

Slope aspect reshapes climate–growth sensitivity and drought response pathways of *Larix gmelinii* var. *principis-rupprechtii* plantations in the semiarid Liupan Mountains

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Abstract

In this study, we examined how slope aspect affects the drought response of *Larix gmelinii* var. *principis-rupprechtii* plantations in the semiarid Liupan Mountains using tree-ring data from 1995 to 2021. Residual chronologies, climate–growth correlations, drought-response indices, and structural equation models were used to compare shady, semishady, and sunny slopes. Growth on shady slopes was mainly limited by temperature and showed stronger lagged effects from the previous year, whereas growth on sunny slopes was more closely related to moisture conditions. Resistance differed significantly among slope aspects, with the highest value on shady slopes and the lowest on semishady slopes, while recovery showed weaker slope-related variation. Resilience also differed among slopes and was controlled by distinct climatic pathways. On shady slopes, water-related factors mainly affected resilience through recovery, indicating a moisture compensation effect. On semishady slopes, resilience was strongly constrained by temperature and atmospheric drought. On sunny slopes, temperature and VPD showed positive overall effects on resilience. These results demonstrate that slope aspect reshapes both climate sensitivity and drought-response pathways, highlighting the importance of slope-specific management in semiarid plantations.

1. Introduction

Forest ecosystems are critical for mitigating soil erosion, increasing ecological stability, enhancing carbon sequestration, and regulating regional climatic conditions (Anderegg, W.R.L. et al., 2022). The Loess Plateau is among the most ecologically sensitive regions worldwide, where semiarid conditions and an increasing drought frequency pose threats to forest productivity and stability (Feng X. et al., 2016; Chen Y. et al., 2015). Over the past decades, elevated aridity has been observed, with increasing vapor pressure deficits (VPDs) and decreasing precipitation levels during the growing season (Gao X. et al., 2017; Wang X. et al., 2019; Hu J. et al., 2022). These climatic changes directly influence tree growth, survival, and recovery, highlighting the importance of ecological resilience, defined as the ability of trees to maintain or restore growth after the occurrence of disturbance (Rebollo et al., 2024; Zhang P. et al., 2024).

Previous studies have indicated that tree growth responses to drought are highly context dependent and vary with species, climatic conditions, and topography (Wang X. et al., 2025; Zhang X. et al., 2021; He W. et al., 2020). Among these factors, the slope aspect is a key microenvironmental factor that modulates water availability, light exposure, and temperature stress, in turn affecting tree resistance, recovery, and overall resilience to drought (Li X. et al., 2020; Wang L. et al., 2013). For example, trees on sunny slopes typically experience greater evapotranspiration and thermal stress levels but may exhibit increased recovery after drought, likely because of an increased photosynthetic capacity, whereas shady slopes may buffer thermal extremes but limit post-drought growth rebound. Despite the recognized importance of the microtopography, quantitative assessments of slope-mediated differences in drought resilience remain limited, particularly with respect to artificial forests in semiarid regions on the Loess Plateau. Most studies focus on natural forests or average growth trends without explicitly linking resistance,

recovery, and resilience metrics to the slope aspect (Lei S. et al., 2019; Guan Z. et al., 2021; Li Z. et al., 2024).

Larix gmelinii var. *principis-rupprechtii*, which constitutes the dominant artificial tree species in the Liupan Mountains, is highly drought tolerant and is widely applied in ecological restoration (Wang W. et al., 2025). However, drought-induced growth declines, limited regeneration, and crown dieback are being increasingly reported, suggesting vulnerability under increased aridity (Xiong Q. et al., 2022). This study aims to bridge this gap by quantitatively assessing slope-mediated drought resilience, thereby employing tree-ring chronology data to evaluate resistance, recovery, and overall resilience across shady, semishady, and sunny slopes. Specifically, we address the following two questions: (1) How does the slope aspect modulate the sensitivity of the residual chronology (RES) to drought, and (2) How do drought-related climatic factors regulate resistance, recovery, and ultimately resilience across different slope aspects? By linking growth dynamics to slope-specific environmental conditions, this study provides insights for the sustainable management of artificial forests under increasing drought risk in semiarid regions.

2. Methods

2.1 Study area

The study area is located in the small watershed of Diediegou (DDG; 106°4'55"–106°9'15" E, 35°54'12"–35°58'33" N), Guyuan city, Ningxia Hui Autonomous Region, China. The DDG watershed covers an area of 25.4 km² and an elevation range of 1975–2615 m and is located in the transition zone between the loess area and the rocky mountainous area of the northern section of the Liupan Mountains. This watershed experiences a typical semiarid continental monsoon climate, with a mean annual air temperature of 6.5°C and a mean annual precipitation amount of 449 mm, occurring mainly from July to September. The frost-free period lasts approximately 130 days, and the mean annual potential evaporation level is approximately 1000 mm.

The main soil types in the upper reaches of the DDG watershed are loessal soil and red clay soil, which constitute a thick soil layer. The middle and lower reaches of the DDG watershed contain gray cinnamon soil with thicknesses ranging from 20–300 cm. The forests comprise mainly *L. gmelinii* var. *principis-rupprechtii* plantations, which are distributed primarily on shady and semishady slopes. The predominant shrub species are *Ostryopsis davidiana*, *Spiraea salicifolia*, and *Hippophae rhamnoides*. The major natural herb species are *Artemisa gmelinii* and *Saussurea amara* (Wang Y. et al., 2013) (Fig. 1).

2.2 Meteorological change trends from 1995 to 2021

From 1995 to 2021, the air temperature in the DDG watershed increased, with a mean annual value of 7.87°C and an increase rate of 0.06°C year⁻¹. The mean annual maximum air temperature decreased slowly at a rate of 0.03°C year⁻¹, but the minimum air temperature increased rapidly at a rate of 0.09°C

year⁻¹. The annual precipitation and standardized precipitation evapotranspiration index (SPEI) increased overall, with an average annual precipitation value of 458.37 mm and annual SPEI values ranging from -1.43 ~ 1.81, with increase rates of 7.02 mm year⁻¹ and 0.05 year⁻¹, respectively. The VPD increased gradually, indicating increasing atmospheric dryness in the DDG watershed (Fig. 2).

