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Dynamic responses of tree-ring growth to drought over Loess Plateau in the past three decades

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ABSTRACT

Since the 1990s, global warming has substantially affected the dynamic responses of forest ecosystems to drought by altering tree growth and ecosystems carbon cycling. The Loess Plateau is a typical vegetation recovery region with an arid and semiarid climate. However, the responses of the vegetation in this region to drought have not been fully studied. We therefore aimed to characterize these responses in tree-ring samples, which were obtained by drilling tree cores with a growth cone, for establishing the tree-ring width chronologies. In addition, we investigated the main factors controlling the radial growth of Chinese pine (*Pinus tabulaeformis*) and its dynamic responses to drought in the Loess Plateau using correlation analysis. Our results show that radial growth in Chinese pine had a positive correlation with precipitation during the last growing season, pre-growing season, and entire current growing season. The correlation between the radial growth and temperature was inconsistent between different sampling sites and time periods. These suggest that precipitation was more likely to affect radial vegetation growth than temperature. Moreover, the drought indices calculated using data before the year 2000 more accurately reflected the vegetation drought situation in Loess Plateau than data from the last 20 years. The drier the place, the more accurately the drought indices represented the responses of vegetation to drought. However, these indices cannot satisfactorily capture the drought responses of vegetation in wet regions. Furthermore, the PDSI was more accurate than the SPEI at capturing the effects of drought on radial vegetation growth. Understanding the response mechanism of the radial growth of Chinese pine to drought can provide theoretical support for ecological protection, forest management, and ecological construction under climate change.

1. Introduction

Global warming is leading to sharp increases in the frequency and intensity of extreme climate events, such as drought (Dai, 2013; Vicente-serrano et al., 2015). Drought is one of the most economically and ecologically destructive extreme events, profoundly impacting terrestrial ecosystem processes (Yi et al., 2012; Allen et al., 2015; Gao et al., 2018). Vegetation also plays a crucial role in terrestrial ecosystems, contributing to mitigation of the greenhouse effect and promoting balance in the global carbon flux (Simon et al., 2012; Trotsiuk et al., 2016). Of all the vegetation types, forests may be the most vulnerable to drought (McDowell and Allen, 2015). Drought can lead to the loss of forest area, resulting in a remarkable reduction in the carbon flux from atmosphere to land (Wei et al., 2017; Yi et al., 2015). Drought also changes stand characteristics, thereby intensifying intraspecific and interspecific competition for resources such as nutrients, water, and space (Clark et al., 2016), leading to tree death (Dai et al., 2015). Therefore, the response mechanism of forest ecosystems to drought must be urgently studied.

Drought is a persistent water shortage phenomenon caused by water budget imbalance (Ashok and Vijay, 2010; Li et al., 2019). Due to different affected objects and forms, drought can be divided into

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meteorological drought, agricultural drought, hydrological drought, and social economic drought (Liu et al., 2015). In addition, different kinds of drought often occur at the same time, and a single drought index is difficult to accurately describe the complex drought conditions. Thus, it is necessary to construct a multi-variable comprehensive drought index to analyze the drought conditions (Su et al., 2019). Researchers have constructed a series of drought indicators, which enable the quantitative evaluation of drought. For example, the standardized precipitation evaporation index (SPEI) and the palmer drought index (PDSI) have been widely used in various studies and are obtained by mathematical statistics and a simple mechanism process, respectively. SPEI is based on the principle of water balance and can describe drought characteristics at different time scales, which is usually applied in frequency analysis (Zhou et al., 2014), spatial and temporal analysis (Guo et al., 2018; Xu et al., 2015), and ecological impact (Wang et al., 2018) of drought. PDSI is also based on the principle of water balance, and reflects drought degree by calculating available soil moisture (Schrier et al., 2013; Zhang et al., 2019; Wang et al., 2022). However, Sheffield et al. (2012) indicated that previously reported increases in global drought have been overstated. Berg and Mccoll (2021) also found that the arid regions will not continue to expand in the future under a warming climate when using the ecohydrological index rather than the atmospheric drought index. Actually, some popular drought indices are based on the hydrological, agricultural, and socio-economic impact of drought. With the increase of drought frequency and severity, the adverse effects of drought on human society and ecosystem increase, and thus effects of drought on ecosystem have been paid more attention, such as the death of trees caused by drought (Millar and Stephenson, 2015).

In recent years, the temperature and precipitation in the Loess Plateau have undergone great changes under the global warming (E et al., 2011). The Loess Plateau is characterized by drought and water shortage, which is caused by climate and human factors. The sustainability of vegetation is largely driven by drought, and thus a comprehensive analysis of vegetation drought process on the Loess Plateau is needed. However, due to the limited periods of records and poor quality of weather data for the Loess Plateau, uncertainties often exist in the results obtained from these indices. Wang et al. (2015) reported that drought frequency in the Loess Plateau has increased from 1961 to 2012. Zhang et al. (2015) found that the annual average potential evapotranspiration in the Loess Plateau have a downward trend from 1961 to 2012. Gao et al. (2017a; 2017b) stated that precipitation in the Loess Plateau region is significantly increasing. Moreover, since the implementation of the Grain for Green project, analysis of the occurrence of drought in the vegetation ecosystem has become more complex. Quantifying the process mechanism of vegetation drought using the existing drought index is difficult. Therefore, studying the dynamic responses of vegetation to drought via its growth characteristics is an important step toward addressing these challenges.

As a typical arid and semiarid region, the Loess Plateau is considered suitable for the study of dendroclimatology, where tree growth is highly sensitive to climate. The tree ring is an important indicator of vegetation growth. Tree-ring width chronologies provides accurate dating, shows strong continuity, and is reproducible and has high resolution; as such, it has become an important method for revealing the relationship between vegetation radial growth and environmental change (Wu, 1990). Some scholars have studied the response of the vegetation radial growth to climate change in different areas of the Loess Plateau and analyzed the influence of some climatic factors on vegetation radial growth (Ma et al., 2015; Wei et al., 2018; Li et al., 2020). The results showed that the same species in different regions have different correlations with some climate factors for different stages of growth periods. The correlations between different species and climate factors in the same area also differed for the same time period. In addition, tree rings can be used in historical climate change reconstruction and provide valuable information for local ecological restoration and construction (Lu and Liang, 2013). Cai et al. (2008) reconstructed the average temperature from April to September in 1826 to 2004 in central and northern Shaanxi Province, which provided scientific data for studying the characteristics and mechanisms of historical climate change and the regional responses to global change. Understanding the radial growth characteristics of vegetation under drought stress provides a basis for studying the impact of climate change on forest ecosystem structures and productivity. However, most of the previous studies were conducted based on a single climatic condition, and the dynamic responses of tree-ring growth to drought in various climatic regions of the Loess Plateau need to be further investigated.

