Fifty years of change in the lower tree line in an arid coniferous forest in the Qilian Mountains, northwestern China

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Research

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Fifty years of change in the lower tree line in an arid coniferous forest in the Qilian Mountains, northwestern China

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Abstract

Background: Tree-line areas exhibit significant changes in response to climate change, including upward migration. Lower tree line dynamics are rarely studied, but as unique features in arid and semi-arid areas, they may influence forest distribution. Here, 8 lower tree-line plots in *Picea crassifolia* Kom. (Qinghai spruce) forest in the arid and semi-arid Qilian Mountains of northwestern China were used to determine changes in tree line location, landscape pattern, and relationships with meteorological factors during 1968-2018.

Results: The results showed that the lower tree line descended by an average of 9.82 m during 1968 to 2018, and exhibited almost no change after 2008. The change in pattern was mainly related to the age of trees in which small trees were dense and

clustered, and large trees became more scattered and evenly distributed. Tree regeneration rates changes in the lower tree line were highly positively correlated with temperature, and also positively related to annual precipitation.

Conclusions: In the past 50 years, the lower tree line in arid areas exhibited a downward trend but it is unclear whether the downward trend of the lower tree line will stabilize or even reverse due to the weakening of climate warming degree.

Keywords: arid mountains, lower tree line, vegetation landscape, climate change

1. Background

Tree lines are apparent vegetation boundaries, commonly defined as the elevational limit of trees greater than 2 m in height [1-3]. The area extent and pattern of tree lines have important geological and ecological meaning, and changes in tree lines play an important role in the development of mountains and regional ecological changes [4-6]. Over the past century, mountain areas have experienced greater climate warming, increased carbon dioxide concentration, and increased extreme weather events than the global average [7, 8]. Tree line ecotones are more sensitive to climate change and are therefore ideally suited for climate change monitoring [9-12].

Tree lines are comprised of the upper and lower forest boundaries, and they determine the distribution of forests in mountain regions. However, the lower tree lines generally only appear in arid or semi-arid mountainous areas worldwide [13, 14]. In the arid and semi-arid mountainous areas along the lower tree line, climate change is more complex than elsewhere [15] and exhibits increases in temperature, decreases in precipitation frequency, and increases in extreme rainfall events [16]. More significant climate change and the scarcity of water resources render tree line vegetation in arid areas more fragile and more susceptible to climate change [17].

Although the mountain environment where the lower tree lines are located is more fragile and sensitive, the lower tree lines received little scientific attention [18]. In contrast, much research has been conducted in the upper lines of mountain forest belts, including studies on distribution, formation mechanism, and the response of tree line regional location and landscape pattern to climate change [7, 19-21]. Research on the lower tree line in the arid and semi-arid areas in northwestern China is also relatively scarce [22].

There are lots of studies pay attention to the relationship between the tree line position, pattern and the change due to meteorological factors. It has been determined that the change in the upper tree line is mainly related to temperature, while the change in the lower tree line is limited by precipitation. The formation of the upper tree line is limited by the growing season mean air temperature of 5.5 to 7.0°C or a growing season mean soil temperature of 6.7-0.8 C at 10 cm soil depth [23, 24]. Further, at lower tree line positions, tree demographic processes are more vulnerable to water stress and balance [25, 26]. Also, radial growth at lower tree lines appears more closely related to climate change, in particular to precipitation from May to June [13].

We chose *Picea crassifolia* Kom. forest lower tree line in the arid region of northwestern China to study the response of the lower tree line position and landscape pattern to climate change. Located in the northwestern arid region of China, forest vegetation of the Qilian Mountains is not only a valuable forest resource, but also have the ecological function of water conservation [27]. *Picea crassifolia* Kom. forest is the dominant and establishment tree species in the Qilian Mountains, [28]. Under the influence of climate change in recent years, vegetation cover and growth in Qilian Mountains have changed significantly[29] and the cover of the main spruce species, *Picea crassifolia* Kom., has also increased, and the boundary of the up tree line has been moving up [30]. The researches of *Picea crassifolia* Kom. mostly focuses on dendroclimatology and pay more attention to the changes in the upper tree line [31-33].

A sample survey along an elevational transect can be used to reconstruct deterioration of tree conditions ; it is a powerful tool to investigate the relationships of tree growth and climate change [20]. We selected a typical watershed in the Qilian Mountains to conduct a sample survey of the lower tree line area to determine changes in, if any, over the past 50 years in: (1) the position of *Picea crassifolia* Kom. forest at the lower tree line, (2) *Picea crassifolia* Kom. landscape pattern at the lower tree line, and (3) the main meteorological factors affecting the changes in *Picea crassifolia* Kom. forest at the lower tree line. This research increases the understanding of processes in the lower tree line position and landscape pattern change in arid and semi-arid regions with climate change.

2. Methods

2.1 Study Area and Method of Field Sampling

We conducted this study at the Dayekouzi (38°26′-38°35′N, 100°14′-100°19′E) and Dakouzi watersheds (38°33′-38°39′N, 100°15′-100°19′E) in the upper reaches of the Heihe River Basin in the Qilian Mountains of China. The watersheds are located in the Xishui Forest District of the middle Qilian Mountains, at an altitude of 2500-4700 m. The foundation species is *Picea crassifolia* Kom. which has patchy distribution on shaded and semi-shaded slopes at an altitude of 2500-3400 m; the area also contains sparse *Qilian juniper (Sabina przewalskii Kom.)*. The soil is mainly mountain gray-brown and subalpine shrub meadow, and is characterized as relatively thin, with mainly silt sand texture [34].

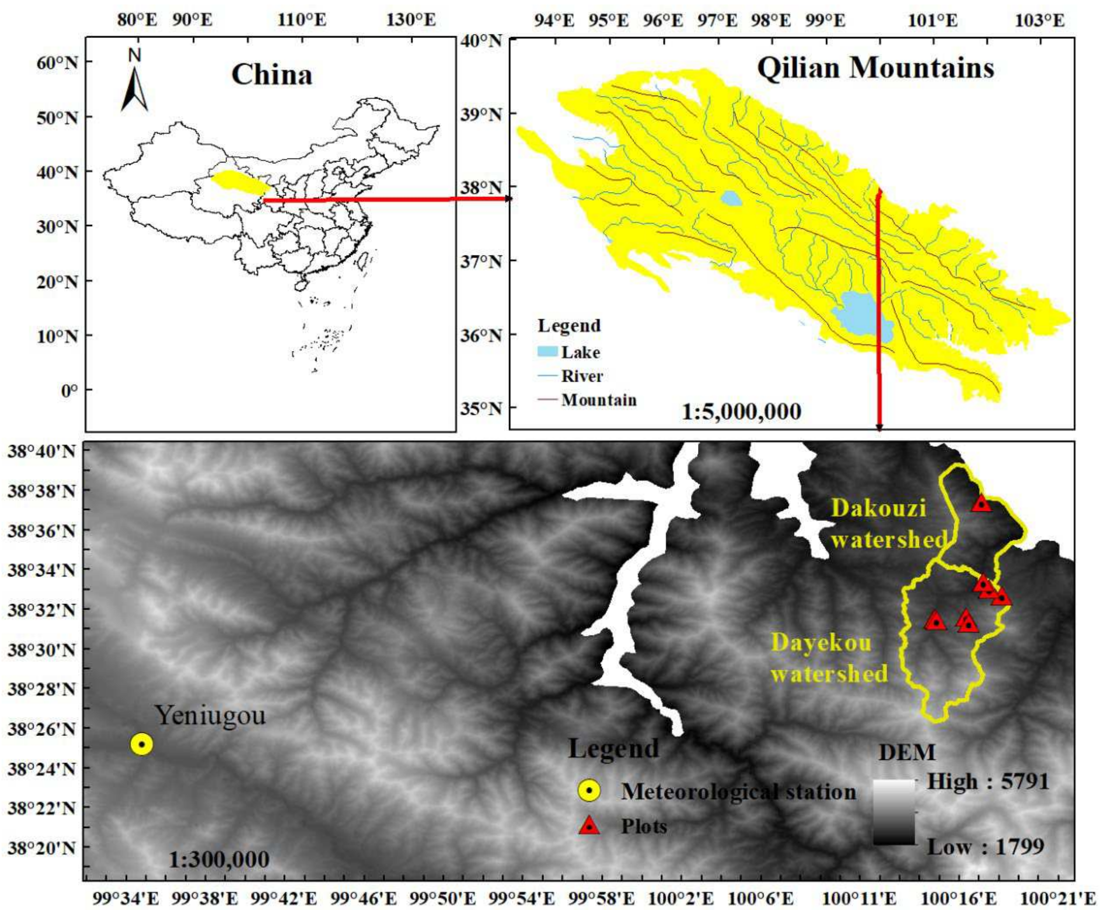

Figure 1. Study Area in the Qilian Mountains of northwestern China.