2.3 Sample selection and collection

L. gmelinii var. *principis-rupprechtii* trees located at the midslope position within the DDG watershed were selected, and 4 sample plots (20×20 m) were randomly established in each slope to measure each tree within the plots. On the basis of the plot conditions, a relative tree height (the ratio of the standing height of an individual tree to the average tree height in the plot) of 1.1 was employed to select dominant trees. To reduce the effect of intraforest competition and determine the influence of climate factors on tree growth (Li J. et al., 2017), 90 dominant trees were selected in this study.

The growth cores of the selected dominant trees were sampled with an increment borer (with a diameter of 5.15 mm). The sampling position was located 1.3 m above the ground. A tree core was drilled along the east–west direction, and another was drilled along the north–south direction, yielding a total of 180 sample cores. The cores were placed in plastic tubes, marked, and brought back to the laboratory for further processing.

2.4 Chronology construction

After the collected cores were dried, fixed, and polished in the laboratory, cross-dating was conducted. The tree-ring width of each core was measured via the LINTAB system (RINNTECH, Heidelberg, Germany) with an accuracy of 0.001 mm. The COFECHA program (Holmes et al., 1983) was employed to verify the accuracy of the visual dating results for all the samples. In accordance with the COFECHA test results, tree cores that were inconsistent with the entire data series were eliminated. Ultimately, 88 tree cores were retained, and two cores of the same tree were chosen to calculate average ring width index (RWI) values to establish the chronology.

The ARSTAN program was selected to establish the RES of *L. gmelinii* var. *principis-rupprechtii*. In the program, a corrected negative exponential function is used to fit the growth trend generated by eliminating the genetic factors of the tree itself and the inhibition and promotion of growth trends caused by interference competition among trees. The sample sequence value and the quotient of the corresponding fitted growth curve value were subsequently revised for standardization (Qin J. et al., 2022). This method can be used to remove the growth trends of trees and nonclimatic signals caused by inconsistent disturbances and highlight the climatic signals among them (Brubaker, 1977). Moreover, the use of this method can reduce the influences of intertree competition, topography, geomorphology, and other factors on the fit of the chronology index data.

Among the chronology indicators, the standard deviation (SD) reflects the interannual variation in tree-ring growth (Fritts, 1976), and the mean sensitivity (MS) and signal-to-noise ratio (SNR) mainly represent

short-term or high-frequency changes in climatic conditions (Savva et al., 2006; Smith, 2008); moreover, the autocorrelation residual index (ARI) reflects the persistent influence of the previous year's growth on the tree-ring sequences of the current year's growth (Li Z. et al., 2011).

2.5 Climate data

All the climate data were obtained from the China Meteorological Data Service Centre (<http://data.cma.cn>). We employed climate data from the Guyuan meteorological station for the 1995–2021 period. The meteorological factors included the monthly average air temperature (TMP), monthly maximum air temperature (TMX), monthly minimum air temperature (TMN), monthly precipitation (PRE), monthly SPEI, and VPD. The SPEI over 12 months was calculated via the SPEI package. Owing to the consistent growth of trees, meteorological data from June of the previous year to October of the current year were selected for climate response analysis. Tree growth significantly decreases when the SPEI is less than -1 ; thus, we defined a year with a SPEI value less than -1 (Wu Q. et al., 2019; Vicente-Serrano et al., 2010) as a drought year, e.g., 2015.

2.6 Resilience analysis

To explore the resilience of tree growth during different climate change periods, we first employed Pearson's correlation analysis to identify the climate factors that most notably affect tree-ring growth. The time sequence superposition method (Bunn, 2010) was subsequently adopted to analyze the sensitivity characteristics of *L. gmelinii* var. *principis-rupprechtii* to climate change events on a yearly scale. Time-sequence superposition analysis constitutes a nonparametric statistical method. By calculating the amplitude of the deviation of the tree-ring index from the mean value in a set of given event years and years before and after the event, the significance of the response of the average tree growth to specific events was evaluated. All of these analysis processes were implemented in SPSS 25 and the burnr package in R (Malevich et al., 2018).

After the year of change was determined, the resistance, recovery and resilience of *L. gmelinii* var. *principis-rupprechtii* were studied by combining RES data and interannual fluctuation data of meteorological factors. The resistance, recovery and resilience of *L. gmelinii* var. *principis-rupprechtii* were calculated as follows (Lloret et al., 2011):

$$R_t = G_r/G_a; R_c = G_b/G_r; R_s = G_b/G_a$$

where R_t , R_c , and R_s denote resistance, recovery, and resilience, respectively, of the trees; G_r denotes the tree-ring value when growth declines significantly; and G_a and G_b denote the mean values of the tree-ring for the 3 years before and the 3 years after a significant decline in growth occurs, respectively. Notably, $R_t > 0.75$ indicates that the tree is highly resistant to extreme events; $R_c > 1.25$ indicates that the tree still exhibits suitable recovery after extreme events; and $R_s > 1$ indicates that the growth value after extreme events is greater than before (Liu. J., 2023).

Differences in Rt, Rc, and Rs among slope aspects were analyzed via the Kruskal–Wallis test, followed by Dunn’s post hoc multiple comparisons test. All the statistical analyses were conducted in R.

3. Results

3.1 Residual chronology and slope-specific growth patterns

The length of the RES of *L. gmelinii* var. *principis-rupprechtii* was 27 a (1995–2021) (Fig. 3). An analysis of the RWI values across different slope aspects revealed a weak, yet slightly positive, temporal trend in the RES. On the shady slope, the linear trend in the RWI indicated a marginal increase over the study period (slope = 0.016; R² = 0.077), suggesting a minor positive growth response. The semishady slope exhibited a similar pattern, with an even lower rate of increase (slope = 0.012; R² = 0.032), whereas the sunny slope demonstrated a comparable trend (slope = 0.021; R² = 0.031). Across all slopes, the low R² values indicate that interannual variability predominated over long-term trends, with limited explanatory power of the linear model. Collectively, these results suggest that the aspect influenced growth dynamics, but the observed RES growth trends remained weak, highlighting the dominant influence of short-term environmental fluctuations over the past two decades.

During the 1995–2021 period, *L. gmelinii* var. *principis-rupprechtii* exhibited slight differences in mean RWI values across slope aspects, with the semishady slope indicating the greatest mean growth (MD = 1.03), followed by the sunny (1.01) and shady slopes (0.95). Interannual variability, reflected by the SD and MS, was greatest on the shady slope, suggesting greater sensitivity to short-term environmental fluctuations. The low autocorrelation values (ARI values ranging from 0.12 to 0.18) suggested low temporal autocorrelation in the residual chronologies from prior years. The signal strength metrics (express population signal (EPS) ≥ 0.8 and SNR ≥ 4 for all slopes) confirmed that the chronologies are robust and representative of population-level growth patterns. Collectively, these results suggest that microsite conditions modulate growth variability and sensitivity, with shady conditions amplifying interannual growth responses to environmental drivers.