In this study, we focused on the dynamic responses of tree-ring growth to drought in the Loess Plateau under climate change. Our aims in this study were to (1) analyze the spatiotemporal evolution characteristics of tree-ring radial growth under different precipitation zones in the Loess Plateau from 1991 to 2020, (2) estimate the relationship between tree-ring radial growth and climate factors, and (3) investigate the correlation between different drought indices and the tree-ring width index. The remainder of this paper is organized as follows: Section 2 describes the materials and methods, Section 3 describes the results, Section 4 contains the discussion, and Section 5 provides our conclusions.

2. Materials and methods

2.1. Study area

The Loess Plateau is a typical area in which the Grain for Green project has been implemented in China. This region has an arid continental monsoon climate and average annual temperature of 3.6–14.3 °C. The annual average precipitation is between 200 and 800 mm, with an uneven spatial and temporal distribution decreasing from southeast to northwest. There is large variation in the inter-annual precipitation, of which most is concentrated from June to September. The Loess Plateau contains many vegetation types, such as desert steppe, steppe, forest steppe, and forest, whose profile gradually changes in the northwest to southeast direction along with the precipitation gradient. In this study, we divided the Loess Plateau into five regions according to the annual average precipitation (Fig. 1). The annual precipitation is >600, 500–600, 400–500, 300–400, and <300 mm in Regions I, II, III, Ⅳ, and Ⅴ, respectively. We did not analyze Region Ⅴ due to the poor water supply, which is lower than required for the growth of Chinese pine (*Pinus tabulaeformis*).

2.2. Tree core sampling and chronology establishment

Tree-ring samples of Chinese pine were collected from 10 sampling sites, which were evenly distributed in the Loess Plateau (Fig. 1). According to the standards and copy principles of the International Tree-Ring Data Bank (Holmes, 1983; Schmid, 1997), we selected 25 Chinese pine at each sampling site and obtained two tree cores at the diameter at breast height (DBH) of each of the selected trees using growth cones with a diameter of 5.15 mm. Detailed information of the sampling sites and selected trees is presented in Table 1.

The tree-ring width chronologies were established through four steps. First, we fixed the dried sample cores into a mold and then polished them with sandpaper until the tree ring was clearly visible. Second, the tree rings were cross-dated. The growth years of each ring were marked from the pith to the bark through the visual at intervals of 10, 50, and 100 years, respectively. The skeleton map was drawn to compare the width of the tree rings on the left and right sides, and the narrow years and extremely narrow years were recorded. All skeleton maps were repeatedly compared and summarized into one map. Third, we measured and verified the tree ring width, and the processed skeleton map was used a Lintab^{TM}6 tree-ring analyzer to measure the tree-core ring-width with a precision of 0.001 mm. The quality of the cross-date was inspected using the COFFECHA procedure (Grissino-Mayer, 2001). This procedure uses the correlation coefficients of each

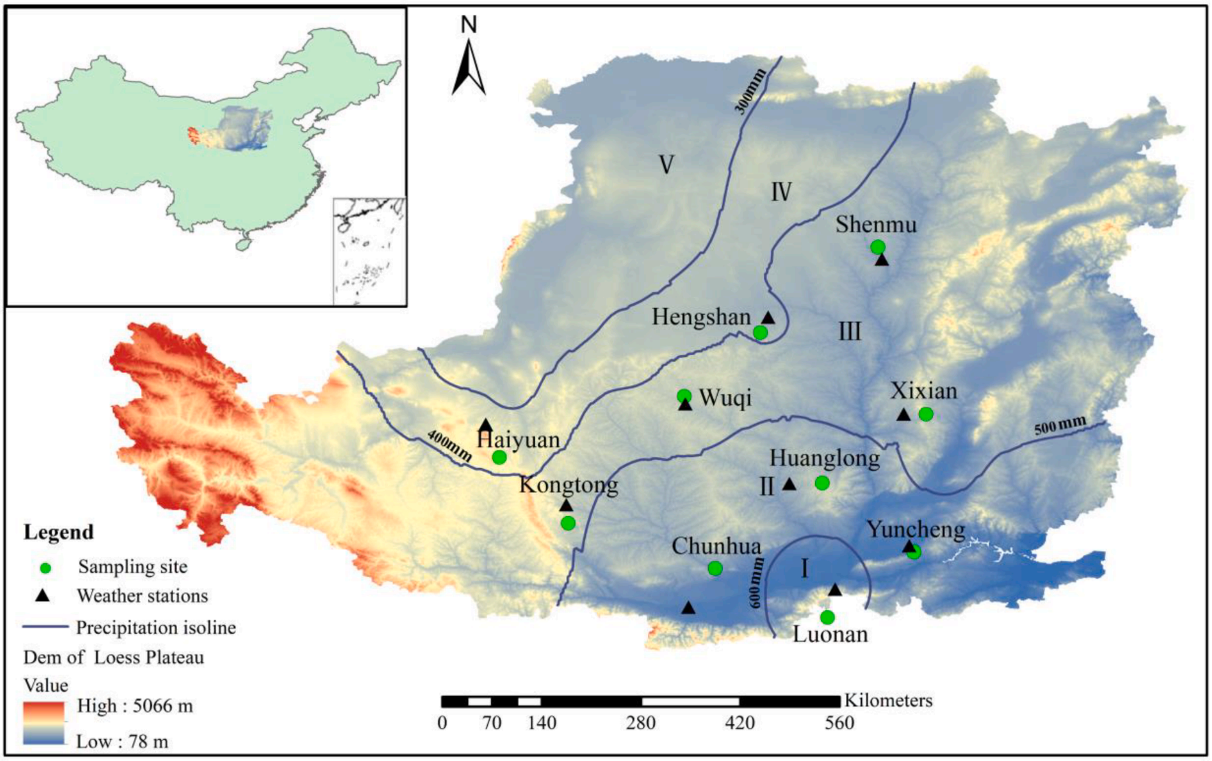


Fig. 1. Map of the Loess Plateau. The purple lines are precipitation contours, the black triangles are the weather stations, and the green dots are the sampling sites (n = 10).

Table 1
The detailed information of sampling sites and selected trees.

