience was confirmed to be composed of low R_t and high R_c (Lloret et al. 2011). Therefore, we found that the change in resilience in the southern and northern regions was completely divergent according to the combination of the changes in R_t and R_c in the four drought events (Fig. S4). The change in resilience in the southern region first increased to its maximum in 2004 and then decreased. In the northern region, the proportion of trees with $R_c > 1$ was greater than $R_t > 1$ in each drought event; thus, the change in resilience showed a process of first decreasing to the minimum value in 2004 and then increasing to the maximum value through drought events. The opposite change in resilience between the northern and southern regions indicated different responses to drought events, showing that the growth of trees in the wetter south is more likely to be inhibited by extremely drought events under warming because southern *Pinus tabulaeformis* lacks mechanisms to recover from dry environments (McNulty et al. 2014). Meanwhile, the spatial heterogeneity of forest landscape and environmental factors, such as diurnal temperature range, tree age, growth consistency, and health, also leads to divergent resilience among forests (Fang and Zhang 2019). Previous studies have shown that resilience varies according to climatic and geographical conditions (Anderegg and Hillerislambers 2016; Clark et al., 2016). Research on pine trees along the precipitation gradient in the Eastern Mediterranean showed higher resilience to drought through eco-physiological adjustments in sustaining trees under dry conditions than in humid conditions (Helman et al., 2017). Gazol (2017) proved that R_t increases and R_c decreases as humidity increases, and that both are partly dependent on the storage of trees, which will have a trade-off between drought resistance and recovery. In addition, our results also confirmed that variability of resilience in forest under climate change. A study in Minnesota indicated that the resilience of regional trees was not a static spatial pattern with an increase in temperature and drought events (Gazol et al. 2018; Lucash et al., 2017). The growth of trees on the LP may decrease under frequent warm-induced drought events, especially in the southern region.

5. Conclusion

Warming-induced drought has become the main limiting factor affecting tree growth in the LP of China. We studied the radial growth of *Pinus tabulaeformis* plantations at seven sites along the precipitation gradient in the LP. The results demonstrated that the drought response of trees was divided into the southern and northern regions, and the effects of warming and extreme drought events in the two regions are different. Humid environment conditions had adverse effects on tree growth in the southern region, whereas drought in the early and middle growing seasons (spring and summer) was the main limiting factor for the growth of *Pinus tabulaeformis* in the northern region. In addition, precipitation has a stress effect on tree growth in the southern region after warming, while the northern region was more dependent on precipitation. However, the temperature-growth relationship in both regions weakened or became negative as the temperature rising over the fifty years. Therefore, the growth inhibition of *Pinus tabulaeformis* plantation in the northern region of the LP may be intensified under continuous warming. Resilience analysis revealed the tendency of resilience in the southern and northern regions was divergent because of the trade-off between trees in drought to adapt to various environments. The trees in the northern region have strong adaptability to frequent

drought, while trees in the southern region are vulnerable and cannot recover from frequent droughts under warming. Based on our study, there are different climate-growth patterns and resilience in the LP, thus future different forest management strategies should be formulated to inhibit productivity reduction and tree mortality. Furthermore, although our study clarified the different climate-growth patterns in the LP, a clear division of southern-northern region not be defined. We recommend that the forest management study of the LP in the future should focus on defining the boundary between the southern and northern regions, so as to give a clear southern-northern scope on the basis of our advices of different forest management and to provide more accurate suggestions for the future implementation of forest management policies in the LP.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2021.119642>.

References

- Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J.C., Breshers, D.D., Zou, C.B., Troch, P.A., Huxman, T.E., 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proc. Natl. Acad. Sci.* 106 (17), 7063–7066. <https://doi.org/10.1073/pnas.0901438106>.
- Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshers, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.* 259 (4), 660–684. <https://doi.org/10.1016/j.foreco.2009.09.001>.
- Anderegg, L.D.L., HilleRisLambers, J., 2016. Drought stress limits the geographic ranges of two tree species via different physiological mechanisms. *Glob. Change Biol.* 22 (3), 1029–1045.
- Anderegg, W.R.L., Schwalm, C., Biondi, F., Camarero, J.J., Koch, G., Litvak, M., Ogle, K., Shaw, J.D., Shevliakova, E., Williams, A.P., Wolf, A., Ziaco, E., Pacala, S., 2015. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* 349 (6247), 528–532. <https://doi.org/10.1126/science.aab1833>.