Table 1
Residual chronology of *Larix gmelinii* var. *principis-rupprechtii* with different slopes

Time	Slope	Samples	MD	SD	MS	ARI	Rbt	EPS	SNR
1995–2021	Shady	30	0.95	0.40	0.44	0.12	0.49	0.93	12.29
	Semishady	29	1.03	0.41	0.44	0.16	0.33	0.86	5.97
	Sunny	29	1.01	0.24	0.24	0.18	0.28	0.80	3.87
Note: MD, mean; SD, standard deviation; MS, mean sensitivity; ARI, autocorrelation residual index; Rbt, mean interseries correlation; EPS, express population signal; SNR, signal-to-noise ratio									

3.2 Climate–growth interactions across slope aspects

The climate–growth relationships clearly differed between the slopes, with the semishady slope representing an intermediate response between the shady and sunny slopes. On the shady slope, radial growth was significantly negatively correlated with the maximum temperature during the previous June and August–October and in the current March, May, July, and October, indicating that excessive thermal stress consistently constrained growth. In contrast, significant positive effects were associated mainly with moisture-related factors, particularly precipitation during the previous August and the current January, the minimum temperature during the previous October and the current June and July, and the SPEI during the current April–July. On the semishady slope, significant responses were more frequent and concentrated during both the late previous growing season and the current growing season. Growth was significantly positively correlated with precipitation in the previous August, the minimum temperature in the previous December and current July, and the SPEI from the previous August to the current July, whereas significant negative effects were observed mainly for the maximum temperature in the current May, July, and October and the VPD in the current July. On the sunny slope, the response pattern shifted toward higher moisture dependence, with significant positive correlations of growth with the SPEI from the previous December to the current February and during the current April, June and September–October and with precipitation in the previous July and the current August. The minimum temperature also yielded positive effects during the current growing season. In contrast, significant negative responses on the sunny slope were limited mainly to the average temperature in the current February and the maximum temperature in the current July. Overall, these results indicate a gradual transition from greater temperature limitations on the shady slope to greater moisture control on the sunny slope, with the semishady slope revealing mixed sensitivity to both thermal and moisture-related factors.

3.3 Slope-mediated resistance, recovery, and resilience

Significant slope-related differences were observed in the drought-response indices, although the strength and pattern of variation differed among resistance, recovery, and resilience (Fig. 5). Resistance (R_t) varied significantly among all three slope aspects, with the highest values obtained on the shady slope, the lowest values obtained on the semishady slope, and intermediate values obtained on the sunny slope. In contrast, recovery (R_c) did not differ significantly among slope aspects, despite a clear tendency toward higher median values on the semishady slope and lower values on the shady slope. Resilience (R_s) demonstrated a partially transitional pattern across slope aspects, namely, compared with the sunny slope, the shady slope exhibited significantly higher values, whereas the semishady slope demonstrated intermediate values that did not differ significantly from those on either of the other two slope aspects. Overall, these results indicate that the slope influenced drought resistance the most; post-drought recovery was less sensitive to slope conditions; and resilience followed a gradient across slope aspects.

SEM results showed that the pathways regulating drought responses differed among slope aspects, which was ultimately reflected in variation in R_s . On the shady slope, resistance (R_t) was mainly regulated by temperature factors, while recovery (R_c) was more strongly affected by water-related

factors, including precipitation, VPD, and SPEI. These factors further influenced R_s , indicating that R_s on the shady slope was jointly controlled by temperature stress and water compensation. On the semishady slope, mean temperature, maximum temperature, and VPD showed strong negative effects on R_t and R_s , while the contribution of R_c to R_s was relatively weak. Therefore, R_s on the semishady slope was mainly controlled by warming and atmospheric drought stress. On the sunny slope, the regulation pattern of R_s changed significantly. Maximum temperature, mean temperature, and VPD showed overall positive effects on R_s , whereas precipitation and SPEI showed negative effects. Overall, the control mechanisms of R_s changed from a water compensation pattern on the shady slope, to a drought stress pattern on the semishady slope, and finally to a temperature and VPD promotion pattern on the sunny slope. These differences in regulation pathways were the main reasons for the variation of R_s among different slope aspects.

4. Discussion

4.1 Slope-related differences in the sensitivity of tree growth to annual climate change

The slope aspect notably altered the climatic sensitivity of radial growth. In general, growth changed from higher temperature limitations and greater lagged effects on the shady slope to more notable moisture control on the sunny slope, while the semishady slope revealed an intermediate pattern. This gradient likely reflects persistent differences in local hydrothermal conditions among slope aspects. On shady slopes, lower solar radiation inputs and suitable soil water conditions can buffer short-term heat stress, but these conditions may also increase the dependence on antecedent moisture conditions. Under such conditions, drought effects from the previous year may persist into the next growing season, especially when the degree of soil water recharge is limited. This mechanism may explain why the shady slope revealed both higher temperature limitations and more notable lagged responses. Similar delayed drought effects have been linked to soil water depletion and increased resistance to water uptake at the soil–root interface (Pan L. et al., 2022; Sperry et al., 1998). On sunny slopes, growth is more directly tied to moisture conditions across a broader part of the year. Stronger responses to precipitation and the SPEI suggest that trees at these sites depend more notably on the current water supply than on thermal conditions. This pattern is consistent with that observed in semiarid forests, where water availability is the dominant controlling factor of growth (Chen M. et al., 2021; Gao S. et al., 2018). At exposed microsites, increased radiation and evaporative demand levels may reduce the buffering effect of local site conditions. Thus, annual growth becomes more tightly coupled to changes in the moisture status.

On the semishady slope, these two modes of control are combined. Growth on this slope responded to previous-year moisture conditions, but it also remained sensitive to the current-year temperature. This pattern suggests that semishady microsites retained some of the delayed moisture dependence found on shady slopes, while growth also shifted toward the more direct water-limited pattern observed on sunny slopes. Such an intermediate response supports the view that semishady slopes function as

transitional environments along the slope gradient (Fang O. et al., 2021). Overall, these results indicate that the slope aspect affected not only the strength but also the period of climatic control on growth. The microtopography therefore resulted in a gradual transition from temperature-limited and lag-sensitive growth on shady slopes to year-round moisture-dependent growth on sunny slopes. This interpretation is consistent with recent studies revealing that the slope aspect can alter the relative importance of temperature and moisture in driving tree growth (Zhao H. et al., 2022; Liao J. et al., 2025).