Site	Latitude (°N)	Longitude (°E)	Elevation (m)	Slope (°)	Mean DBH (cm)	Mean tree height (m)	Sampling time
Luonan (LN)	34.12	109.98	1086	27	20.9	9	2021.06.20
Chunhua (CH)	34.74	108.56	1520	20	23.5	13	2021.06.03
Huanglong (HL)	35.82	109.91	1270	16	30.5	18	2021.06.05
Yuncheng (YC)	34.95	111.08	1003	22	22.6	7	2021.06.19
Kongtong (KT)	35.32	106.69	1660	18	22.8	8	2021.06.10
Wuqi (WQ)	36.93	108.17	1440	21	12.5	5	2021.06.09
Xixian (XX)	36.70	111.23	1370	24	28.9	12	2021.06.18
Shenmu (SM)	38.82	110.62	1200	16	20.4	8	2021.06.07
Haiyuan (HY)	36.15	105.82	1910	25	21.7	10	2021.06.25
Hengshan (HS)	37.73	109.13	1250	16	17.5	5	2021.06.08

tree-ring width sequence moving back and forth in the main sequence to calculate and check whether there is any error in dating and measurement. If there is any problem, the sample cores with problems will be measured again or the sample cores with large errors will be removed to ensure the accurate dating of each tree ring. Finally, the tree-ring width chronologies were established. The age and tree-ring width trends during the growth of trees, i.e. the growth trend, should be removed before analyzing the changes in radial growth width of trees. In this study, we used the negative exponential function method of the dplR package in R language to de-trend and standardize the data for tree-ring width. Negative exponential function is a relatively conservative de-trend method, which is usually standardized in the form of ratio for de-trend sequences to obtain dimensionless sequence (Shao and Wu, 1994). The measured value of tree-ring width was then divided by the annual growth fitting value to obtain the index sequence. Thus, the standardized chronology, difference chronology, and autoregression chronology were created. The standardized chronology does not contain some factors such as tree age, but includes the influence of various environmental factors on tree growth and its high and low frequency information.

2.3. Weather data and drought index

In this study, we obtained 30 years (1991–2020) of weather data from the China Meteorological Data Network (https://data.cma.cn/). We collected the data from 10 weather stations closest to the sampling sites (Fig. 1), which included information about the temperature (T), precipitation (P), relative humidity (RH), and vapor pressure deficit (VPD). We used the above data to calculate the net radiation (Rn), and the detailed processes can be found in the FAO (1998) data. The distribution of the multiyear monthly mean of T, P, RH, VPD, and Rn of these 10 meteorological stations is shown in Fig. 2. The PDSI and standardized precipitation evaporation index (SPEI) data for 1990–2020 and 1990–2018 with a spatial resolution of 0.5° × 0.5° were obtained from the data-sharing network of the Royal Netherlands Meteorological Institute (https://climexp.knmi.nl).

2.4. Statistical analysis

The correlation and significance between the tree-ring width index of Chinese pine and the 30-year monthly mean values of T, P, RH, VPD, and Rn were analyzed using Pearson correlation coefficient. Pearson correlation coefficient is widely used to measure the degree of correlation between two variables, and its value is between −1 and 1. Pearson correlation coefficient between two variables is defined as the quotient of their covariance and standard deviation, which is calculated by the following equation:

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \quad (1)$$

The significance of these correlations was tested by *t* test (Zhao, 2021). *T* test mainly includes four steps: (1) proposing null hypothesis; (2) Select test statistics; (3) Calculate the observed value and P-value of the test statistic. The purpose of this step is to calculate the observed value and the corresponding P-value of the *T*-statistic; (4) Give the significance level and make a decision. In this study, the correlations were considered significant when p value is <0.05.

In addition, we investigated the correlation between the tree-ring width index and drought index (PDSI and SPEI) at different time scales.

3. Results

3.1. Statistical characteristics of tree-ring width chronologies

The statistical characteristics of the tree-ring width chronologies of Chinese pine are shown in Table 2. The series inter-correlation in this region ranged from 0.46 to 0.58, indicating that the chronology of each sampling site provided an accurate representation of the Chinese pine in this region and could represent the average growth status. The mean sensitivity of each sampling site was 0.27–0.35, which suggested that there was large inter-annual variation in the tree rings of Chinese pine in this region. The Chinese pine in Hengshan was the most sensitive to climate change. The standard deviations of the sampling sites ranged 1.18–1.94, implying that significant variation in the climate conditions. The first-order autocorrelation of the sampling sites was 0.36–0.77, indicating that climate factors in the current year would affect the radial growth of the Chinese pine in the next year. The signal-to-noise ratio of the sites ranged 5.36–12.50. These data show that the information contained in our collected samples could represent the overall characteristics of the Loess Plateau and were, therefore, suitable for the correlation analysis via tree-ring width chronologies.

Although removing their growth trend, the growth degree of the tree-ring width index of Chinese pine was found to vary according to the

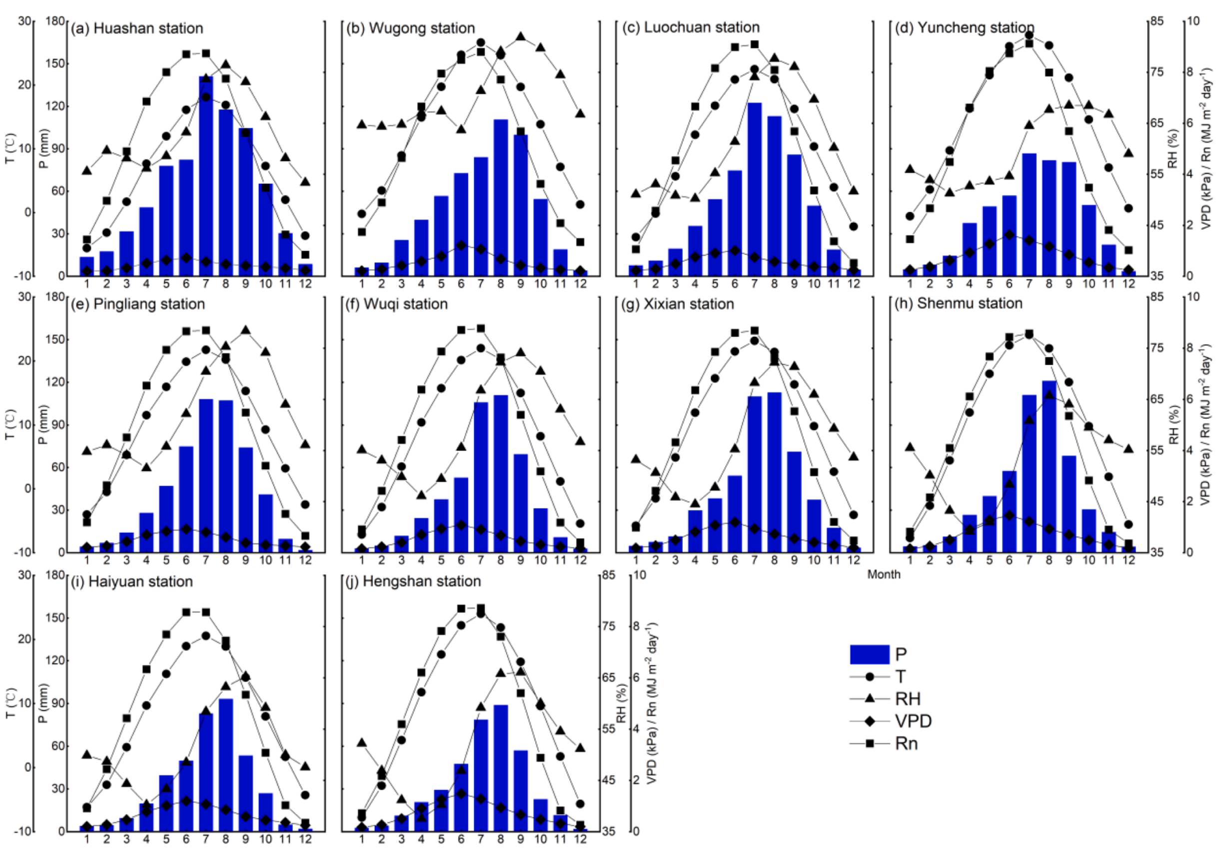


Fig. 2. The multi-year monthly mean of temperature (T), precipitation (P), relative humidity (RH), vapor pressure deficit (VPD), and net radiation (Rn) of the selected 10 meteorological stations. The blue bars are precipitation, and the lines with circles, triangles, diamonds, and squares represent T, RH, VPD and Rn, respectively.