- Bai, M., Mo, X., Liu, S., Hu, S., 2019. Contributions of climate change and vegetation greening to evapotranspiration trend in a typical hilly-gully basin on the Loess Plateau, China. *Sci. Total Environ.* 657, 325–339. <https://doi.org/10.1016/j.scitotenv.2018.11.360>.
- Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405 (6787), 668–673. <https://doi.org/10.1038/35015049>.
- Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Comput. Geosci.* 92 (3), 303–311. <https://doi.org/10.1016/j.cageo.2003.11.004>.
- Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.-J., Schall, P., Spathelf, P., Rock, J., 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scand. J. For. Res.* 24 (6), 473–482. <https://doi.org/10.1080/02827580903418224>.
- Briffa, K.R., Schweingruber, F., Jones, P., Osborn, T., Harris, I., Shiyatov, S., Vaganov, E. A., Grudd, H., 1998. Trees tell of past climates: But are they speaking less clearly today? *Philos. Trans. Royal Soc. London Series B Containing Papers of a Biological Character* 353 (1365), 65–73. <https://doi.org/10.1098/rstb.1998.0191>.
- Brodrribb, T.J., Pittermann, J., Coomes, D.A., 2012. Elegance versus speed: examining the competition between conifer and angiosperm trees. *International Journal of Plant Sciences - INT J PLANT SCI* 173 (6), 673–694. <https://doi.org/10.1086/666005>.
- Chen, H., Shao, M., Li, Y., 2008. Soil desiccation in the Loess Plateau of China. *Geoderma* 143 (1–2), 91–100. [0.1016/j.geoderma.2007.10.013](https://doi.org/10.1016/j.geoderma.2007.10.013).
- Chen, Y., Wang, K., Lin, Y., Shi, W., Song, Y.I., He, X., 2015. Balancing green and grain trade. *Nat. Geosci.* 8 (10), 739–741. <https://doi.org/10.1038/ngeo2544>.
- Clark, J.S., Iverson, L., Woodall, C.W., Allen, C.D., Zimmermann, N.E., 2016. The impact of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Glob. Change Biol.* 22 (7) n/a-n/a. [doi:10.1111/gcb.13160](https://doi.org/10.1111/gcb.13160).
- Cole, L.E.S., Bhagwat, S.A., Willis, K.J., 2014. Recovery and resilience of tropical forests after disturbance. *Nat. Commun.* 5 (1) <https://doi.org/10.1038/ncomms4906>.
- Delpierre, N., Soudani, K., Francois, C., Köstner, B., Pontailler, J.Y., Nikinmaa, E., Misson, L., Aubinet, M., Bernhofer, C., Granier, A., Grünwald, T., Heinesch, B., Bernard, L., Ourcival, J.M., Rambal, S., Vesala, T., Dufrière, E., 2009. Exceptional carbon uptake in European forests during the warm spring of 2007: A data-model analysis. *Glob. Change Biol.* 15, 1455–1474. <https://doi.org/10.1111/j.1365-2486.2008.01835.x>.
- Desoto, L., Varino, F., Andrade, J.P., Gouveia, C.M., Campelo, F., Trigo, R.M., Nabais, C., 2014. Different growth sensitivity to climate of the conifer *Juniperus thurifera* on both sides of the Mediterranean Sea. *Int. J. Biometeorol.* 58 (10), 2095–2109. <https://doi.org/10.1007/s00484-014-0811-y>.
- Dorado-Liñán, I., Piovesan, G., Martínez-Sancho, E., Gea-Izquierdo, G., Zang, C., Cañellas, I., Castagneri, D., Di Filippo, A., Gutiérrez, E., Ewald, J., Fernández-de-Una, L., Hornstein, D., Jantsch, M.C., Levanić, T., Mellert, K.H., Vacchiano, G., Zlatanov, T., Menzel, A., 2019. Geographical adaptation prevails over species-specific determinism in trees' vulnerability to climate change at Mediterranean rear-edge forests. *Glob. Change Biol.* 25 (4), 1296–1314. <https://doi.org/10.1111/gcb.2019.25.issue-410.1111/gcb.14544>.
- Duan, J., Zhang, Q.-B., Lv, L.-X., 2013. Increased variability in cold-season temperature since the 1930s in subtropical China. *J. Clim.* 26 (13), 4749–4757. <https://doi.org/10.1175/JCLI-D-12-00332.1>.
- Eilmann, B., Zweifel, R., Buchmann, N., Pannatier, E.G., Rigling, A., 2011. Drought alters timing, quantity, and quality of wood formation in Scots pine. *J. Exp. Bot.* 62 (8), 2763–2771. <https://doi.org/10.1093/jxb/erq443>.