4.2 Drought resistance and recovery strategies across slope aspects

The slope aspect modified the trade-off of drought resistance and recovery in *L. gmelinii* var. *principis-rupprechtii*. In our study, resistance differed most clearly among slopes, whereas recovery varied less notably. Resilience was significantly higher on shady than on sunny slopes, while semishady slopes showed intermediate values. These differences likely resulted from contrasting microenvironmental conditions among slope aspects. On shady slopes, relatively favorable moisture conditions may buffer drought effects and help trees maintain growth during drought (Ponce-Campos, G.E. et al., 2013). However, the SEM showed that R_t was mainly associated with temperature factors, whereas water-related factors mainly affected R_c and further contributed to R_s . This suggests that moisture conditions mainly played a compensatory role in overall resilience rather than directly controlling resistance. Reduced light and lower temperature may also constrain photosynthesis and carbohydrate accumulation after drought. This may limit subsequent recovery even when immediate drought damage is moderate (Au et al., 2022; McDowell et al., 2008). These processes may explain why the shady slope showed relatively high R_t but relatively low recovery.

On sunny slopes, trees are exposed to higher solar radiation, temperature, and evaporative demand. These conditions can increase drought stress, but they may also favor rapid carbon assimilation and growth after drought. The SEM showed that temperature and VPD had positive overall effects on R_s , whereas precipitation and SPEI had negative effects. This suggests that resilience on sunny slopes may depend more on post-drought growth capacity associated with thermal and atmospheric conditions than on direct moisture compensation. Greater light availability may further support rapid carbon assimilation after drought (Jin T. et al., 2011; Wei J. et al., 2018). However, the observed R_s on sunny slopes remained lower than that on shady slopes, indicating that these positive climatic pathways did not translate into higher overall resilience. However, this does not mean that water limitation is unimportant. Severe or prolonged drought may still restrict growth when soil moisture becomes insufficient. The semishady slope combined features of both end-member environments. However, its R_s was more strongly constrained by warming and atmospheric drought than that of the shady slope. The SEM showed strong negative effects of temperature and VPD on R_t and R_s , while the contribution of R_c to R_s was relatively weak (Fig. 6). Thus, moisture compensation may be less effective on the semishady slope than on the shady slope. Although its observed resilience remained intermediate, its climatic constraints were relatively strong. This interpretation is consistent with its mixed climate sensitivity in the correlation analysis and with broader studies suggesting that drought resilience emerges from interactions between

local environmental conditions and tree physiological adjustment (Fang O. et al., 2019; Ma Q. et al., 2023; Xu C. et al., 2017; Allen et al., 2016; Hartmann, 2011). Overall, our results suggest that slope aspect not only affects drought intensity but also changes the balance between maintaining growth during drought and restoring growth after drought. This microtopography-driven trade-off is an important mechanism shaping drought resilience in semiarid plantations.

4.3 Implications of different slope resilience strategies for forest management

The slope-related differences in climate sensitivity and drought resilience indicate that artificial forests in the Liupan Mountains should be managed according to local site limitations rather than as a uniform system. On shady slopes, relatively notable lagged effects and lower recovery capacity suggest that repeated drought may have lasting effects on growth. The main management goal at these sites should therefore be to improve post-drought recovery. Measures that reduce competition and enhance local water retention may be effective. Selective thinning can reduce competition for water and light. Litter retention, soil conservation, and small-scale water-holding practices may also help buffer delayed drought effects. These approaches are reasonable because slope-related differences in soil water storage can strongly influence growth performance in larch plantations in the Liupan Mountains (Liu Z. et al., 2018). These findings are also consistent with evidence that targeted stand management can reduce drought vulnerability under climate change (McCauley et al., 2022).

On semishady slopes, observed resilience showed intermediate characteristics, but the SEM indicated relatively strong constraints from temperature and atmospheric drought. These stands therefore represent transitional environments, but they should not simply be regarded as sites with intermediate climate sensitivity. Management should focus on maintaining stand structural stability under climatic stress. Moderate density control may help balance light conditions and water use. However, excessive canopy opening should be avoided because it may increase thermal and evaporative stress. Maintaining a relatively stable stand structure may reduce additional climatic stress on these slopes. This interpretation agrees with recent studies showing that topographic heterogeneity can increase spatial variation in drought resistance and resilience across forest landscapes (Sang et al., 2024).

On sunny slopes, high temperature and evaporative demand make water availability important for maintaining drought resistance, although the SEM showed that the overall Rs response was positively associated with temperature and VPD rather than with precipitation or SPEI. These stands may recover more effectively at the whole-response level after drought, but severe water limitation may still reduce their resistance during prolonged drought. Management at these sites should therefore continue to prioritize water conservation. Maintaining surface cover, limiting soil disturbance, and avoiding excessive stand density may help conserve soil moisture during dry years. Moreover, semiarid forests should be closely monitored under future warming because stronger evaporative demand may increase drought risk when drought becomes more frequent or prolonged (Cook et al., 2018). Recurrent severe drought

may still increase hydraulic failure and mortality risk, even in stands that even when some climatic pathways positively contribute to Rs (Choat et al., 2018).

Overall, our results suggest that slope-specific management can improve the long-term stability of artificial forests in the Liupan Mountains. Shady slopes require reduced competition and improved water retention to promote post-drought recovery. Semishady slopes require stable stand structure to reduce additional thermal and atmospheric drought stress. Sunny slopes require water conservation to maintain drought resistance under high evaporative demand. Such a slope-based approach may improve both stand-level resilience and landscape-scale stability under ongoing climate change.