Table 2
The statistical characteristics of tree-ring width chronologies.

Site	SD	SK	MS	AR1	SI	SNR
Luonan (LN)	1.33	1.13	0.27	0.36	0.49	5.36
Chunhua (CH)	1.91	1.47	0.34	0.69	0.51	9.99
Huanglong (HL)	1.53	1.38	0.30	0.70	0.48	6.07
Yuncheng (YC)	1.63	1.56	0.34	0.60	0.46	6.49
Kongtong (KT)	1.65	1.15	0.33	0.58	0.58	12.15
Wuqi (WQ)	1.24	0.74	0.29	0.41	0.58	12.50
Xixian (XX)	1.21	1.92	0.27	0.61	0.52	11.87
Shenmu (SM)	1.18	1.47	0.29	0.51	0.61	17.63
Haiyuan (HY)	1.94	0.42	0.28	0.77	0.51	5.36
Hengshan (HS)	1.44	1.46	0.35	0.49	0.47	6.36

Note: SD: Standard deviation; SK: Skewness; MS: Mean sensitivity; AR1: First order autocorrelation; SI: Series inter-correlation; SNR: Signal-to-noise ratio.

site (Fig. 3). This was attributed to the different environmental factors of the various sites, including P, T, RH, VPD, and Rn. For example, at Chunhua, Huanglong, and Haiyuan, the tree-ring width index changed only slightly during the study period, but at Wuqi, Shenmu, and Hengshan, the index changed dramatically. However, the chronologies of all ten of the sites showed narrow rings in the year 2000. Due to the different tree ages in the different sites, we selected a time period (1991–2020) when there were Chinese pine planted in all of the sites for further analysis. The tree-ring width index of each sampling site showed a slight upward trend from 1991 to 2020 (Fig. 4). The PDSI showed a notable upward trend in all of the sites; however, the trend of SPEI for each site was not significant ($p < 0.05$). All three indices showed a remarkable decrease in the year 2000; therefore, the potential influence of meteorological factors on the radial growth of Chinese pine in different regions needs to be studied.

3.2. *Response of tree radial growth to climate variables*

Due to the lag in tree growth in response to some climatic factors, we defined the growth year of Chinese pine as beginning in the previous September and ending in the current September (P9–C9). To investigate the effects of the climate factors during different time periods on tree growth, we divided the growth year into three periods: the previous September to December (P9–12), current January to April (C1–4), and current May to September (C5–9). The mean value of T, RH, VPD, and Rn and the sum of P during the entire growth year and the three defined periods were calculated. Correlation analysis was then conducted between these mean/sum values of each climatic factor and the tree ring width chronologies for the entire growth year and those three defined periods.

Correlation analysis of the radial growth of Chinese pine and each climatic factor was presented in Fig. 5. Precipitation always had a positive effect on the radial growth of Chinese pine. For example, the radial growth at all of the sites showed a positive correlation with precipitation in the P9–12 period and was positively correlated with the precipitation in the C1–4 and C5–9 period at most sites but was not found to be significant in most cases. Trees are dormant during the P9–12 period, and thus almost all of precipitation is stored in the soil in this period. In addition, there is less precipitation in the C1–4 period, and trees absorb

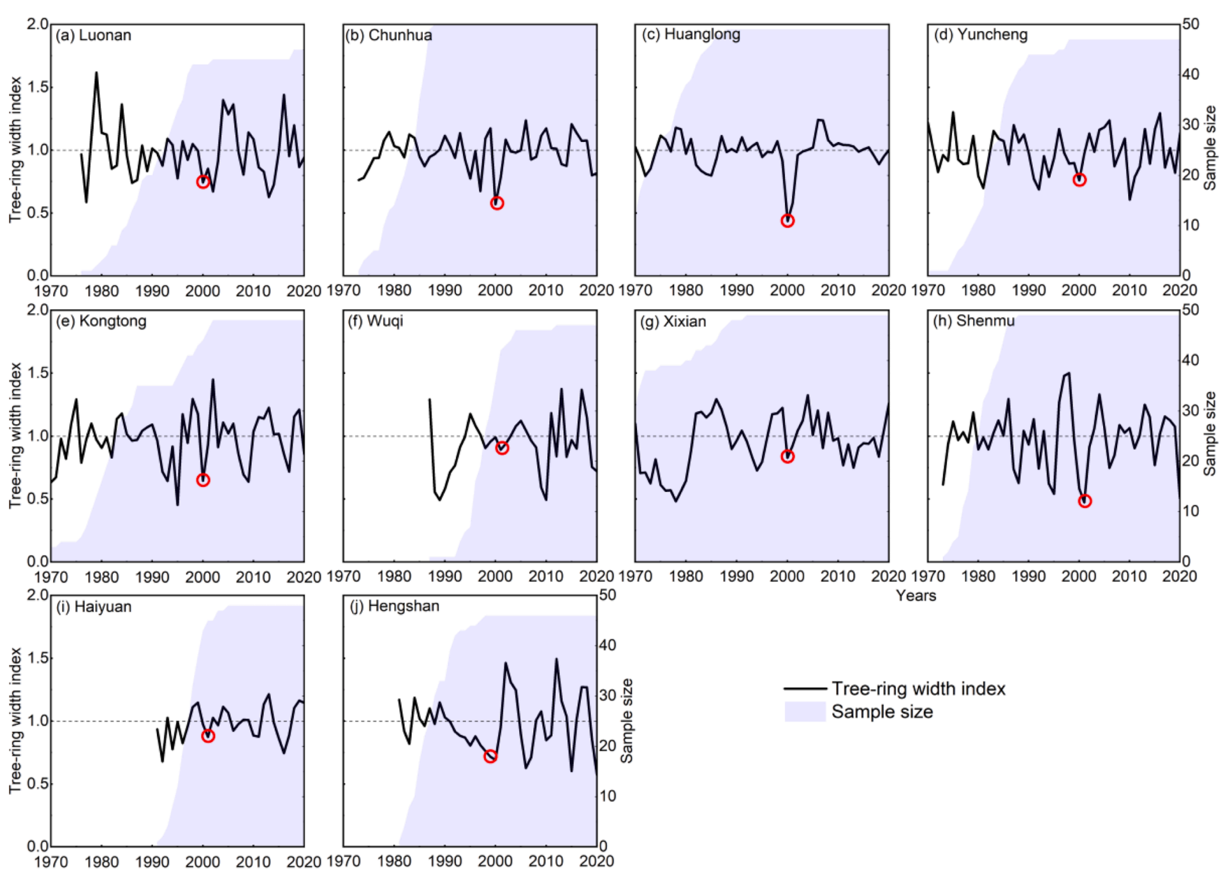


Fig. 3. The tree-ring width chronologies of Chinese pine for the ten sites.