All plots were surveyed between July 31 and Oct. 11, 2018. Plots were set up on the edge of the *Picea crassifolia* Kom. tree line. A total of 8 plots were surveyed, except for plot 1 in the Dakouzi watershed, plots were in the Dayekou watershed (Figure 1); details are presented in table 1 and Figure 2. We set the spline perpendicular to the slope direction and along the slope direction to ensure that one side is parallel to the maximum slope of the area and includes the boundary of the tree line. All trees with height of <1.3 m were defined as small trees, and trees with height of ≥1.3 m were defined as large trees. We recorded tree positions (x and y coordinates, defined with respect to the lower left corner of the plot), size (diameter at breast height (1.3 m; (DBH) [35]), tree height and crown width of all trees with height > 1.3 m. Height of 1.3 m meets the division of the tree line (＞ 2 m), and the measurement height of breast diameter. The area of each plot is 50×30 m^2.

Table1 Characteristics of the sites, in aspect, 1 for shaded slopes (N (0-22.5°, 337.5-360°)), 2 for semi-shaded (NE (22.5-67.5°), E (67.5-112.5°), NW (292.5-337.5°)), and 3 for partly-sunny slopes (SW (112.5-157.5°), SE (202.5-247.5°), and W (247.5-292.5°)).

Plot Number	Latitude	Longitude	Elevation (m)	Aspect	*Picea crassifolia Kom.(number)*	Qilian Juniper (number)
1	100.29°E	38.62°N	2595	2	156	0
2	100.30°E	38.54°N	2980	2	397	10
3	100.29°E	38.55°N	2800	1	282	0
4	100.27°E	38.53°N	3013	2	176	1
5	100.25°E	38.53°N	2852	3	75	68
6	100.25°E	38.52°N	2848	2	112	25
7	100.27°E	38.52°N	3091	1	61	0
8	100.29°E	38.56°N	2673	2	170	1

Figure 2. Examples of conditions in sample spots.

We used climate data from the nearest meteorological station at Yeniugou (**Figure 1**) located at a mean distance of < 45 km and altitude of 3,180 m. We calculated climate variables of average monthly temperature, monthly precipitation, seasonal average temperature, seasonal precipitation, annual average temperature, annual precipitation from 1964-2013 to determine the relationship between *Picea crassifolia* Kom. lower tree line change and climate.

2.2 Tree Recruitment and tree line position

Tree age calculation of each sample was based on the survey results of the *Picea crassifolia* Kom. forest sample plot established in the Guantai area (100.15°E, 38.32°N) in Dayekou watershed. This plot was established in a monospecific *Picea crassifolia* Kom. forest to study basic characteristics; in this plot, we obtained tree cores (at 1.3 m) and measured breast diameter (at 1.3 m) of 358 trees with a height of > 1m. Trees in the sample plot cover *Picea crassifolia* Kom. forests of various ages, and the age of each tree was determined with tree core sampling [35]. Based on the data from the Guantai site, we first calculated the average DBH of each tree age group. Then, we fitted a function between DBH and the age of the tree. The simulation found that the power function had the best fit. The formula was Y = $4.8827X^{0.9661}$ (R^2 = 0.7253, P <0.001) (Figure 3). Using this simulation formula, we calculated the age of all *Picea crassifolia* Kom. forests in the sample based on the DBH data of each tree in the sample survey. Then we calculated the age structure of *Picea crassifolia* Kom. forest in each plot to expresse the results of changes in the relative rates of tree recruitment and mortality over time by a population of live trees [36].

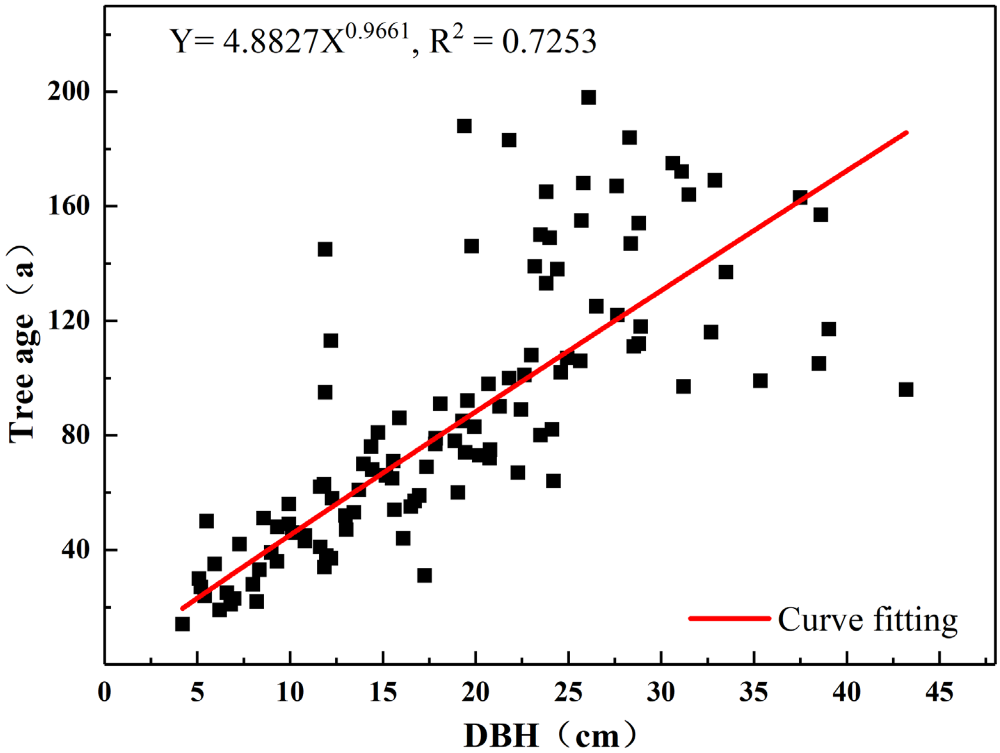

Figure 3. Functional relationship between diameter at breast height and age of trees in Guantai sampling.

To determine the rate of tree line shift from 1918 to 2018, we defined the lower tree line position for an individual slope as the mean elevation of the 20 lowermost *P. crassifolia* trees>2 m in height that were alive in a given year [3]; then, using this definition, we determined the elevation (y coordinate) of the upper and lower tree line of *Picea crassifolia* Kom. forest in different years (1968, 1978, 1988, 1998, 2008, and 2018). Then we calculated the average elevation of the lower forest line in different periods.

2.3 Spatial pattern analysis

In each plot, we assessed the spatial pattern (clumped, random, or regular) of trees using a method based on Ripley’s K function [37]. This function uses all tree-to-tree distances to calculate a measure of the spatial pattern at various distances (t). Ripley’s K statistic is an average isotropic measure of the type of spatial pattern. The specific calculation method is as follows:

The secondary structure characteristics can be simplified to the following formula：

$$\mathrm{K(t)} = \lambda^{-1} \tag{1}$$

Where t is any value> 0. K is the average number of points in an area unit, estimated by n / A, A is the plot area, and n is the total number of points (number of individual plants). In practice, the following formula was used to estimate:

$$\widehat{K}(t) = \left(\frac{A}{n^2}\right)\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{W_{ij}}I_i(u_{ij}) \quad (i \neq j) \tag{2}$$

Where u_ij is the distance between two points i and j, when u_ij≤t, I_i (u_ij) = 1, when u_ij> t is, I_i (u_ij) = 0; W_ij is the center of point i, and u_ij is the radius. The ratio of the circumference of A to area A, with H (t) representing K^ (t) / π

$$H(t) = \sqrt{\frac{\widehat{K}(t)}{\pi}} \tag{3}$$

Spatial pattern was obtained with:

$$L(t) = \widehat{H}(t) = \sqrt{\frac{\widehat{K}(t)}{\pi}} - t \tag{4}$$

L(t) was used to represent the pattern of the forest. Where, L (t) should be equal to 0 at all scales t, when distribution is random. If L (t)> 0, the population is distributed in clusters at scale t; if L (t) <0, the population is uniformly distributed at scale t.