5. Conclusion

This study demonstrated that slope aspect is a key factor shaping the drought response of *L. gmelinii* var. *principis-rupprechtii* in the Liupan Mountains. Slope aspect affected both the climatic controls on radial growth and the balance between drought resistance and recovery, ultimately resulting in differences in resilience. On shady slopes, resistance was mainly regulated by temperature, whereas water-related factors mainly affected recovery and provided a compensatory effect on resilience. On semishady slopes, resilience was more strongly constrained by temperature and atmospheric drought, while the contribution of recovery was relatively weak. On sunny slopes, the regulation pattern changed, with temperature and VPD showing positive overall effects on resilience, whereas precipitation and SPEI showed negative effects. These results indicate that microtopography not only modifies drought intensity but also reshapes the pathways through which trees maintain growth during drought and recover after drought. Therefore, drought-response mechanisms can differ markedly even within the same plantation. Our findings highlight the importance of microsite conditions in understanding drought resilience in semiarid plantations and support slope-specific management rather than uniform stand-level treatments.

Declarations

Data statement

The raw data supporting the conclusions of this article are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no competing interests.

Ethics approval

This article does not contain any studies with human participants or animals. The collection materials of the plants, complies the relevant institutional, national, and international guidelines and legislation.

Consent to publish

All authors have read and agreed to the published version of the manuscript.

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Author Contribution

Weiyue Wang✉Writing—original draft, Data curation, Formal analysis, Visualization✉. Dongmei Wang, Pengtao Yu (Data curation, Conceptualization). Yanfang Wan, Yanhui Wang (Writing—review & editing).

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Figures

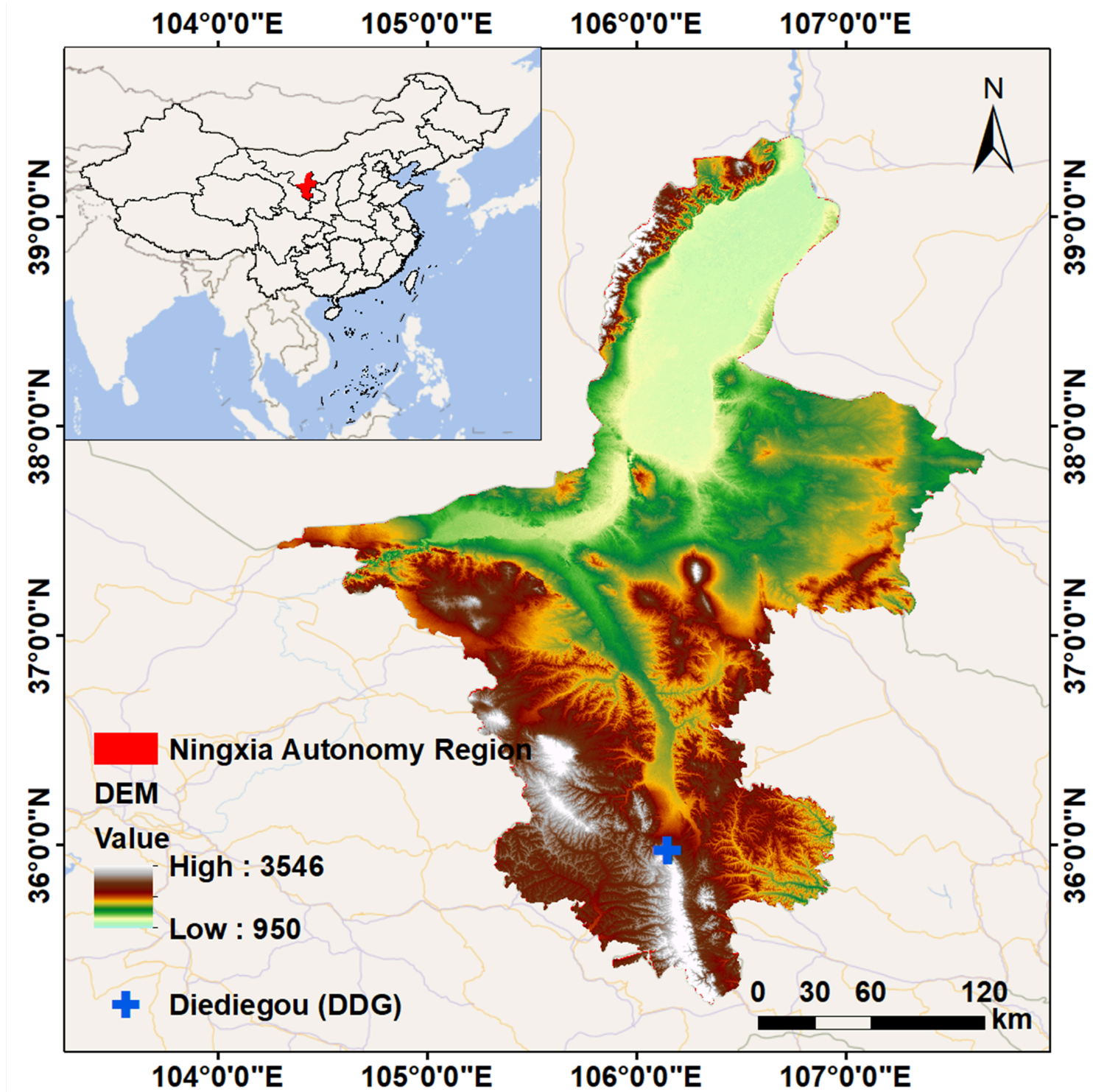


Figure 1

Location of the study area.