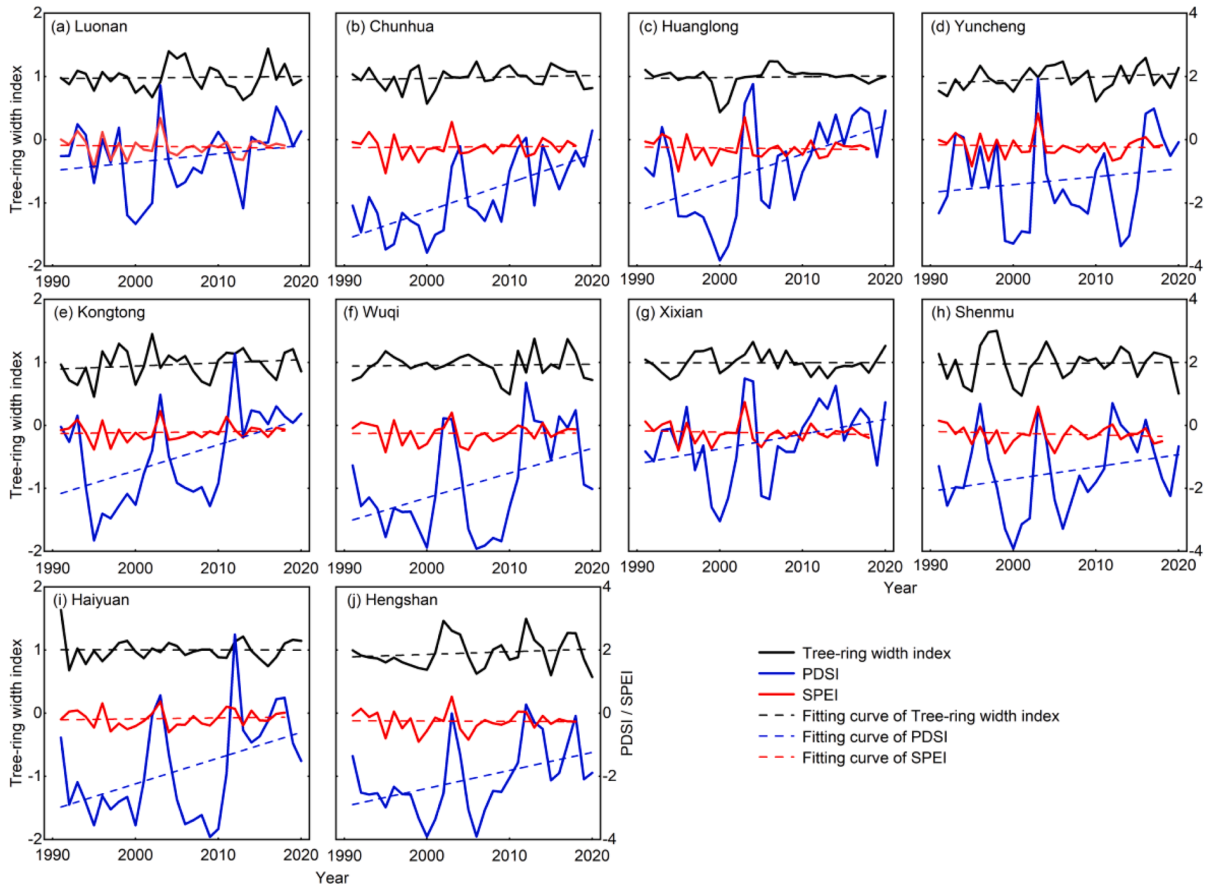


Fig. 4. Trends for tree-with index, Palmer Drought Index, and Standardized Precipitation Evaporation Index for the ten sites.

the water stored in the soil. Hence, this indicates the lag effect of precipitation on tree growth. However, contrasting relationships between the radial growth of Chinese pine and temperature were observed when comparing different locations. In Xixian and Haiyuan, the radial growth was positively correlated with the temperature in all three periods but negatively correlated with the temperature in Chunhua and Huanglong. In addition, the relationship between the two was more complex at other sites. Relative humidity and vapor pressure deficit are closely connected with precipitation. With the increase of precipitation, the relative humidity increases and thus the water vapor pressure decreases. Thus, the radial growth of Chinese pine was positively correlated with the relative humidity but negatively correlated with the vapor pressure deficit in most cases. Similar to temperature, there was no obvious effect of net radiation on radial growth.

The correlation coefficient between the radial growth of Chinese pine and climatic factors showed changes according to spatial gradient (Fig. 6). The correlations between the annual tree-ring width and temperature, precipitation, and relative humidity were positive. Such correlations for temperature and relative humidity increased along the precipitation gradient but decreased for precipitation. The correlation between the radial growth and vapor pressure deficit changed from a negative correlation to a weak positive correlation along the precipitation gradient. This correlation with net radiation showed an opposite pattern from the vapor pressure deficit. The thresholds for the relationship between annual tree-ring width and vapor pressure deficit and net radiation transition along the water gradient were those regions with annual precipitation greater than 600 mm.

3.3. Relationship between tree-ring width chronologies and PDSI and SPEI

We evaluated the correlation between the annual tree-ring width of Chinese pine and the PDSI and SPEI (Fig. 7). Generally, the tree-ring width positively correlated with the PDSI at most sites and for most time periods (Fig. 7a), which indicates that the PDSI could accurately capture the response of vegetation to drought in this region. In particular, the correlation was found to be significant ($p < 0.05$) in most cases in Hengshan, Haiyuan, and Shenmu, the driest sites among the selected 10 stations (Fig. 1). For the entire growth year (P9–C9), the PDSI had a positive response to the tree-ring width at all sites, and the highest correlation coefficient was 0.6 in Hengshan. However, the relationship between the tree-ring width and SPEI differed across months at all sites (Fig. 7b). During P9, C5, and the entire growth year, the tree-ring width positively correlated with the SPEI at most sites. For other time periods, the SPEI could not accurately reflect the effect of drought on the tree-ring width. Overall, the PDSI was more accurate than the SPEI at describing the effects of drought on the radial vegetation growth in this region.