- Engelbrecht, B.M.J., 2012. Plant ecology: Forests on the brink. *Nature* 491 (7426), 675–676. <https://doi.org/10.1038/nature11756>.
- Fan, Z.M., Li, J., Yue, T.X., 2012. Changes of climate-vegetation ecosystem in Loess Plateau of China. *Procedia Environ. Sci.* 13 (1), 715–720. <https://doi.org/10.1016/j.proenv.2012.01.064>.
- Fang, K., Gou, X., Chen, F., D'Arrigo, R., Li, J., 2010. Tree-ring based drought reconstruction for the Guijiu Mountain (China): linkages to the Indian and Pacific Oceans. *Int. J. Climatol.* 30 (8), 1137–1145. <https://doi.org/10.1002/joc.1974>.
- Fang, K., Gou, X., Chen, F., Liu, C., Davi, N., Li, J., Zhao, Z., Li, Y., 2011. Tree-ring based reconstruction of drought variability (1615–2009) in the Kongtong Mountain area, northern China. *Global Planet. Change* 80–81 (Jan.), 190–197. <https://doi.org/10.1016/j.gloplacha.2011.10.009>.
- Fang, O., Zhang, Q.-B., 2019. Tree resilience to drought increases in the Tibetan Plateau. *Glob. Change Biol.* 25 (1), 245–253.
- FAO, 2020. State of the world's Forests 2020 (SOFO): FORESTS, BIODIVERSITY AND PEOPLE. Food and Agriculture Organization of the United Nations. <http://www.fao.org/3/ca8985en/CA8985EN.pdf>.
- Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C. S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev. Ecol. Syst.* 35 (1), 557–581. <https://doi.org/10.1146/annurev.ecolsys.35.021103.105711>.
- Fritts, H.C., 1976. *Tree Rings and Climate*. *entific American* 226 (5), 567.
- Fritts, H.C., Swetnam, T.W., 1989. Dendroecology: A tool for evaluating variations in past and present forest environments. *Adv. Ecol. Res.* 19 (4), 111–188. [https://doi.org/10.1016/s0065-2504\(08\)60158-0](https://doi.org/10.1016/s0065-2504(08)60158-0).
- Gao, L., Gou, X., Deng, Y., Wang, Z., Gu, F., Wang, F., 2018. Increased growth of Qinghai spruce in northwestern China during the recent warming hiatus. *Agric. For. Meteorol.* 260–261, 9–16. <https://doi.org/10.1016/j.agrformet.2018.05.025>.
- Gazol, A., Camarero, J.J., Vicente-Serrano, S.M., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., Sangüesa-Barreda, G., Novak, K., Rozas, V., Tiscar, P.A., Linares, J.C., Martín-Hernández, N., Martínez del Castillo, E., Ribas, M., García-González, I., Silla, F., Camisón, A., Génova, M., Olano, J.M., Longares, L.A., Hevia, A., Tomás-Burguera, M., Galván, J.D., 2018. Forest resilience to drought varies across biomes. *Glob. Change Biol.* 24 (5), 2143–2158. <https://doi.org/10.1111/gcb.2018.24.issue-510.1111/gcb.14082>.
- Gazol, A., Camarero, J.J., Anderegg, W.R.L., Vicente-Serrano, S.M., 2017. Impacts of droughts on the growth resilience of Northern Hemisphere forests. *Glob. Ecol. Biogeogr.* 26 (2), 166–176. <https://doi.org/10.1111/gcb.2017.26.issue-210.1111/gcb.12526>.
- Gazol, A., Camarero, J.J., Gutiérrez, E., Popa, I., Andreu-Hayles, L., Motta, R., Nola, P., Ribas, M., Sangüesa-Barreda, G., Urbinati, C., Carrer, M., Vetaas, O., 2015. Distinct effects of climate warming on populations of silver fir (*Abies alba*) across Europe. *J. Biogeogr.* 42 (6), 1150–1162.
- Gentilesca, T., Camarero, J.J., Colangelo, M., Nole, A., Ripullone, F., 2017. Drought-induced oak decline in the western Mediterranean region: an overview on current evidences, mechanisms and management options to improve forest resilience. *IFOREST* 2017,10(-), 796–806.
- Gessner, U., Naeimi, V., Klein, I., Kuenzer, C., Klein, D., Dech, S., 2013. The relationship between precipitation anomalies and satellite-derived vegetation activity in Central Asia. *Global Planet. Change* 110 (pt.a), 74–87. <https://doi.org/10.1016/j.gloplacha.2012.09.007>.
- Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. *Global Planet. Change* 63 (2–3), 90–104. <https://doi.org/10.1016/j.gloplacha.2007.09.005>.

- Griar, J., Zupani, M., Ufar, K., Koch, G., Schmitt, U., Oven and Primo, 2006. Effect of Local Heating and Cooling on Cambial Activity and Cell Differentiation in the Stem of Norway Spruce (*Picea abies*). *Ann. Botany* 97(6), 943–951. doi:10.1093/aob/mcl050.
- Gruber, A., Baumgartner, D., Zimmermann, J., Oberhuber, W., 2009. Temporal dynamic of wood formation in *Pinus cembra* along the alpine treeline ecotone and the effect of climate variables. *Trees* 23 (3), 623–635. <https://doi.org/10.1007/s00468-008-0307-7>.
- Gruber, A., Pirkebner, D., Florian, C., Oberhuber, W., 2012. No evidence for depletion of carbohydrate pools in Scots pine (*Pinus sylvestris* L.) under drought stress. *Plant Biol. (Stuttg)* 14, 142–148. <https://doi.org/10.1111/j.1438-8677.2011.00467.x>.
- Guo, Mingming, Zhang, Yuandong, Liu, Shirong, Gu, Fengxue, Wang, Xiaochun, Li, Zongshan, Shi, Chunming, Fan, Zexin, 2019. Divergent growth between spruce and fir at alpine treelines on the east edge of the Tibetan Plateau in response to recent climate warming. *Agric. For. Meteorol.* 276–277, 107631. <https://doi.org/10.1016/j.agrformet.2019.107631>.
- Hansen, J., Beck, E., 1994. Seasonal changes in the utilization and turnover of assimilation products in 8-year-old Scots pine (*Pinus sylvestris* L.) trees. *Trees* 8, 172–182. <https://doi.org/10.1007/BF00196844>.
- He, M.H., Yang, B., Brauning, A., 2013. Tree growth-climate relationships of *Juniperus tibetica* along an altitudinal gradient on the southern Tibetan Plateau. *Trees* 27 (2), 429–439. <https://doi.org/10.1007/s00468-012-0813-5>.
- Helman, David, Lensky, Itamar M., Yakir, Dan, Osem, Yagil, 2017. Forests growing under dry conditions have higher hydrological resilience to drought than do more humid forests. *Glob. Change Biol.* 23 (7), 2801–2817. <https://doi.org/10.1111/gcb.2017.23.issue-7.10.1111/gcb.13551>.
- Hoover, David L., Knapp, Alan K., Smith, Melinda D., 2016. Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology* 95 (9), 2646–2656.
- IPCC, 2013. *Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (ed), pp. 1–30, Cambridge University Press, Cambridge.
- IPCC, 2018. *Global warming of 1.5 C: An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press, Cambridge.
- Jiang, Yuan, Zhang, Wentao, Wang, Mingchang, Kang, Muye, Dong, Manyu, Liang, Eryuan, 2014. Radial growth of two dominant montane conifer tree species in response to climate change in north-central China. *PLoS ONE* 9 (11), e12537. <https://doi.org/10.1371/journal.pone.0112537>.
- Jiao, Liang, Jiang, Yuan, Wang, Mingchang, Kang, Xinyu, Zhang, Wentao, Zhang, Lingnan, Zhao, Shoudong, 2016. Responses to climate change in radial growth of *Picea schrenkiana* along elevations of the eastern Tianshan Mountains, northwest China. *Dendrochronologia* 40, 117–127. <https://doi.org/10.1016/j.dendro.2016.09.002>.
- Kagawa, Akira, Sugimoto, Atsuko, Maximov, Trofim C., 2006. Seasonal course of translocation, storage and remobilization of ¹³C pulse-labeled photosynthate in naturally growing *Larix gmelinii* saplings. *The New Phytologist* 171 (4), 793–804. <https://doi.org/10.1111/nph.2006.171.issue-4.10.1111/j.1469-8137.2006.01780.x>.
- Keyimu, Maierdang, Li, Zongshan, Fu, Bojie, Chen, Weiliang, Wei, Jingshu, Jiao, Lei, Gao, Guangyao, Lü, Yihe, 2021. Spatial differences in the radial growth responses of black locust (*Robinia pseudoacacia* Linn.) to climate on the Loess Plateau, China. *Dendrochronologia* 67, 125832. <https://doi.org/10.1016/j.dendro.2021.125832>.