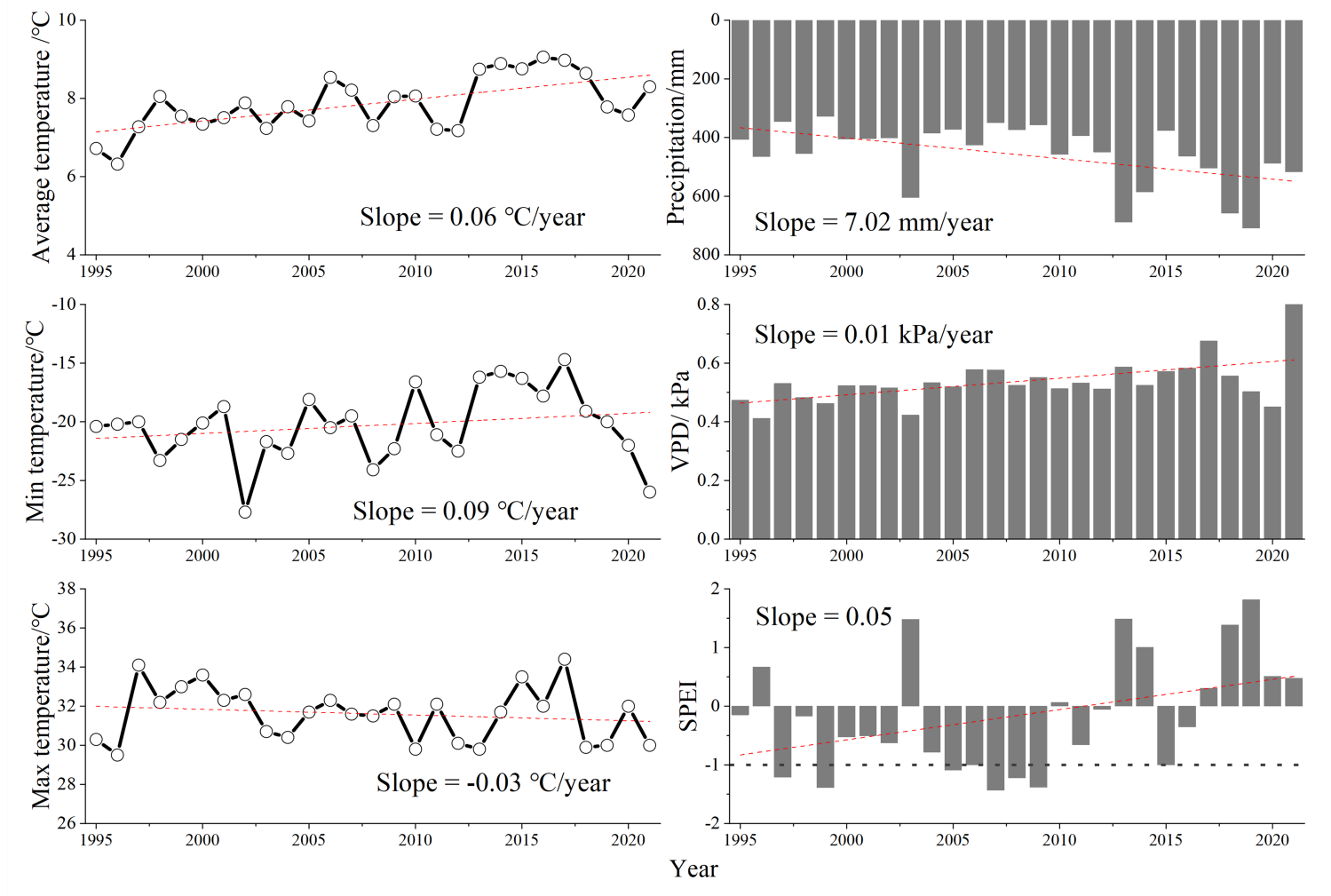


Figure 2

Interannual variation trend of climate factors at the Guyuan meteorological station (1995–2021).

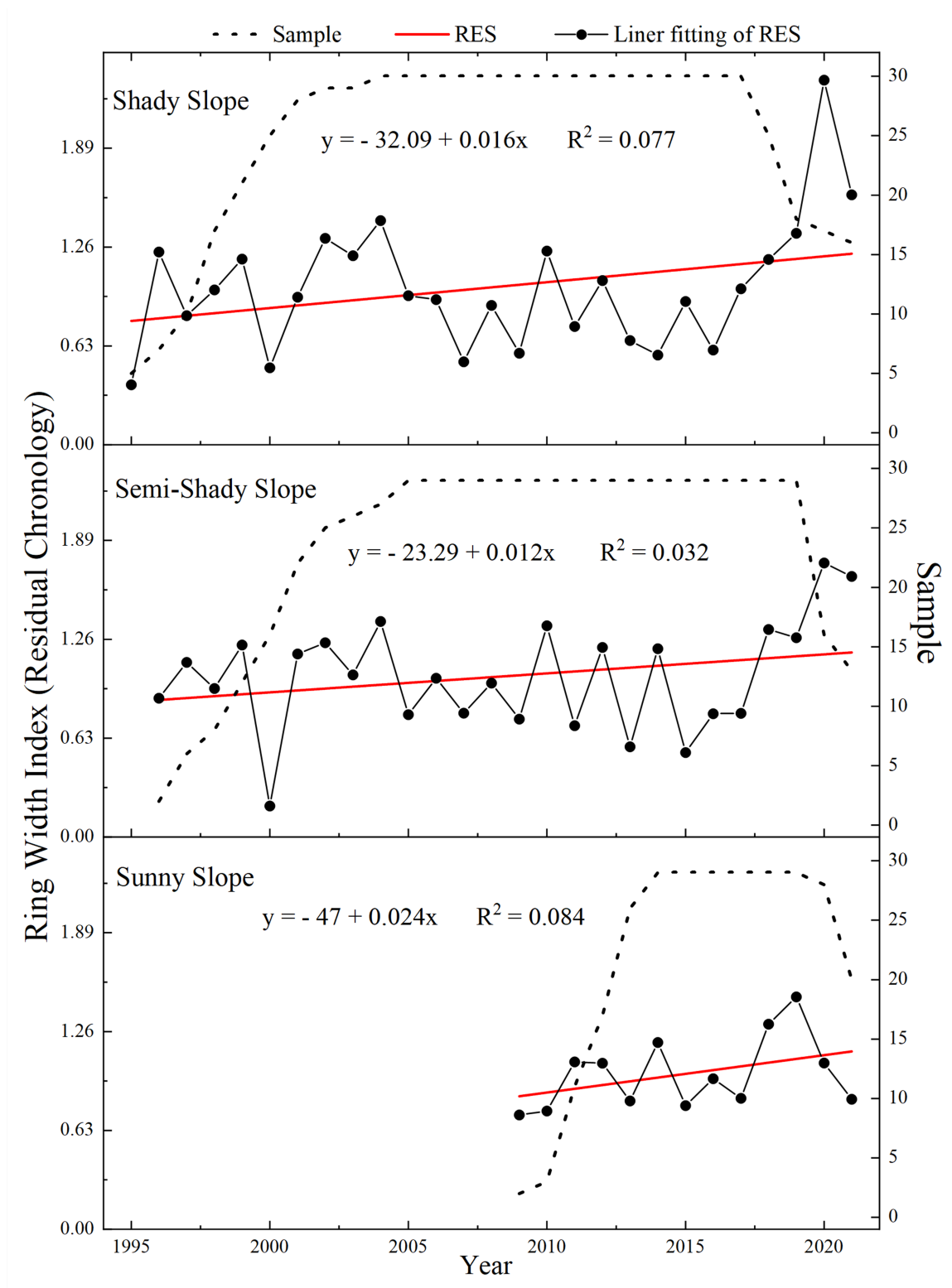


Figure 3

Residual chronology (RES) of *Larix gmelinii* var. *principis-rupprechtii* across three slope aspects (shady, semishady, and sunny slopes) from 1995 to 2021. The black solid circles indicate annual residual ring width index values, the red lines indicate linear trends in the RES, and the black dashed lines denote the sample size.