All of the tree-ring indices, PDSI, and SPEI decreased remarkably in 2000, and the trends of these three factors after 2000 were inconsistent (Fig. 4). Thus, we divided the entire growth year into three time periods, T1 (1991–2000), T2 (2001–2010), and T3, (2011–2020), to analyze the correlation between the tree-ring width index and drought index (Fig. 8). For T1, the determination coefficient (R^2) between the PDSI and tree-ring width index in most of the sampling sites was larger than in T2 and T3 (Fig. 8a). Only in Kongtong, Xixian, and Shenmu was the R^2 of T2 larger than those of T1 and T3. Moreover, the R^2 between the SPEI and tree-ring width index in T1 was also larger than those in T2 and T3 at most of the sampling sites. The R^2 for the PDSI was generally larger than that of the SPEI at the same sampling sites. These results indicate that the drought index before the year 2000 could, therefore, more accurately reflect the drought situation in the Loess Plateau than the drought index of the previous 20 years; this also suggested that the PDSI was

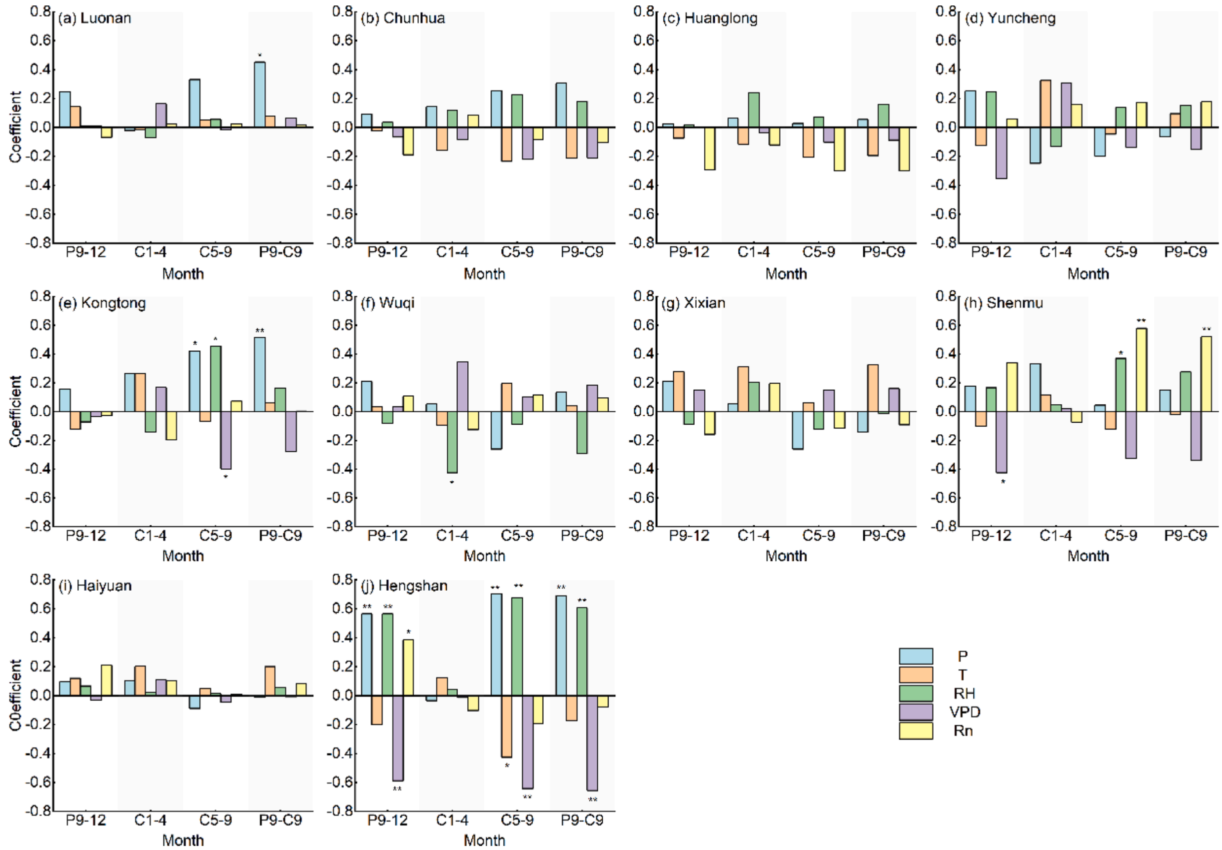


Fig. 5. The correlation between the radial growth of Chinese pine and each climatic factor. "*" indicates that the correlation passes the significance test at the p < 0.05 level, and "**" is at the p < 0.01 level.

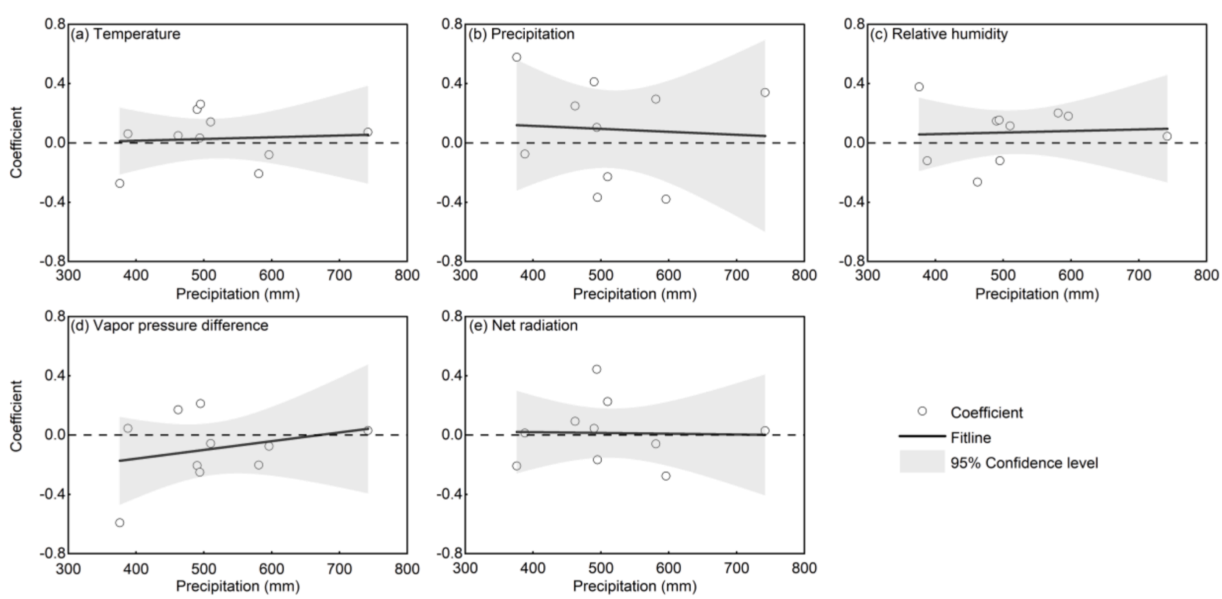


Fig. 6. The pattern of the correlation coefficients between tree-ring width and climatic factor with precipitation gradient.

more accurate than the SPEI in this region.