To test for significance of the deviation of L(t) from zero, Manly [38] proposed to use the Monte Carlo stochastic simulation method to fit 95% confidence interval. Using t as the abscissa and the upper and lower envelope traces as the ordinate. We used the actual distribution data of the population (dot map) to calculate the L(t) value at different scales. Values within the envelope range indicated random distribution, values above indicated aggregate distribution, and values below indicated even distribution.

We analyzed the spatial pattern of trees in each plot using the Ripley's K function and Monte Carlo stochastic simulation method in ADE4 package [39]. The confidence interval was 99%, P＜0.01; the interval selected was1 m, and the maximum scale was selected to be half of the minimum side length of plot. Plot sides were 15 m.

2.4 Correlation analysis between tree regeneration and climate change variables

We determined the annual regeneration rate of trees from 1968 to 2013 based on the calculated age of trees. The formula was as follows:

$$N_i = N_S \frac{1}{(1-m)^j}. \quad (5)$$

Where N_i was the number of trees recruited in year i, N_S was the number of trees recruited that survived until 2013, m was mortality rate (which we assumed represented a constant value of 4.9% per year), and j was the time interval from year i to 2013. The value of N_S was obtained for each tree age class; Ns value of 0 indicated that all of the trees that were recruited in year i (N_i) have died.

To study the impact of climate change on tree recruitment in tree line ecotones, we used Pearson's correlation coefficient between tree recruitment rates and values of climate variables in a given year using SPSS 19 [40]. Significance level was P = 0.01 or P = 0.05. If the sample's correlation coefficient is greater than or equal to this critical value, the correlation passes the test

3. Results

3.1 Basic characteristics of plots

We counted the basic information of the plots at the lower tree line (Table 2). Combines with Table 1 we can find that the number of *Picea crassifolia* Kom. trees on shaded and semi-shaded slopes plots was higher than that on the partly-sunny slope. There were sporadic Qilian junipers on the semi-shaded slope. The number of Qilian junipers on the partly-sunny slope was almost the same as that of *Picea crassifolia* Kom. Canopy and tree line density at the lower tree line at an altitude below 2600 m and above 3000 m were slightly lower than those in other tree line plots. The smaller the stand density, the larger the average breast diameter and average tree age.

Table 2. Survey characteristics of the sites.

Plot Number	Stand density （number/hm^2）	Average breast diameter（cm）	Average forest age（a）
1	1040	5.4	39
2	2647	6.0	42
3	1880	9.5	46
4	1173	8.5	44
5	500	18.0	69
6	747	13.2	59
7	407	16.3	66
8	1133	12.3	51

The age structure of trees at the lower tree line is similar age structure at all three sampling sites. The younger trees that have been recruited since 1980 reached 68 % of the current population ; and reached 78% since 1960. (Figure 4).

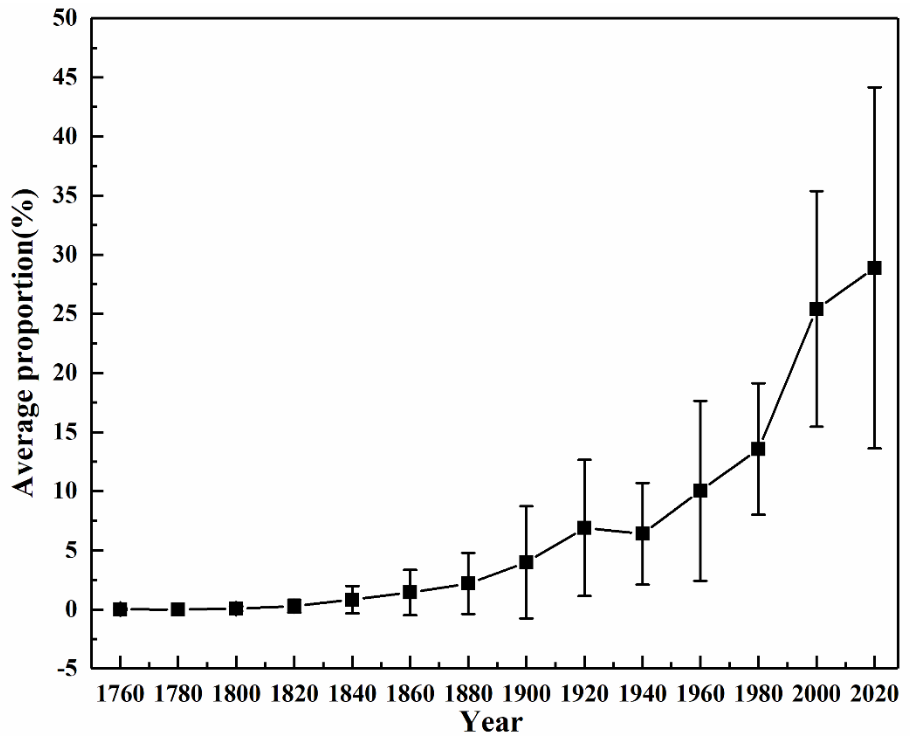

Figure 4. The age structure of the tree populations at the in the tree line ecotones plots at the lower tree line.

3.2 Dynamic changes in tree line position of the lower tree line

The change in the lower tree line position is shown in Figure 5. Tree line in Plot 1 did not had a tree line in 1968 and descended by 8.11 m from 1978 to 2018; the rate of descent has been decreasing from 1978 to 2018. The tree line for plot 2, 3, and 4 descended by 23.55, 18.85, and 10.20 m, respectively, between 1968 and 2018. In plot 3, the rate of tree line descent first decreased, and then increased slightly from 1998 to 2008; while in plot 2 and 4, it showed a slight upward trend from 1968 to 1998, and then fell sharply.

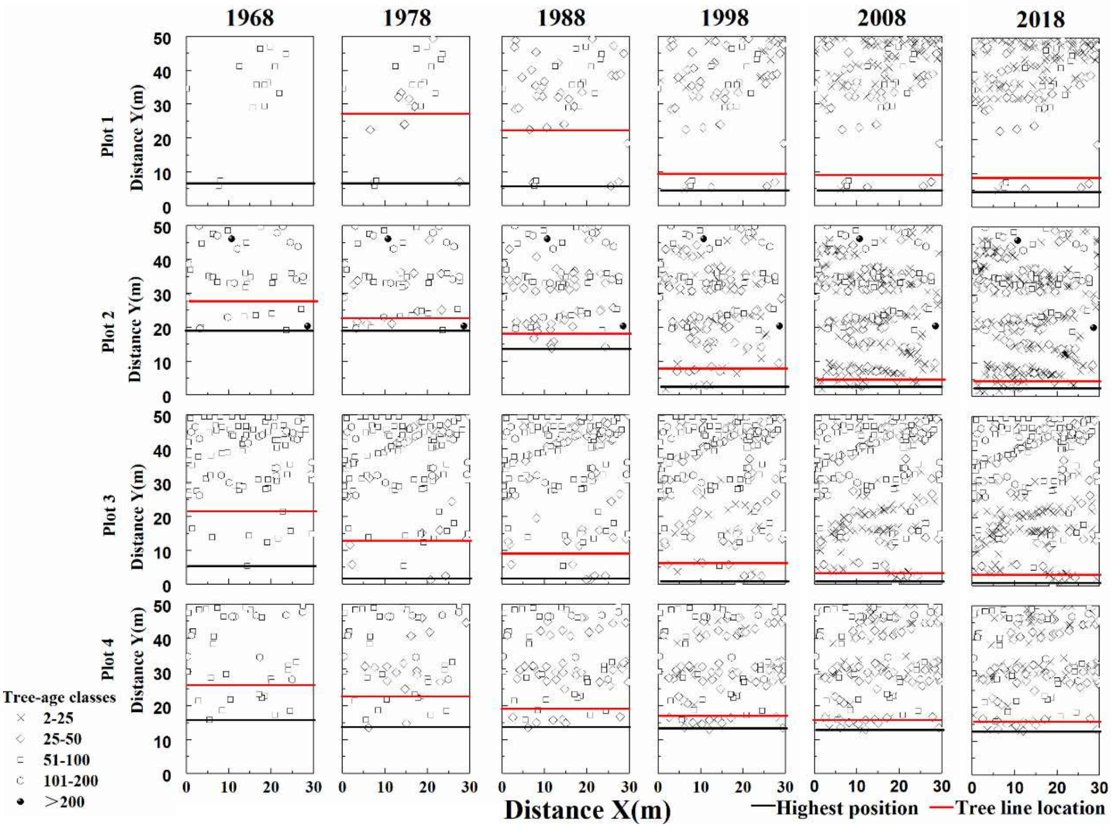

Figure 5a. Changes in position of the lower tree line (1) (Distance Y(m) is the distance along the slope direction and Distance X(m) is the distance spline perpendicular to the slope direction.)