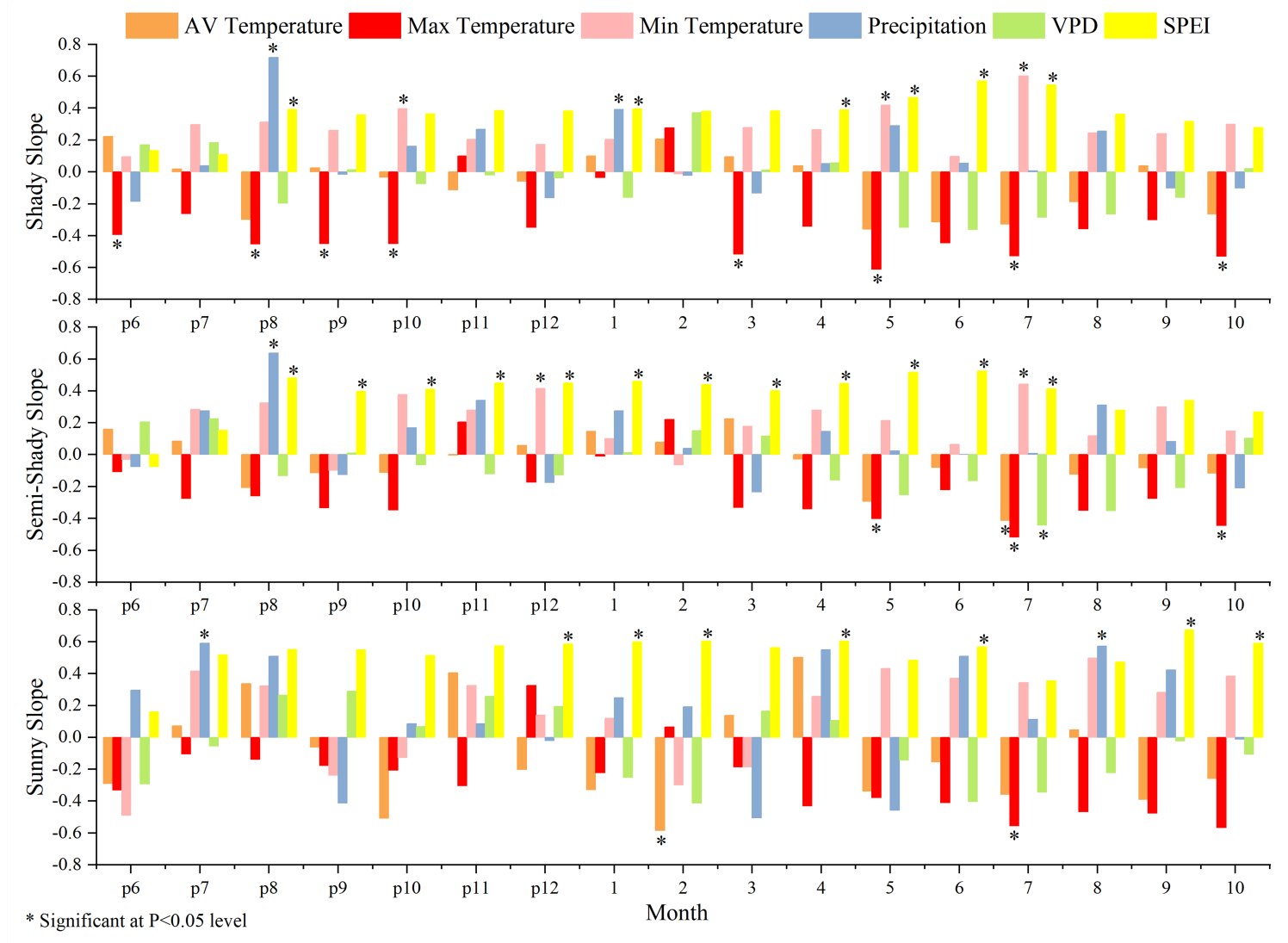


Figure 4

Correlation coefficients between the residual chronology and meteorological factors. Note: p indicates the previous year.