4. Discussion

Precipitation plays an important role in tree growth. In this study, we divided the Loess Plateau into five regions based on the annual precipitation level. The correlation between the annual precipitation and the tree-ring width of Chinese pine gradually weakened and approached zero with decreasing precipitation. This indicates that the growth of Chinese pine was mainly limited by low precipitation. In addition, the tree radial growth was positively correlated with precipitation in the previous September to December (P9–12) (Fig. 5), which may have been due to the substantial reduction in the water consumption of Chinese pine after September and, thus, could have resulted in a larger water

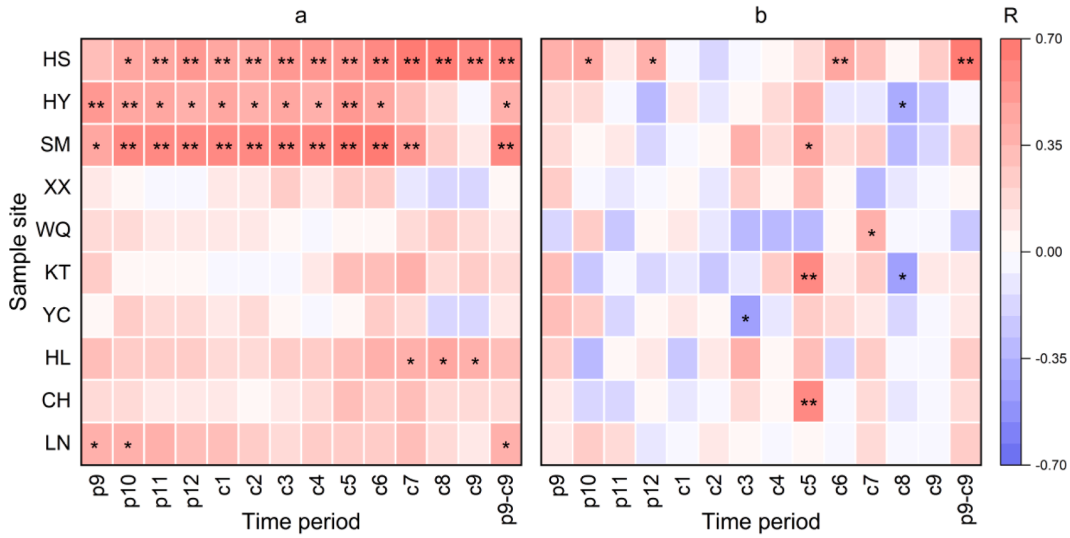


Fig. 7. The correlation coefficient (R) between tree-ring width chronologies and (a) Palmer Drought Index (PDSI) and (b) Standardized Precipitation Evaporation Index (SPEI). "*" indicates that the correlation passes the significance test at the $p < 0.05$ level, and "**" is at the $p < 0.01$ level.

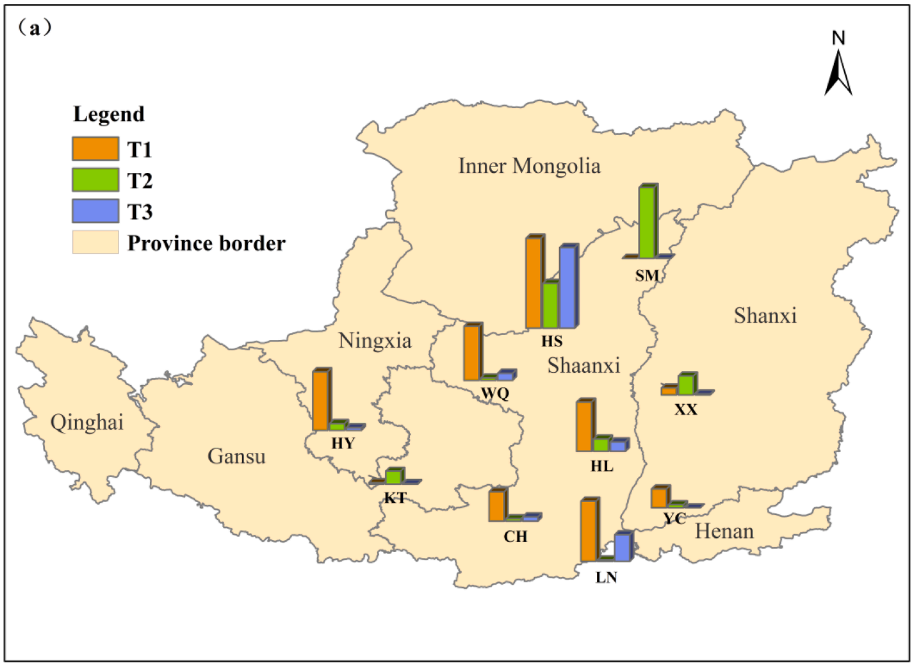
reserve. Such favorable conditions at the end of the previous year could have increased the accumulation of photosynthetic products and promoted cell growth in Chinese pine earlywood in the next year (Li et al., 2020). We found a positive, but not significant, correlation between the radial growth and precipitation in the pre-growing season of the current year at most sampling sites (Fig. 5). This may have been due to the precipitation from January to April only accounting for 11 % of the annual precipitation, which was not enough to have a significant effect on the radial growth of Chinese pine (Liang et al., 2015). The correlation for the current year's growing season varied with the sampling site (Fig. 5). For example, the radial growth of Chinese pine was the most vigorous in the early stage of growth from May to June at Wuqi. At this time, it is important that there is sufficient precipitation, but this was limited and insufficient to promote the radial growth of Chinese pine. July–August is another crucial period for the radial growth of Chinese pine, but precipitation is sufficient during this time period and, thus, is not a limiting factor for their growth (Li et al., 2007). This result is similar to that of Liang et al. (2015), who also conducted correlation analysis in Wuqi.

Temperature is also a factor affecting tree growth. At Chunhua and Huanglong, there was a negative correlation between the radial growth of Chinese pine and the temperature in the late period of the previous year and the early period of the current year (Fig. 5). Due to a rise in temperature in the middle and late growing season, the stomata of the Chinese pine close to reduce water transpiration, resulting in a decreased photosynthetic rate. The reductions in the synthesis and storage of organic matter are not conducive to the growth of trees in the current year and can even affect the growth of trees in the next year (Chen et al., 2011). This is consistent with the findings of Yang et al. (2022) in the central and western Qinling Mountains. During the growing season, trees experience vigorous physiological activities and require a sufficient amount of water and supply of heat to maintain normal metabolic demand. High temperature in the growing season often exceeds the physiological threshold, resulting in increased respiration and decreased photosynthetic rates. This is consistent with the results of Hou et al. (2007), Nirmal and Mahadev (2013), and Song et al. (2017). The analysis of correlations at the other sampling sites indicated they differed and were not significant (Fig. 5), indicating that temperature is not the main factor influencing growth.