The descent of the tree line in plots 5-8 was relatively slow than plots1-4 (Figure 5b), moving down by 3.54, 2.58, 6.36, and 5.41m, respectively, between 1968 and 2018. The decline rate in plots 5, 7, and 8 first decreased and increased during 1988-1998, and then rapidly decreased. The descent rate of the tree line in plot 6 slowed in 1998-2008, and then stabilized.

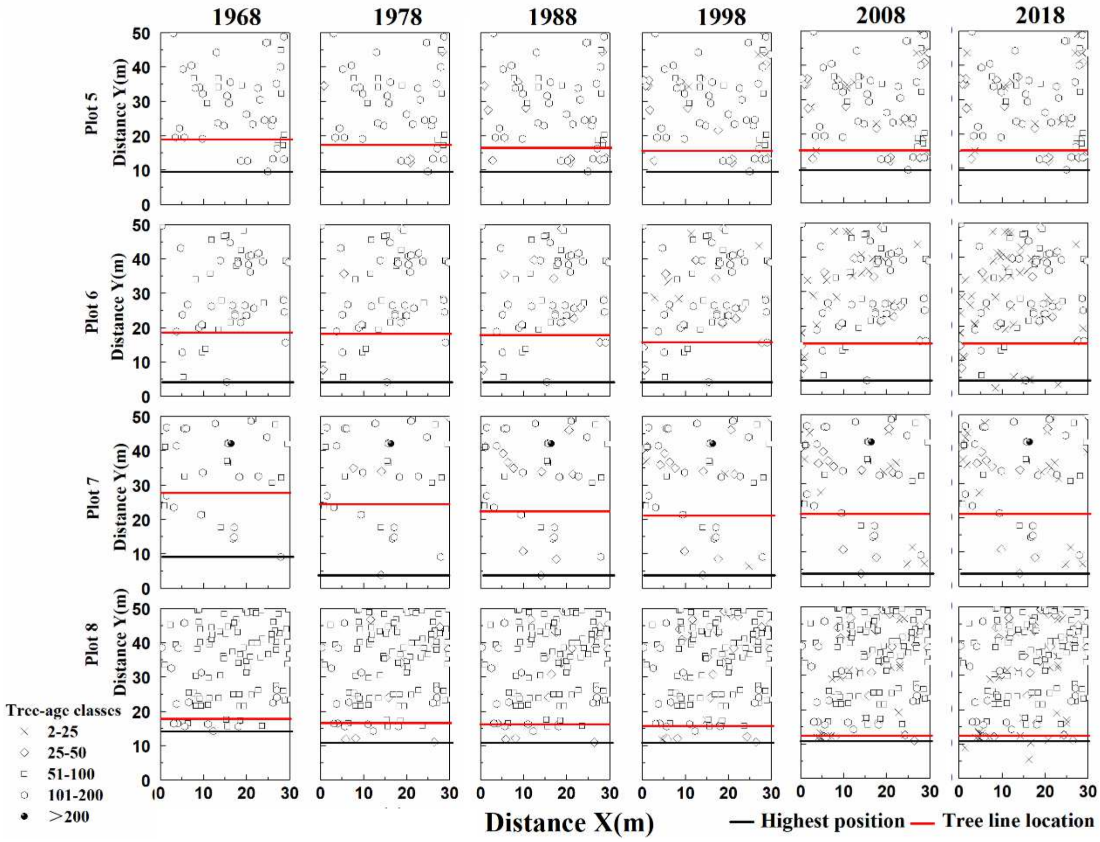

Figure 5b. Changes in position of the lower tree line (2)

The lower tree line has moved down by an average of 9.82 m in the last 50 years (Table 4). The decline was greatest in 1988-1998. Although the descent continued after 1998, the extent was much smaller and the lower tree line remained almost unchanged from 2008 to 2018.

Table 4. Decadal and 50-year mean distance and standard deviation of descent elevation of the lower tree line.

Year	1968-1977	1978-1987	1988-1997	1998-2007	2008-2018	Total for 1968-2018
Mean (m)	2.98	2.83	3.05	1.34	0.00	9.82
Standard Deviation(m2)	2.44	1.85	3.64	1.43	0.00	7.53

3.3 Dynamics of the spatial pattern at the lower tree line

Changes in spatial pattern at the lower tree line were determined with point-pattern analysis at different scales and in different years (Figure 6). In our analysis of spatial point patterns, we found that not all plots exhibited uniform distribution at all scales, and there was a trend to shift from random to cluster distribution at the lower tree line. Plots with older average tree ages were more randomly distributed at all scales. We also found that trees of different ages clustered together and clear boundaries occurred. Small trees were dense and clustered, and large trees became more scattered and evenly distributed (Figure 7).