- Kienast, Felix, Schweingruber, Fritz Hans, Bräker, Otto Ulrich, Schär, Ernst, 1987. *Tree-ring studies on conifers along ecological gradients and the potential of single-year analyses*. *Can. J. For. Res.* 17 (7), 683–696.
- King, Gregory M., Gugerli, Felix, Fonti, Patrick, Frank, David C., 2013. Tree growth response along an elevational gradient: Climate or genetics? *Oecologia* 173 (4), 1587–1600. <https://doi.org/10.1007/s00442-013-2696-6>.
- Kramer, K., Vreugdenhil, S.J., Werf, D.C.V.D., 2008. Effects of flooding on the recruitment, damage and mortality of riparian tree species: A field and simulation study on the Rhine floodplain. *For. Ecol. Manage.* 255 (11), 3893–3903. <https://doi.org/10.1016/j.foreco.2008.03.044>.
- Li, X., Piao, S., Wang, K., Wang, X., Wang, T., Ciais, P., Chen, A., Lian, X., Peng, S., Peñuelas, J., 2020. Temporal trade-off between gymnosperm resistance and resilience increases forest sensitivity to extreme drought. *Nat. Ecol. Evol.* <https://doi.org/10.1038/s41559-020-1217-3>.
- Li, C., Zhang, C., Luo, G., Chen, X., Maisupova, B., Madaminov, A., Han, Q., Djenbaev, B., 2015. Carbon stock and its responses to climate change in Central Asia. *Glob. Change Biol.* 21 <https://doi.org/10.1111/gcb.12846>.
- Li, Jinbao, Chen, Fahu, Cook, Edward R., Gou, Xiaohua, Zhang, Yongxiang, 2010. Drought reconstruction for North Central China from tree rings: the value of the Palmer drought severity index. *Int. J. Climatol.* 27 (7), 903–909. [https://doi.org/10.1002/\(ISSN\)1097-008810.1002/joc.v27:710.1002/joc.1450](https://doi.org/10.1002/(ISSN)1097-008810.1002/joc.v27:710.1002/joc.1450).
- Liang, Eryuan, Leuschner, Christoph, Dulamsuren, Choimaa, Wagner, Bettina, Hauck, Markus, 2016. Global warming-related tree growth decline and mortality on the north-eastern Tibetan plateau. *Clim. Change* 134 (1–2), 163–176.
- Liu, Qiang, Fu, Yongshuo H., Zhu, Zaichun, Liu, Yongwen, Liu, Zhuo, Huang, Mengtian, Janssens, Ivan A., Piao, Shilong, 2016. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. *Glob. Change Biol.* 22 (11), 3702–3711. <https://doi.org/10.1111/gcb.2016.22.issue-1110.1111/gcb.13311>.
- Liu, Y., Lei, Y., Sun, B., Song, H., Sun, J., 2012. Annual precipitation in Liancheng, China, since 1777 AD derived from tree rings of Chinese pine (*Pinus tabulaeformis* Carr.). *Int. J. Biometeorology* 57. doi:10.1007/s00484-012-0618-7.
- Liu, Y., Shi, J., Shishov, V., Vaganov, E., Yang, Y., Cai, Q., Sun, J., Wang, L., Djansaitov, I., 2004. Reconstruction of May–July precipitation in the north Helan Mountain, Inner Mongolia since A.D. 1726 from tree-ring late-wood widths. *Chin. Sci. Bull.* 49 (4), 405–409. <https://doi.org/10.1007/BF02900325>.
- Liu, Y., Zhang, X., Song, H., Cai, Q., Li, Q., Zhao, B., Liu, H., Mei, R., 2017. Tree-ring-width-based PDSI reconstruction for central Inner Mongolia, China over the past 333 years. *Clim. Dyn.* 48 (3), 867–879. <https://doi.org/10.1007/s00382-016-3115-6>.
- Lloret, F., Keeling, E.G., Sala, A., 2011. Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* 120 (12), 1909–1920. <https://doi.org/10.1111/more.2011.120.issue-1210.1111/j.1600-0706.2011.19372.x>.