The results of the correlation analysis between the radial growth and drought index showed a positive correlation between the tree-ring width and the PDSI on both monthly and annual scales. Our results indicated that water availability was the main factor limiting the radial growth of Chinese pine in the study area. The PDSI reflects the degree of soil–water availability. For example, the PDSI and tree-ring width index in Shenmu, Hengshan, and Haiyuan showed a significant positive correlation at both monthly and annual scales, which could reflect the drought degree of these sites through the variation of tree-ring width index. This is similar to the findings of Li et al. (2020) in the central Loess Plateau and of Zhao et al. (2021) in the semiarid region of northeast China. In addition, the SPEI played an important role in restricting the radial growth of Chinese pine in the pre-growth season of the current year. The increase in temperature in the pre-growth season of the current year helps accelerate root elongation and the germination rate; additionally, it promotes evaporation and, thus, leads to a decrease in the SPEI index. Therefore, the radial growth of Chinese pine showed a negative correlation with the SPEI index of the previous growing season of the current year (Fig. 7). From May to July, both temperature and precipitation are suitable for tree growth, leading to increased respiration and transpiration rates. Hence, the correlation coefficient between the SPEI and the radial growth of Chinese pine from May to July was mainly positive (Qi et al., 2020).

Due to climate change, the Loess Plateau has experienced both warming and drying trends and the greening of vegetation. The increased vapor pressure deficit caused by climate warming accelerates the evaporative loss of surface water, which, in turn, amplifies the phenomenon of atmospheric drying through land–atmosphere feedback. Under high carbon dioxide (CO_2) concentrations, plant leaf stomata close, compensating for the adverse effect of the saturated water pressure difference on plant growth (Lian et al., 2021). In the calculation of the drought index, precipitation and actual evapotranspiration are the two main input variables, representing the atmospheric water supply and water demand, respectively. Precipitation is a direct input variable for most of the land process models, and the actual evapotranspiration needs to be estimated based on other meteorological variables. Under climate change, the frequency of droughts is aggravated by increased CO_2 concentration, but the CO_2 concentration is often set as a fixed value in the actual evapotranspiration calculation process. The correlation between the tree-ring width index and the drought index (PDSI and SPEI) after the year 2000 is very weak (Fig. 8), and ignoring the actual increase in CO_2 concentration is likely the reason for this finding. Therefore, the popular drought index cannot accurately characterize the response mechanism of vegetation to drought, so evapotranspiration and water availability in the root zone on both sides of supply and demand must be described instead.

In this study, we clarified the response mechanism of the radial



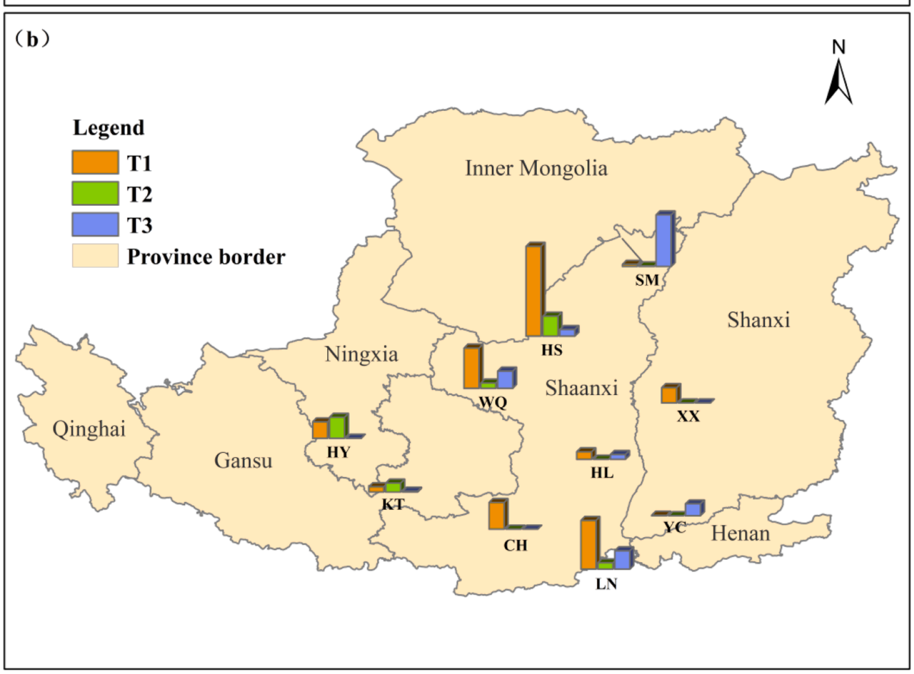


Fig. 8. The determination coefficients (R^2) between tree-ring width index and (a) Palmer Drought Index (PDSI) and (b) Standardized Precipitation Evaporation Index (SPEI). T1 represents the period of 1991–2000, T2 is 2001–2010, and T3 is 2011–2020.

growth of Chinese pine to different climatic factors in the Loess Plateau and its responses to different drought indices. However, the pine plots in the study area still show differences in slope, slope position, altitude, and stand density. The effects of density and altitude on the growth process of DBH and volume are also very obvious. The responses of pine to these and climatic factors need to be further explored. In addition, collecting tree core can time-consuming and expensive, and thus building model is an alternative method. It may be a good choice to evaluate vegetation drought in Loess Plateau using a new vegetation drought index by calculating vegetation water demand and water consumption process and then constructing a vegetation drought index.

5. Conclusions

In this study, we analyzed the dynamic responses of annual tree-ring growth of Chinese pine (*Pinus tabulaeformis*) to drought in the Loess Plateau. By sampling the pine forest under different precipitation zones, we established the tree-ring width chronology of 10 sample sites. In order to determine the main factors affecting the radial growth of trees on the Loess Plateau, we analyzed each chronological and climatic factor and conducted a temporal and spatial correlation analysis of the drought index. The main results of this study are as follows:

(1) The parameters of the tree-ring width chronologies of Chinese pine on the Loess Plateau contain much climate information and have potential for the study of tree-ring ecology and climate;

(2) The radial growth of Chinese pine was positively correlated with

the precipitation and relative humidity but negatively correlated with the vapor pressure deficit in most cases;

(3) The drier the site, the more accurately the drought indices represented the responses of the vegetation to drought, but these indices could not satisfactorily capture the drought responses of vegetation in wet regions;

(4) PDSI was more accurate than the SPEI in this region. The drought index before the year 2000 could more accurately reflect the drought situation in the Loess Plateau than the most recent drought index based on data after 2000, and a new vegetation drought index may be needed in the further study.

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CRediT authorship contribution statement

Ai Wang: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Xuerui Gao:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Zeyu Zhou:** Conceptualization, Formal analysis, Methodology, Writing – original draft. **Hao Yang:** Conceptualization, Methodology. **Xuehua Zhao:** Conceptualization, Methodology. **Yuemeng Wang:** Conceptualization, Methodology. **Min Li:** Conceptualization, Methodology. **Xining Zhao:** Funding acquisition, Resources, Supervision.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109423.

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