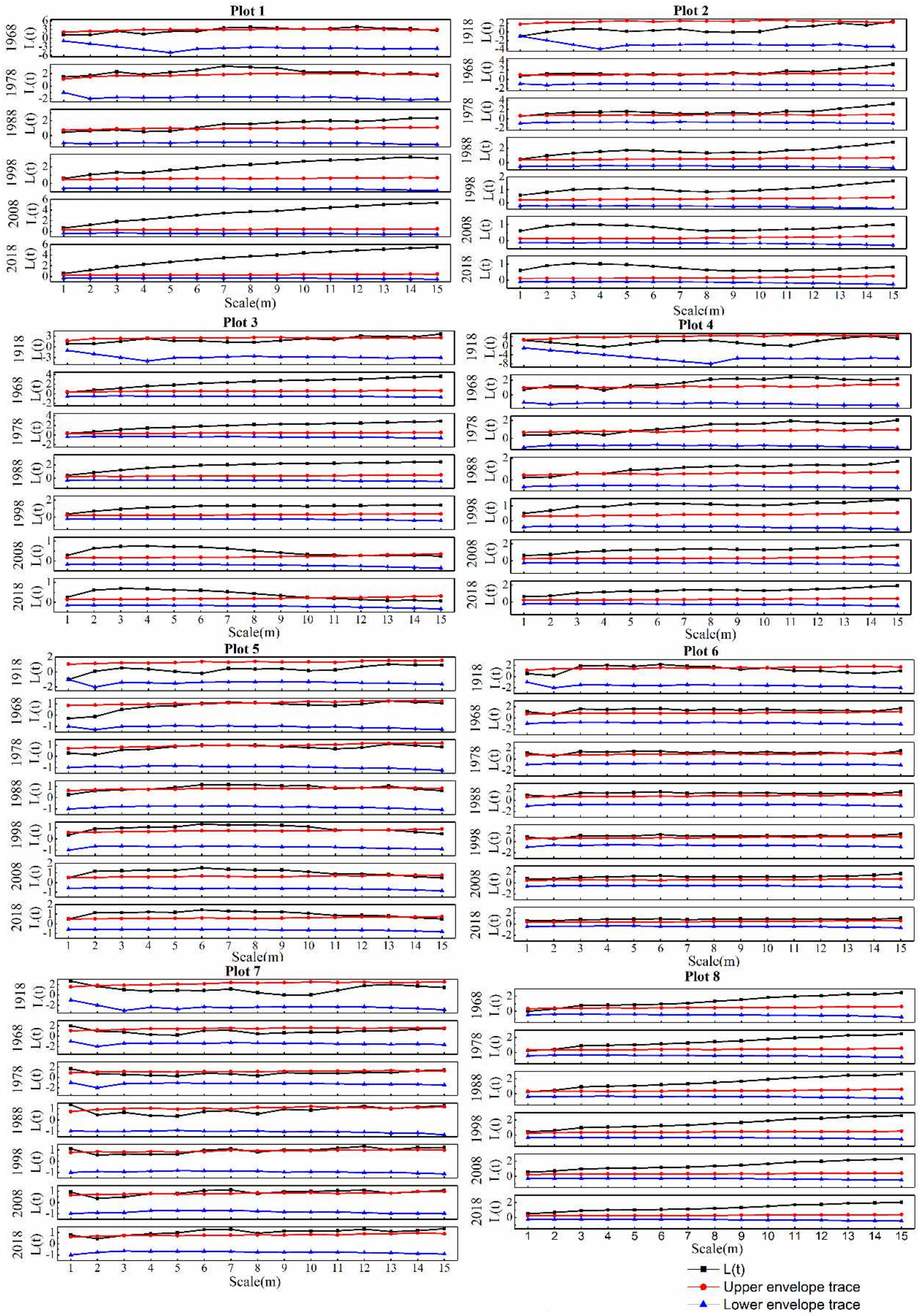

Figure 6. The change in point pattern (Graph of L(t) versus distance (t) for trees at each plot) at the lower tree line. The black line shows L(t), and the red and blue lines

show the 99% confidence envelope for a random distribution.

Figure 7. Layering of trees of different ages.

3.4 Relationship between tree line changes and meteorological factors

We calculated climate trends at the Yeniugou weather station, and determined that the temperature increased at a mean rate of 0.41°C decade from 1968 to 2008, and there is a slight drop after 2008. The annual average temperature in the region increased by a total of 2.00°C from 1968 to 1998 but decreased by a total of 0.49°C from 1998 to 2013. In general, the rate of temperature increase was lowest in autumn (0.02°C per year) and highest in summer (0.06°C per year) from 1968 to 2013. Annual precipitation increased with a mean rate of 0.82 mm per year. Spring precipitation decreased slightly (by 0.13 mm per year), whereas summer precipitation increased significantly (0.91 mm per year). Fall and winter precipitation changed little. Therefore, the change in annual precipitation was mainly caused by increased summer precipitation.

Analysis of meteorological factors and changes in the location of the lower tree line (Table 4) showed that the trend in temperature warming from 1968 to 2007 has been weakening, especially in 1998-2007 (the increase in temperature was < 1°C), while the lower tree line descent from 1968 to 2007 also slowed. There was a slight decrease in temperature after 2008, and the elevation of the lower tree line remained unchanged.

The correlation between different meteorological factors and tree renewal rate calculated for each plot is shown in Figure 8. The results show that the change in tree recruitment was not significantly correlated with precipitation ($-0.023<r<0.272$, $0.056<P<0.937$) except with annual precipitation ($r=0.299$, $P=0.035$). The regeneration rate of trees at the lower tree line was highly correlated with the monthly average temperature from June to July and September, the summer average temperature and the annual average temperature. Also, regeneration rate of trees at the lower tree line was correlated with monthly average temperature of February and August.

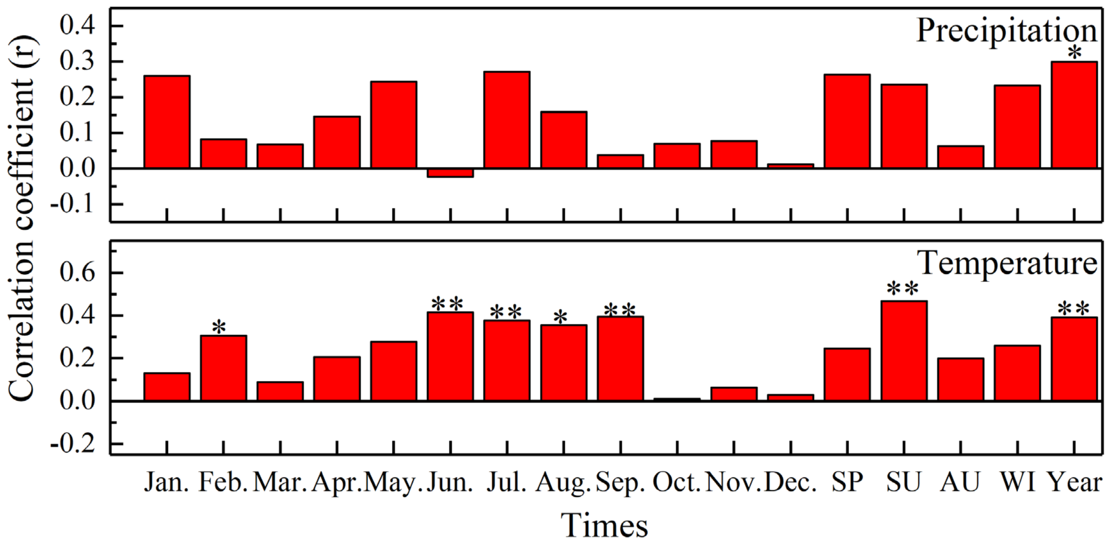

Figure 8. Pearson's correlation coefficients between the tree recruitment rate and temperature, and precipitation. (SP=Spring, SU=Summer, AU=Autumn, WI=Winter, * means $P<0.05$, ** means $P<0.01$)

4. Discussion

We sampled a typical *Picea crassifolia* Kom. watershed in the Qilian Mountains to determine changes in the location and pattern of the lower tree line and their relationship with climate change.

4.1 Variability in lower tree line position

The lower tree line decreased by an average of 9.82 m from 1968 to 2018, with the *Picea crassifolia* Kom. tree line ecotone exhibiting a downward tendency to expand. In a study of the upper tree line at high latitudes and altitudes, Harsch et al. (2009) found that 52% of the mountain tree line positions have shifted upward [41]; an advance of the tree line has been observed in Europe, North America, New Zealand, and in other regions worldwide [42, 43]. In some forests where the tree line did not expand upward significantly such as in subalpine fir forests in Glacier National Park, USA, tree line areas experienced a gradual alteration from tundra to forest [44]. At high altitudes and latitudes, the tendency of tree line area to expand had been detected and attributed to the warming temperature [45-47].

In the Qilian Mountains, vegetation cover of vegetation appears to have been increasing during 1982-2014 [48]. Carbon mass of *Picea crassifolia* Kom. forest in the Qilian Mountains has increased by 1.202 kg/m^2 from 1964 to 2013 [49]. One survey showed that *Picea crassifolia* Kom. forest population density increased 23-fold at the tree line, but the tree line position was not significantly altered during the past 100 years [50]. Another survey indicated that the elevation of the upper tree line shifted upward between 6.1 to 10.4 m from 1957 to 1980, but showed no obvious change in 1980 to

2007 [30]. Further, the number, area, and concentration of forest patches have been increasing from 1968 to 2017 in relatively flat and partly-sunny areas, but the rate of area increase and ascent of the tree line slowed after 2008 [51]. Our research results are similar to those from the Qilian Mountains; the lower tree line in the Qilian Mountains has shifted down in the past 50 years, but the shift is not large, and the expansion rate has begun to decline after 1998, with no change after 2008.

4.2 Pattern characteristics of *Picea crassifolia* Kom. forest

In site survey, 78% of the trees were recruited after 1960, therefore, most of the trees were small [52]. With an increase in tree age, the landscape pattern gradually changed from cluster to random distribution. The reason for this was that the young trees assemble in the direction of a parent-tree seed propagation and in an environment with less shade and rain; large trees were randomly distributed after the self-organization process of competition and self-thinning [30, 53], which describes plant mortality due to competition in crowded even-aged stands [54, 55]. The self-thinning rule predicts that for a crowded even-aged plant population a log-log plot of average plant mass versus plant density will reveal a "self-thinning" line with a slope of -3/2 [56, 57]. The major factor driving the self-thinning process is competition among plants [58]. Meanwhile the landscape change form cluster to random with an increase in tree age we observed was also consistent with one of the most important principles in plant ecology, namely, the competition-density principle which states that for a given dominant height or age, average tree size decreases as density increases due to competition for site resources such as light, water, nutrients and space [59].