- Lu, Fei, Hu, Huifeng, Sun, Wenjuan, Zhu, Jiaojun, Liu, Guobin, Zhou, Wangming, Zhang, Quanfa, Shi, Peili, Liu, Xiuping, Wu, Xing, Zhang, Lu, Wei, Xiaohua, Dai, Limin, Zhang, Kerong, Sun, Yirong, Xue, Sha, Zhang, Wanjun, Xiong, Dingpeng, Deng, Lei, Liu, Bojie, Zhou, Li, Zhang, Chao, Zheng, Xiao, Cao, Jiansheng, Huang, Yao, He, Nianpeng, Zhou, Guoyi, Bai, Yongfei, Xie, Zongqiang, Tang, Zhiyao, Wu, Bingfang, Fang, Jingyun, Liu, Guohua, Yu, Guirui, 2018. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proc. Natl. Acad. Sci.* 115 (16), 4039–4044. <https://doi.org/10.1073/pnas.1700294115>.
- Lucash, Melissa S., Scheller, Robert M., J. Gustafson, Eric, R. Sturtevant, Brian, 2017. Spatial resilience of forested landscapes under climate change and management. *Landscape Ecol.* 32 (5), 953–969. <https://doi.org/10.1007/s10980-017-0501-3>.
- Maaten-Theunissen, M., Kahle, H.P., Maaten, E., 2012. Drought sensitivity of Norway spruce is higher than that of silver fir along an altitudinal gradient in southwestern Germany. *Ann. Forest Sci.* 70 (2), 185–193. <https://doi.org/10.1007/s13595-012-0241-0>.
- Mantgem, P., Stephenson, N., Byrne, J., Daniels, L., Franklin, J., Fulé, P., Harmon, M., Larson, A., Smith, J., Taylor, A. and Veblen, T. (2009) Widespread increase of Tree Mortality Rates in the Western United States. *Science* (New York, N.Y.) 323, 521–524. doi:10.1126/science.1165000.
- McNulty, S.G., Boggs, J.L., Sun, G., 2014. The rise of the mediocre forest: why chronically stressed trees may better survive extreme episodic climate variability. *New Forest.* 45:403–415 45, 403–415. <https://doi.org/10.1007/s11056-014-9410-3>.
- Merlin, M., Perot, T., Perret, S., Korboulewsky, N., Vallet, P., 2014. Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. *For. Ecol. Manage.* 339, 22–33. <https://doi.org/10.1016/j.foreco.2014.11.032>.
- Mori, Akira S., Furukawa, Takuya, Sasaki, Takehiro, 2013. Response diversity determines the resilience of ecosystems to environmental change. *Biol. Rev. Camb. Philos. Soc* 88 (2), 349–364. <https://doi.org/10.1111/brv.2013.88.issue-210.1111/brv.12004>.
- O'Brien, M.J., Engelbrecht, B.M.J., Joswig, J., Pereyra, G., Schuldt, B., Jansen, S., Kattge, J., Landhäusser, S.M., Levick, S.R., Preisler, Y., Väinänen, P. and Macinnis-Ng, C. (2017) A synthesis of tree functional traits related to drought-induced mortality in forests across climatic zones. *J. Appl. Ecol.* 54(6), 1669–1686. doi:https://doi.org/10.1111/1365-2664.12874.
- Oribe, Y., Kubo, T., 1997. Effect of heat on cambial reactivation during winter dormancy in evergreen and deciduous conifers. *Tree Physiol.* 17 (2), 81–87. <https://doi.org/10.1093/treephys/17.2.81>.
- Pan, Y., Birdsey, R.A., Phillips, O.L., Jackson, R.B., 2013. The structure, distribution, and biomass of the world's forests. *Annu. Rev. Ecol. Syst.* 44 (1), 593–622. <https://doi.org/10.1146/annurev-ecolsys-110512-135914>.
- Pasho, Edmond, Julio Camarero, J., Vicente-Serrano, Sergio M., 2012. Climatic impacts and drought control of radial growth and seasonal wood formation in *Pinus halepensis*. *Trees* 26 (6), 1875–1886. <https://doi.org/10.1007/s00468-012-0756-x>.
- Peng, S., Ding, D., Liu, W., 2019. 1 km monthly temperature and precipitation dataset for China from 1901 to 2017. *Earth Syst. Sci. Data* 11, 1931–1946. <https://doi.org/10.5194/essd-11-1931-2019>.
- Peng, Shouzhong, Gang, Chengcheng, Cao, Yang, Chen, Yunming, 2018. Assessment of climate change trends over the Loess Plateau in China from 1901 to 2100. *Int. J. Climatol.* 38 (5), 2250–2264. <https://doi.org/10.1002/joc.2018.38.issue-510.1002/joc.5331>.