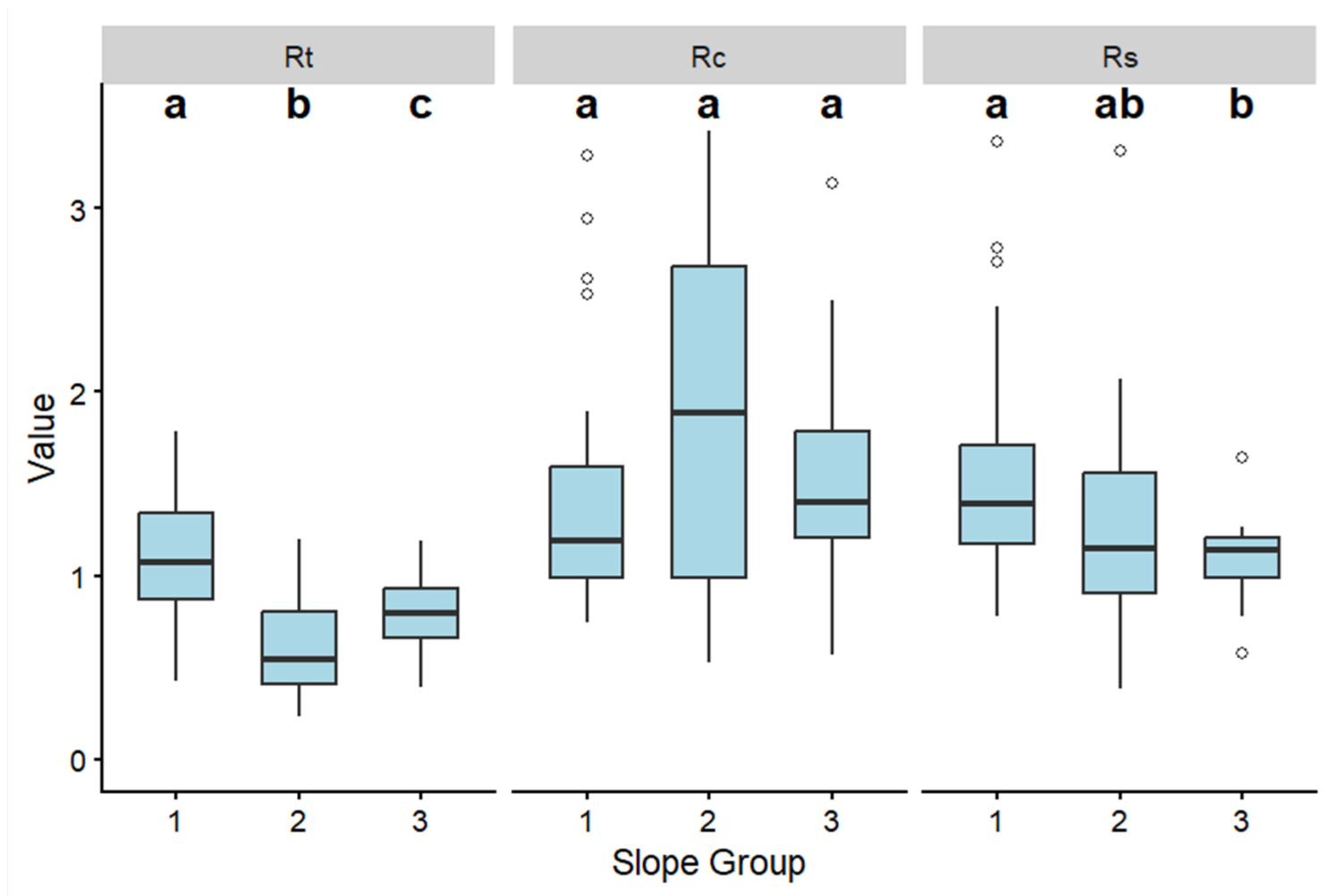


Figure 5

Resistance, recovery and resilience of tree-ring growth in a drought year (2015). The numbers 1, 2, and 3 on the X-axis denote shady, semishady and sunny slopes, respectively. The centerline in each box indicates the median. The open circles indicate outliers. The different lowercase letters indicate significant differences among slope groups at $P < 0.05$.

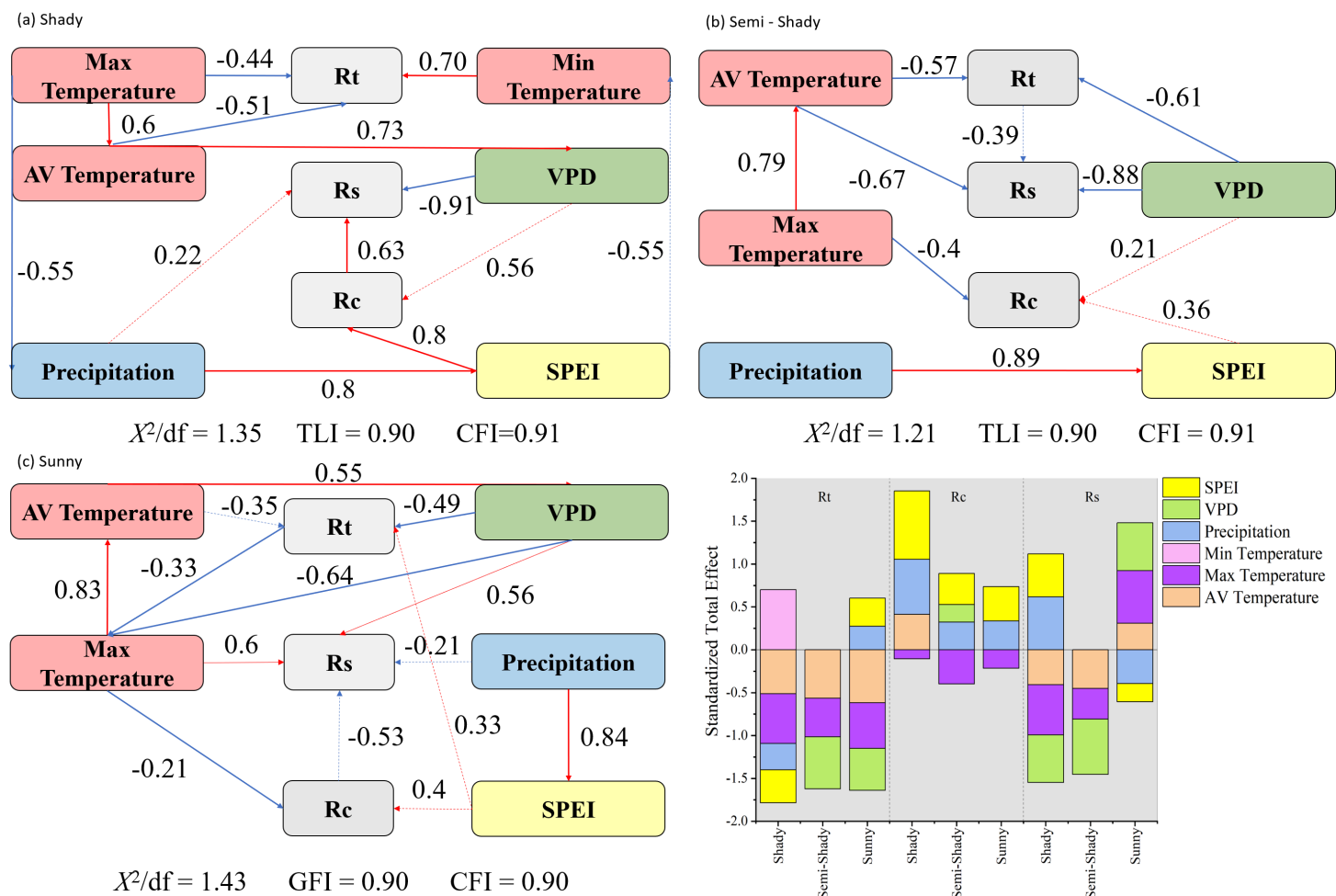


Figure 6

Structural relationships among drought-related climatic factors, resistance (Rt), recovery (Rc), and resilience (Rs) across different slope aspects. Solid arrows indicate significant paths, whereas dashed arrows indicate nonsignificant paths. Numbers represent standardized path coefficients. Red and blue arrows indicate positive and negative effects, respectively.