4.3 Meteorological factors

Meteorological factors affect the distribution of tree lines and tree regeneration rates [3]. In our study, the regeneration rate of *Picea crassifolia* Kom. forest at the lower tree line position was highly correlated with temperature, and moderately with annual precipitation. The main meteorological factor that affects the distribution of the alpine tree line in China is the temperature during the growing season, and mostly precipitation affects the distribution of the tree line indirectly through temperature [60]. For *Picea crassifolia* Kom. forests that grow in high-altitude areas with sufficient rainfall, June temperatures control the melting of snow and ice, and July-August temperatures affect radial growth [61], and average temperature in the wettest season (growth season) has a significant effect on *Picea crassifolia* Kom. forests growth [17]. The expansion and regeneration at the lower tree line is also limited by annual rainfall [14]. A study which combined remote sensing and plot surveys in *Picea crassifolia* Kom. forests in Dayekou watershed revealed that the upper tree line was distributed at the threshold of mean annual air temperature at the upper elevation boundary of −2.59 to −2.73°C, while the lower tree line was distributed at the threshold of mean annual precipitation of 378.1 to 372.3 mm [62].

5. Conclusions

We used site surveys to investigate the change of the *Picea crassifolia* Kom. lower tree line position and landscape pattern in the Qilian Mountains. Our results showed that the lower tree line of *Picea crassifolia* Kom. forest had a descending trend from 1968-2008, and almost no change after that. Tree regeneration rates changes in lower tree lines were highly correlated with temperature, and also related to annual precipitation. In the past 50 years, the lower tree line of *Picea crassifolia* Kom. montane forests in arid areas exhibited a downward trend under climatic conditions of higher temperatures and increased precipitation. However, it is unclear whether the downward trend of the lower forest line will stabilize or even reverse due to the weakening of climate warming degree and warrants further investigation.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: Z.H. and S.F. conceived and designed the experiments; S.F. performed the experiments, analyzed the data and wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Figures

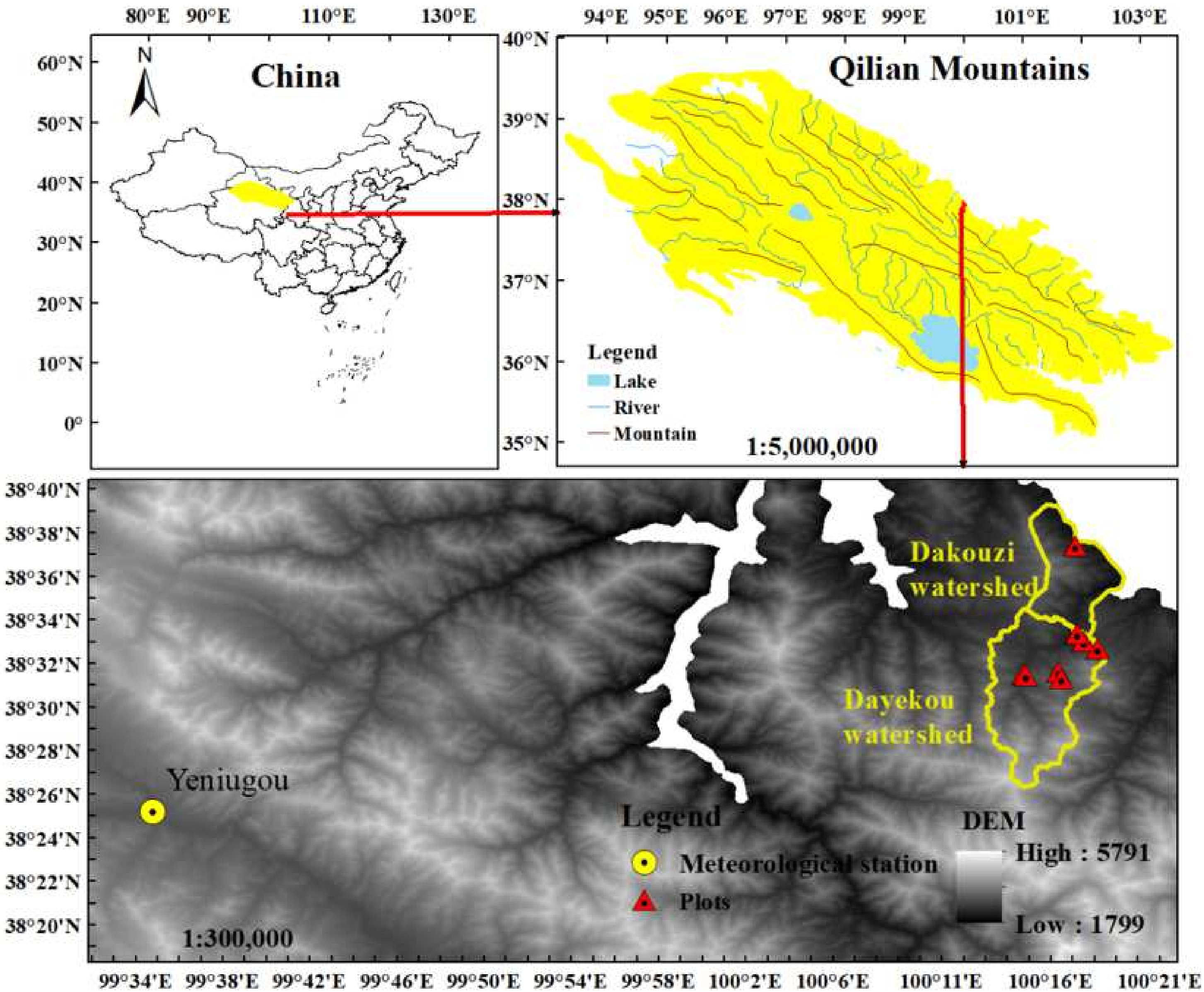

Figure 1

Study Area in the Qilian Mountains of northwestern China.

Figure 2

Examples of conditions in sample spots.