- Piao, Shilong, Ciais, Philippe, Huang, Yao, Shen, Zehao, Peng, Shushi, Li, Junsheng, Zhou, Liping, Liu, Hongyan, Ma, Yuecun, Ding, Yihui, Friedlingstein, Pierre, Liu, Chunzhen, Tan, Kun, Yu, Yongqiang, Zhang, Tianyi, Fang, Jingyun, 2010. The impacts of climate change on water resources and agriculture in China. *Nature* 467 (7311), 43–51. <https://doi.org/10.1038/nature09364>.
- Piao, Shilong, Friedlingstein, Pierre, Ciais, Philippe, Viovy, Nicolas, Demarty, Jérôme, 2007. Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. *Global Biogeochem. Cycles* 21 (3), n/a–n/a. <https://doi.org/10.1029/2006GB002888>.
- Ping, R., Rossi, S., Gricar, J., Liang, E., Cufar, K., 2015. Is precipitation a trigger for the onset of xylogenesis in *Juniperus przewalskii* on the north-eastern Tibetan Plateau? *Ann. Bot.* 115 (4), 629–639. <https://doi.org/10.1093/aob/mcu259>.
- Qiu, Linjing, Wu, Yiping, Yu, Mengzhen, Shi, Zhaoyang, Yin, Xiaowei, Song, Yanni, Sun, Ke, 2021. Contributions of vegetation restoration and climate change to spatiotemporal variation in the energy budget in the loess plateau of china. *Ecol. Ind.* 127, 107780. <https://doi.org/10.1016/j.ecolind.2021.107780>.
- Rossi, Sergio, Anfodillo, Tommaso, Cufar, Katarina, Cuny, Henri E., Deslauriers, Annie, Fonti, Patrick, Frank, David, Gricar, Jožica, Gruber, Andreas, Huang, Jian-Guo, Jyske, Tuula, Kaspar, Jakub, King, Gregory, Krause, Cornelia, Liang, Eryuan, Mäkinen, Harri, Morin, Hubert, Nöjd, Pekka, Oberhuber, Walter, Prislán, Peter, Rathgeber, Cyrille B.K., Saracino, Antonio, Swidrak, Irene, Treml, Václav, 2016. Pattern of xylem phenology in conifers of cold ecosystems at the Northern

- Hemisphere. *Glob. Change Biol.* 22 (11), 3804–3813. <https://doi.org/10.1111/gcb.2016.22.issue-1110.1111/gcb.13317>.
- Rossi, S., Menardi, R., Anfodillo, T., 2006. Trephor: A new tool for sampling microcores from tree stems. *Iawa J.* 27 (1), 89–97. <https://doi.org/10.1163/22941932-90000139>.
- Solberg, Bård, Hofgaard, Annika, Hytteborn, Håkan, 2002. Shifts in radial growth responses of coastal *Picea abies* induced by climatic change during the 20th century, Central Norway. *Ecoscience* 9 (1), 79–88. <https://doi.org/10.1080/11956860.2002.11682693>.
- Song, Huiming, Liu, Yu, 2011. PDSI variations at Kongtong Mountain, China, inferred from a 283-year *Pinus tabulaeformis* ring width chronology. *J. Geophys. Res. (Atmos.)* 116 (D22), n/a–n/a. <https://doi.org/10.1029/2011JD016220>.
- Song, Huiming, Liu, Yu, Li, Qiang, Gao, Na, Ma, Yongyong, Zhang, Yanhua, Liang, Eryuan, 2014. Tree-ring based may–july temperature reconstruction since AD 1630 on the Western Loess Plateau, China. *PloS one* 9 (4), e93504. <https://doi.org/10.1371/journal.pone.0093504>.
- Song, Wenqi, Mu, Changcheng, Zhang, Yuandong, Zhang, Xu, Li, Zongshan, Zhao, Huiying, Wang, Xiaochun, 2020. Moisture-driven changes in the sensitivity of the radial growth of *Picea crassifolia* to temperature, northeastern Tibetan Plateau. *Dendrochronologia* 64, 125761. <https://doi.org/10.1016/j.dendro.2020.125761>.
- Vanhellemont, Margot, Sousa-Silva, Rita, Maes, Sybryn L., Van den Bulcke, Jan, Hertzog, Lionel, De Groot, Stefanie R.E., Van Acker, Joris, Bonte, Dries, Martel, An, Lens, Luc, Verheyen, Kris, 2018. Distinct growth responses to drought for oak and beech in temperate mixed forests. *Sci. Total Environ.* 650, 3017–3026. <https://doi.org/10.1016/j.scitotenv.2018.10.054>.
- Vanoni, M., Bugmann, H., Nötzli, M., Bigler, C., 2016. Drought and frost contribute to abrupt growth decreases before tree mortality in nine temperate tree species. *For. Ecol. Manage.* 382, 51–63. <https://doi.org/10.1016/j.foreco.2016.10.001>.
- Vicente-Serrano, Sergio M., Camarero, J. Julio, Azorin-Molina, Cesar, 2014. Diverse responses of forest growth to drought time-scales in the Northern Hemisphere. *Glob. Ecol. Biogeogr.* 23 (9), 1019–1030. <https://doi.org/10.1111/geb.2014.23.issue-910.1111/geb.12183>.
- Walck, J., Hidayati, S., Dixon, K., Thompson, K.E.N., Poschlod, P., 2011. Climate change and plant regeneration from seed. *Glob. Change Biol.* 17, 2145–2161. <https://doi.org/10.1111/j.1365-2486.2010.02368.x>.
- Wang, X., Pederson, N., Chen, Z., Lawton, K., Zhu, C., Han, S., 2019. Recent rising temperatures drive younger and southern Korean pine growth decline. *Sci. Total Environ.* 649, 1105–1116. <https://doi.org/10.1016/j.scitotenv.2018.08.393>.
- Wang, Yunqiang, Shao, Ming'an, Zhu, Yuanjun, Liu, Zhipeng, 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. *Agric. For. Meteorol.* 151 (4), 437–448. <https://doi.org/10.1016/j.agrformet.2010.11.016>.
- Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating palmer drought severity index. *J. Clim.* 17 (12), 2335–2351. [https://doi.org/10.1175/1520-0442\(2004\)017<2335](https://doi.org/10.1175/1520-0442(2004)017<2335).
- Wen, M., Cheng, D., Song, J., Zhang, G., Lai, W., Jiang, W., 2018. Impacts of climate change on aridity index and its spatiotemporal variation in the Loess Plateau of China, from 1961 to 2014. *Environ. Earth Sci.* 77 (4), 137. <https://doi.org/10.1007/s12665-018-7304-y>.
- White, M., Running, S., Thornton, P., 1999. The impact of growing-season length variability on carbon assimilation and evapotranspiration over 88 years in the eastern US deciduous forest. *Int. J. Biometeorology* 42, 139–145. doi:10.1007/s004840050097.
- Xu, Jinmei, Lu, Jianxiong, Bao, Fucheng, Evans, Robert, Downes, Geoffrey, Huang, Rongfeng, Zhao, Youke, 2012a. Cellulose microfibril angle variation in *Picea crassifolia* tree rings improves climate signals on the Tibetan plateau. *Trees-Struct Funct* 26 (3), 1007–1016. <https://doi.org/10.1007/s00468-012-0678-7>.
- Xu, Xiangtao, Piao, Shilong, Wang, Xuhui, Chen, Anping, Ciais, Philippe, Myneni, Ranga B., 2012b. Spatio-temporal patterns of the area experiencing negative vegetation growth anomalies in China over the last three decades. *Environ. Res. Lett.* 7 (3), 035701. <https://doi.org/10.1088/1748-9326/7/3/035701>.
- Yang, Chen, Fu, Meichen, Feng, Dingrao, Sun, Yiyu, Zhai, Guohui, 2021. Spatiotemporal changes in vegetation cover and its influencing factors in the loess plateau of china based on the geographically weighted regression model. *Forests* 12 (6), 673. <https://doi.org/10.3390/f12060673>.
- Zhang, B., Tian, L., Zhao, X., Wu, P., 2021. Feedbacks between vegetation restoration and local precipitation over the Loess Plateau in China. *Science China Earth Sci.* 64 (6), 920–931. <https://doi.org/10.1007/s11430-020-9751-8>.
- Zhang, Fangyue, Quan, Quan, Ma, Fangfang, Tian, Dashuan, Hoover, David L., Zhou, Qingping, Niu, Shuli, De Laender, Frederik, 2019. When does extreme drought elicit extreme ecological responses? *J. Ecol.* 107 (6), 2553–2563.
- Zhang, Xiaoping, Zhang, Lu, Zhao, Jing, Rustomji, Paul, Hairsine, Peter, 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. *Water Resour. Res.* 44 (7) <https://doi.org/10.1029/2007WR006711>.
- Li, Zhi, Zheng, Fen-li, Liu, Wen-zhao, Flanagan, Dennis C., 2010. Spatial distribution and temporal trends of extreme temperature and precipitation events on the Loess Plateau of China during 1961–2007. *Quat. Int.* 226 (1–2), 92–100. <https://doi.org/10.1016/j.quaint.2010.03.003>.