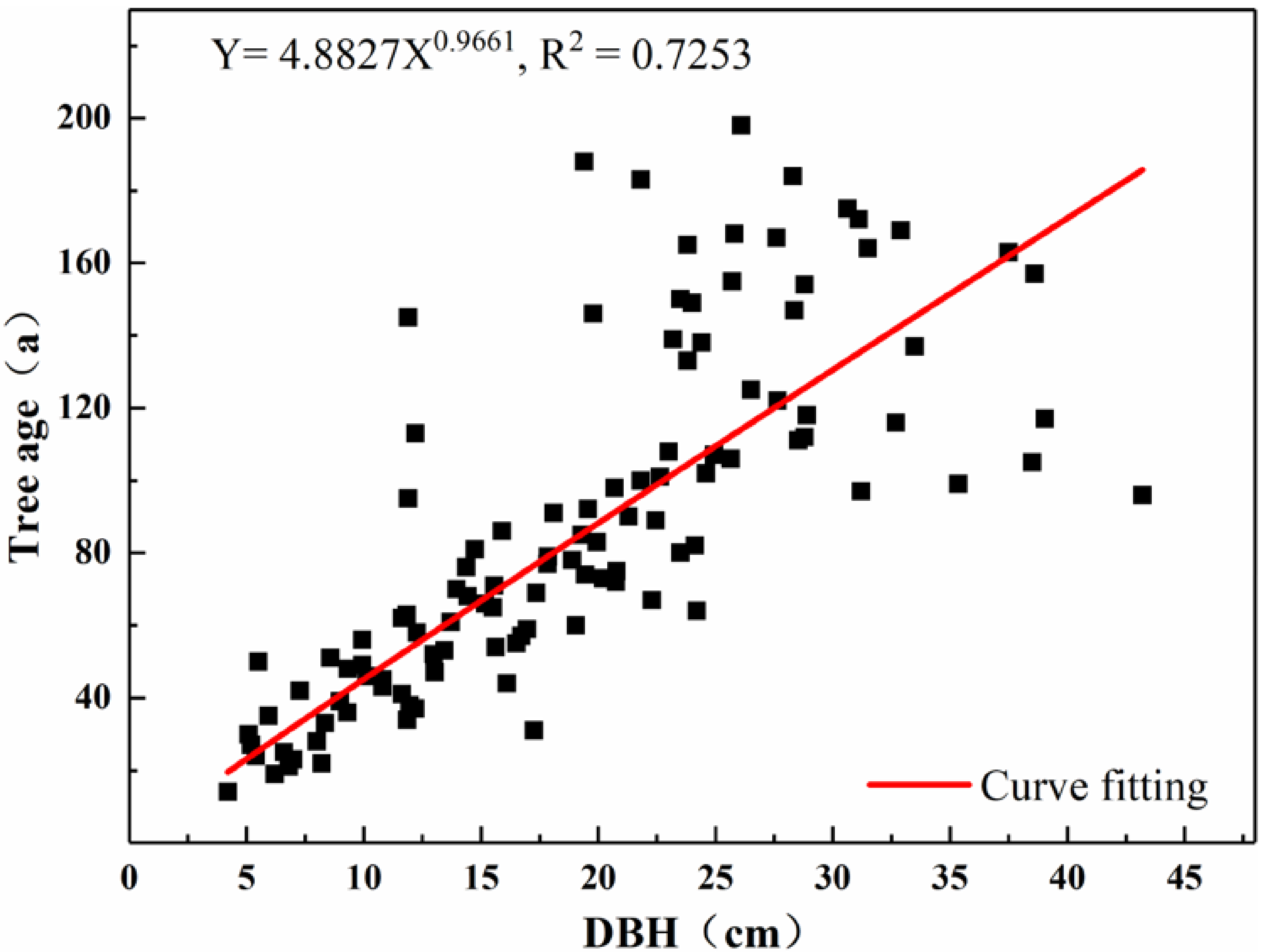

Figure 3

Functional relationship between diameter at breast height and age of trees in Guantai sampling.

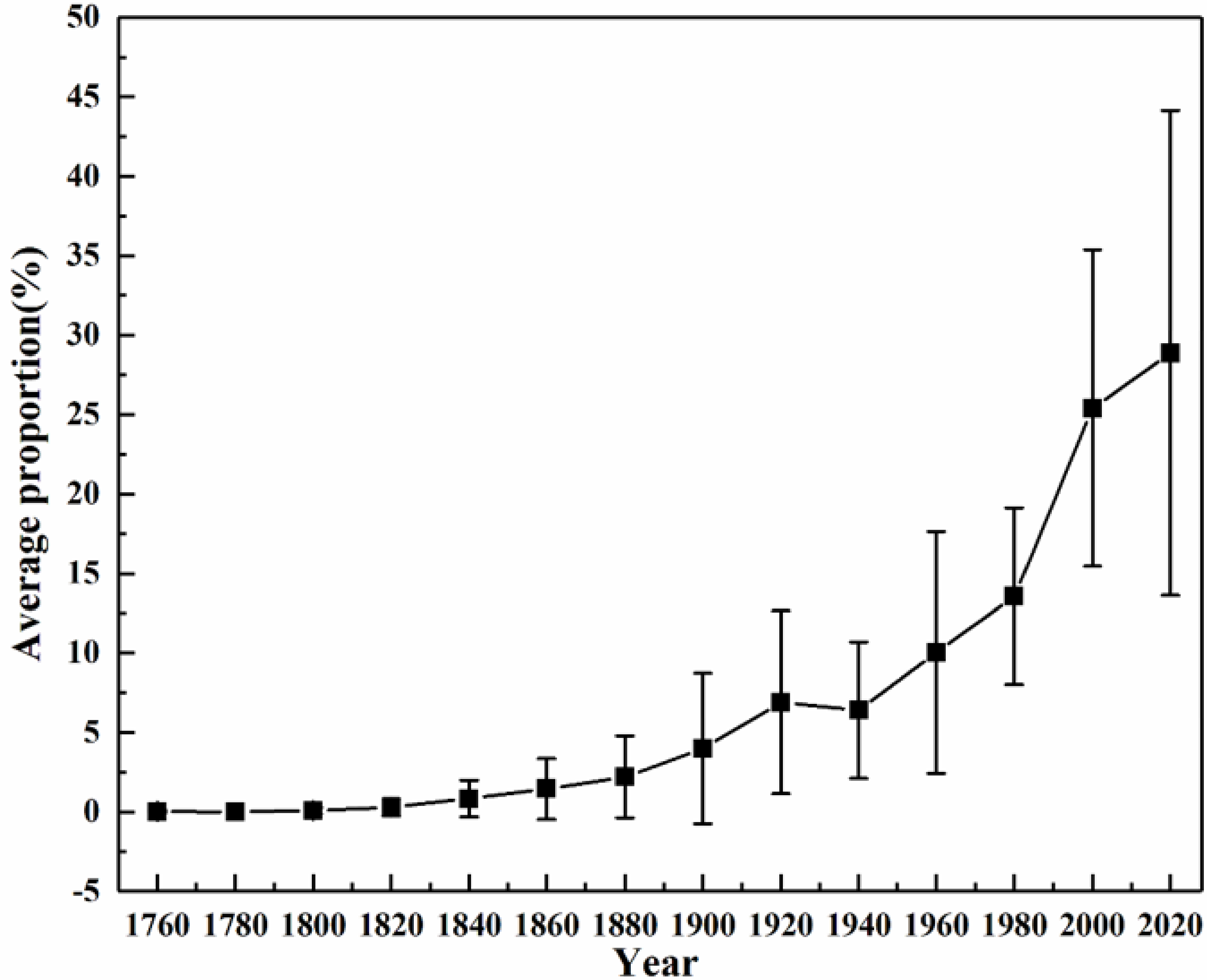

Figure 4

The age structure of the tree populations at the in the tree line ecotones plots at the lower tree line.

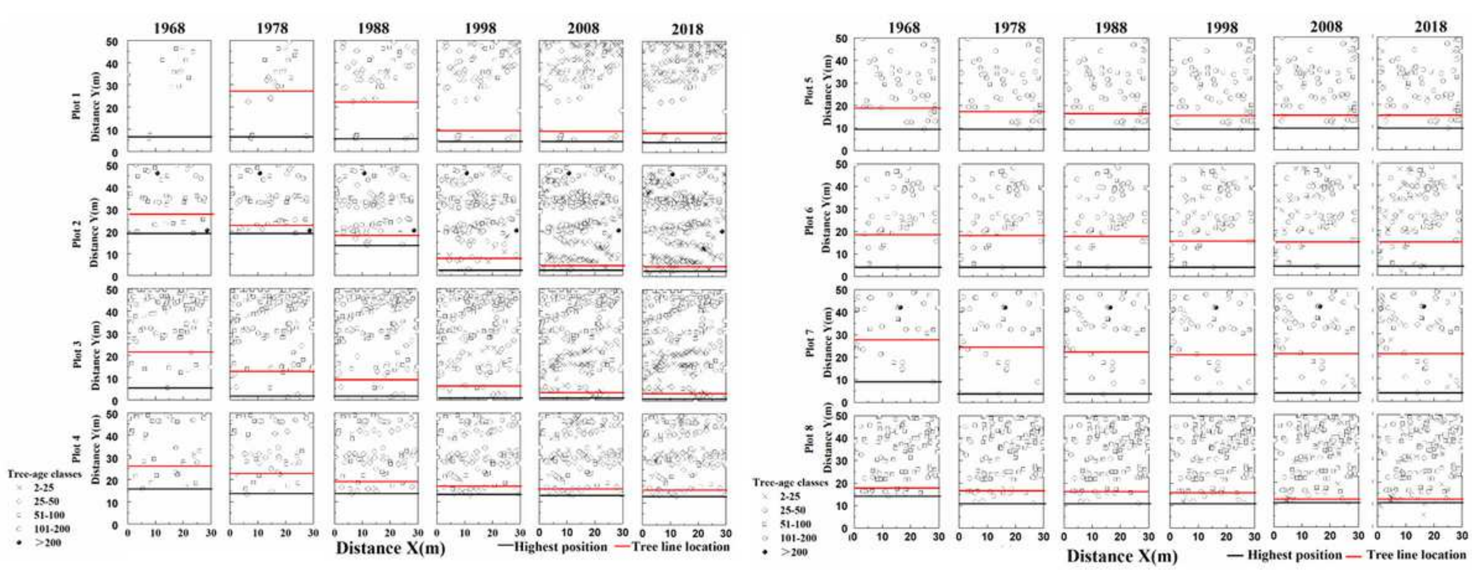

Figure 5

a. Changes in position of the lower tree line (1) (Distance Y(m) is the distance along the slope direction and Distance X(m) is the distance spline perpendicular to the slope direction.) b. Changes in position of the lower tree line (2)

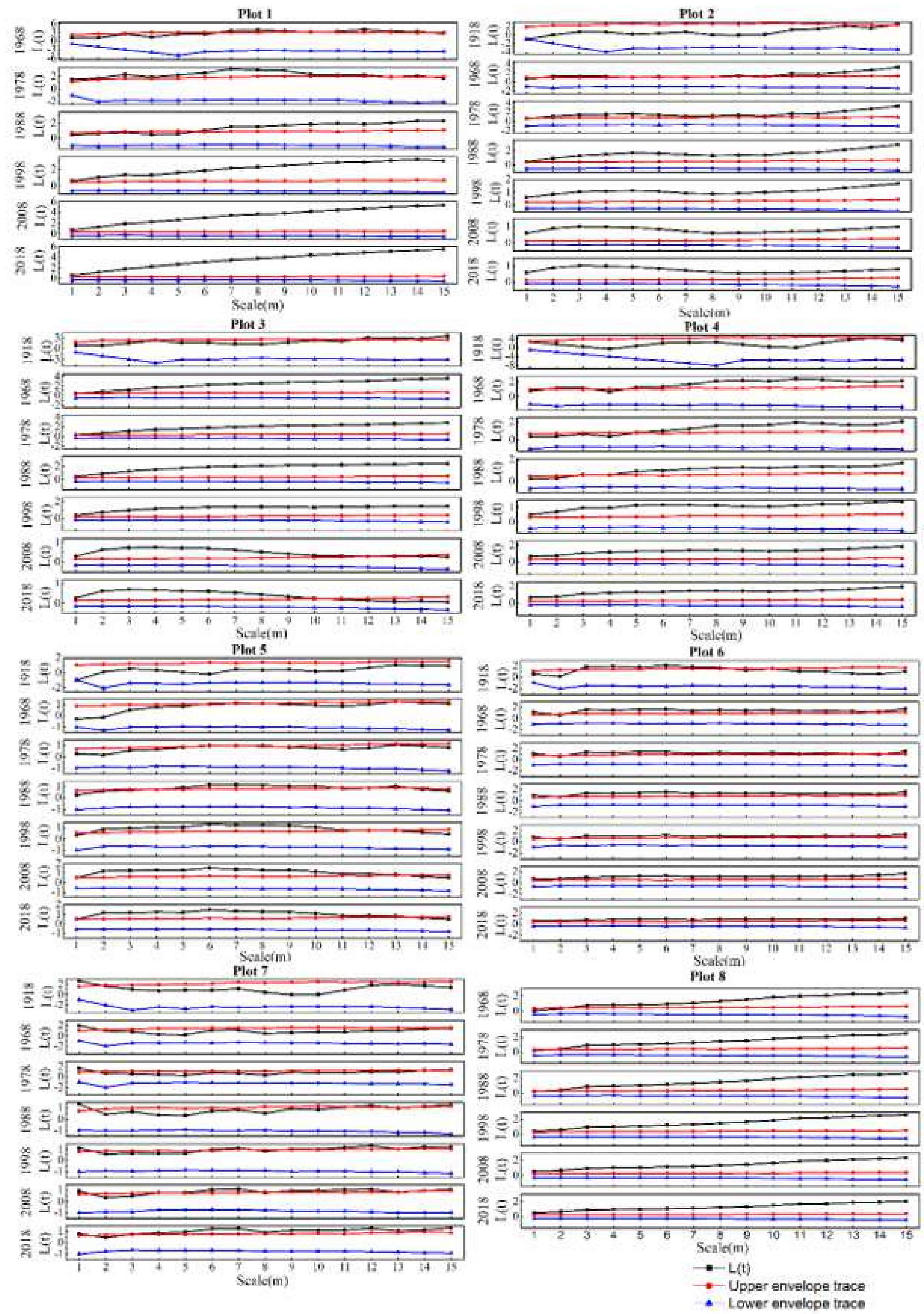

Figure 6

The change in point pattern (Graph of L(t) versus distance (t) for trees at each plot) at the lower tree line. The black line shows L(t), and the red and blue lines show the 99% confidence envelope for a random distribution.

Figure 7

Layering of trees of different ages.

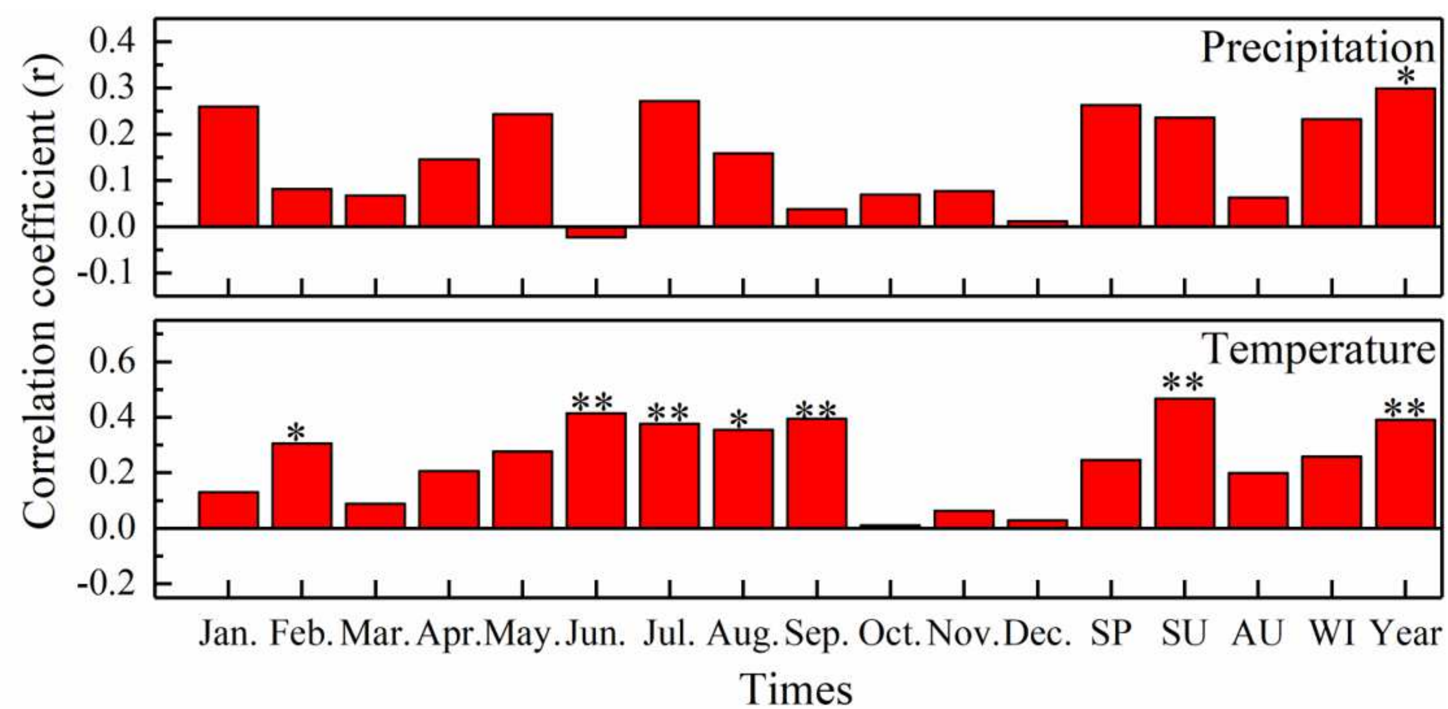

Figure 8

Pearson’s correlation coefficients between the tree recruitment rate and temperature, and precipitation. (SP=Spring, SU=Summer, AU=Autumn, WI=Winter, * means P<0.05, ** means P<0.01)